To Professor Lauren Cooper and the Mechanical Engineering Department

Activities for Mech E's Final Design Report

A Cal Poly Mechanical Engineering Senior Project

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6-9-2021

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Abstract

This document will describe the development of a solution for enforcing the topics covered in the ME 329 - Mechanical System Design curriculum by bringing quality equipment to a classroom setting. The project Sponsor, Professor Lauren Cooper, has also noticed a lack of hands-on experience for many students entering this class. Our team is attempting to develop a solution for this problem.

To better understand what students would want to learn, or would have liked to learn more about, we conducted surveys of past, present, and future students as well as conducted interviews with professors that have taught the course. We also researched past projects from different schools as well as articles of similar products that are and were on the market. All of this information led to the conclusion that students will most benefit from (and enjoy) a lab project where they first learn fundamental gear train concepts with an exploratory approach, then work on a project that combines the theoretical concepts learned in the course with the experimental results obtained from a physical apparatus.

Through ideation, concept prototyping, functional decomposition, and morphological decision-making, we came up with a two-part solution. The solution will be a pair of activities that students will complete over a multi-week period. The first activity will be a modular, hands-on apparatus that students can configure with different parameters to see how these changes affect the systems performance. In the second, students will apply their knowledge from the exploratory lab into a design activity that models a real-world scenario, in this case a wind turbine.

To prototype the activities, we purchased a number of components, screws, and measuring devices. Many of the components came from a single online supplier, ServoCity. These components were picked for their configuration capability, being able to be arranged into many configurations. The rest of the components require only a small amount of modification or are 3D printed.

Both designs were tested against technical engineering specifications, as well as at least some amount of user testing from current or former students and faculty. Both designs met the specifications, and we are confident they will serve well as solutions to the problem posed.

In addition to creating prototypes, we also developed lesson plans and lab manuals for both activities. The former provides suggestions to professors for how to implement the activity including optimal group sizes, time to spend on each activity, and work to require of students. The latter prepares students to interact with the activities and walks them through guided activities to facilitate discovery of important concepts.

The following report describes the background, objectives, design process, prototyping process, and verification process for this project as well as the recommendations and next steps for our Sponsor after receiving the results.

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1. Introduction

Our challenge is to design a lab-based project that the typical student taking the course can get a basic understanding of industrial grade components, while applying analytical problem solving learned in the lecture portion of the course. This lab will also serve as a stepping-stone to future labs of the course as well as a project that models a real-world scenario. A typical engineering student will encounter gears throughout their early curriculum. In these low-level classes, they usually encounter gear speed and diameter ratios along with some torque analysis, which were all analytical and theoretical. These were just brief discussions and equations that did not fully explore the in-depth analysis that goes into gear design. By the time that these students reach the junior level course "Mechanical System Design," many students will have never held a physical gear.

Lauren Cooper is one of the professors who teaches the design course in Cal Poly. In addition to teaching classes Professor Cooper has been interested in learning how to teach high level engineering curriculum more effectively and has conducted significant research into the topic over the years. Throughout her time at Cal Poly, she has noticed a need to better enforce the analytical and conceptual teachings that come with gear analysis. To achieve her goal of creating a lab that accomplishes her vision, we four diverse ME students have accepted the challenge to find a solution. Our team is composed of Jack "Diego" Cerron, Brennen Irey, Jose Chavez, and James "Jim" Popolow. We are all soon-to-be graduates of Cal Poly's Mechanical engineering program at the time of this project. Between the four of us we have experience with designing and analyzing power drive systems, mechatronics, educational activity design, and many other skills that make us well-suited to take on this project.

The following details the design process we used to determine what the customer wanted this project to accomplish. The first major step was to gather background information:

- meetings with sponsors and stakeholders
- surveys with past students and future students to the design course
- referencing existing and relevant products
- relevant educational technical documents
- and regulations and standards of equipment.

We also implemented certain design objectives to better understand and organize our findings:

- the problem statement (Section 3.1), which was drafted after extensive interviews and surveys
- a boundary diagram (Section 0), that summarizes the idea what the project should lead up to
- a need and want list (Section 3.3), used to ensure the sponsors needs are met
- QFD or house diagram (Section 3.4), weighs the sponsors needs and wants with constraints
- specifications about our product (Section 3.5), includes different parameters
- and the design process (Sections 4.1 and 5.1), for developing each component of our solution.

2. Background

Our background research consisted of product, customer, and technical research. Our customer research included sponsor and stakeholder meetings as well as surveys sent out to mechanical engineering students at Cal Poly. Our customer research helped us define our problem and the customer's needs/wants. Our product research consisted of searching for patents and existing products that were related to our project. The technical research we completed focused on finding examples of similar projects and labs used by other universities.

2.1 Customer Meetings and Interviews

To gather information about the goals for our project we conducted meetings with our sponsor, interviews of other ME 329 professors, and surveys of ME 329 students. The most important questions we wanted to answer are listed below[1].

1. Which teaching techniques have worked in the past and why?
2. Which did not work and why?
3. What aspects are most important for an effective lab activity?
4. Which concepts would be the best to build a lab activity around?

2.1.1 Primary Stakeholder Meetings

With Professor Cooper as our primary stakeholder, it was particularly important that we gather information about her past experiences and what she was looking for from this project. To summarize our initial meeting [1]:

- Students sometimes have difficulty connecting lab activities with real world applications
- Most existing lab activities are either not hands-on, feel like a toy, or are too abstracted from industry application
- An activity related to wind turbines might be great for both Dr. Cooper and students
- The best topics to cover would be gears, gear trains, and/or fasteners
- Quality of parts are not *as* important as the context of the lab experiment

2.1.2 Secondary Stakeholder Interviews

In addition to Professor Cooper, we have also gathered information from other educators including:

- Professor Schuster [2]
- Dr. Widmann [3]
- Professor Mello [4]

We found that, in general, they agreed on several key things. The solution should be:

- Safe
- Easy for faculty to use
- Easy for students to use
- Easy for the department to acquire and maintain
- Hands-on and interactive
- As high quality as possible

[1] The full list can be found in Appendix A Stakeholder Interview Request and Questions

All interviewees agreed that gears and gear trains were probably the best concepts to focus the activities around. Shafts, bearings, and lead screws were also mentioned as secondary concepts. Through anecdotes, we also compiled a list of previously attempted labs and feedback about them.

Table 1. Previously attempted ME 329 lab activities

Lab	Pros	Cons
Lego technics design builds	Models real systems Safe; lower speeds/loads Exaggerated limitations	Felt like a toy often be too weak to accomplish proposed design goals.
Passing around components	Exposure to industrial parts	Not enough exposure to applications
Parts from a bag quizzes	Teaching concepts	Not very interactive or exploratory
DC motors parameterization	Produced good data in response to changing parameters	Too simple and focus too narrow
'See-through' car transmission	Applicable to real world	Small window, hard for groups
Open ended design projects	Practicing design concepts	Doesn't teach foundational concepts, skips straight to applying them
Mechanical System Dissections	Experience with real parts	Hard to acquire/maintain

Many of these past activities address some of the need outlined by Professor Cooper, but none of them address it entirely. Our product should attempt to maximize the best aspects from these previous activities and minimize all of the drawbacks that are the reason there is still a need to be filled.

2.1.3 Student Interest Survey

While our product is a teaching tool for professors, it directly impacts their students as well. We wanted to know what types of lab activities students prefer and what topics they would find most useful in a lab activity, so we put together a Microsoft Forms survey and sent it to past, present, and future ME 329 students. We received 88 responses; 50 from students who have already taken the class, 35 from those who were currently in it, and 3 from students who have yet to take it.

1. <u>What type of lab activity would be most useful to have more of in classes like ME 329?</u>
   This first question presented students with a list of descriptions of different types of lab activities. They were allowed to select any number of them to indicate which ones they find most useful.

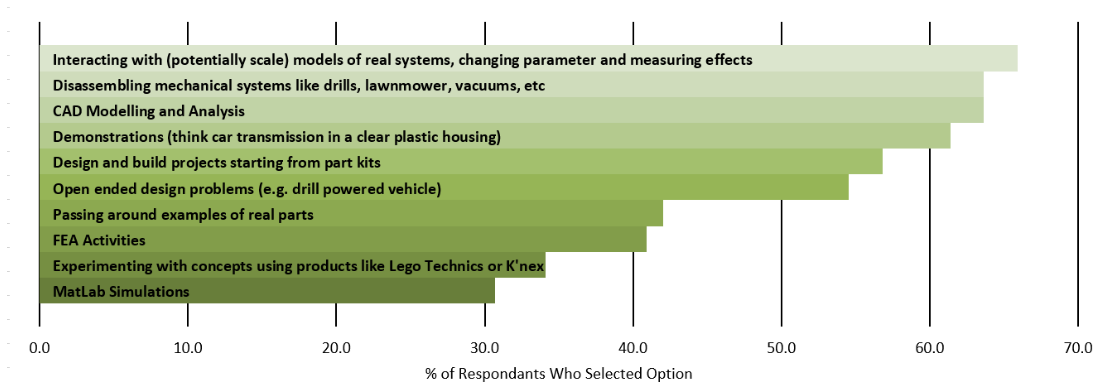

Figure 1. Responses from students indicating which lab activity they would find most beneficial.

The results of this question, shown in Figure 1, clearly indicate that most students find hands-on activities, which apply concept to real world scenarios, useful. While CAD Modelling and Analysis scored very high, the rest of the high scoring options are all hands-on[2] and interactive[3], while the 'virtual' activities such as FEA and MATLAB simulations were some of the lowest scoring. In fact, the option most similar to the goals of this project was the highest scoring, confirming interest our product.

2. <u>In a few words, what is it about the types of activities you selected that makes them useful?</u>
   The responses[4] to this question would help us to understand which aspects to make sure to include in our solution.

Unsurprisingly, the idea of getting hands-on experience with systems design concepts taught in lecture resonates with Cal Poly students. Words related to this were the most common in responses and appear largest in Figure 2. After that, almost all the medium size words such as 'real', 'real-world', and 'interactive' support the type of solution Professor Cooper is looking for.

Figure 2. Student survey Q2 responses, the more common the word, the larger it is.

3. <u>Which of the following would be the most interesting/useful to you as the topic of a lab activity?</u>

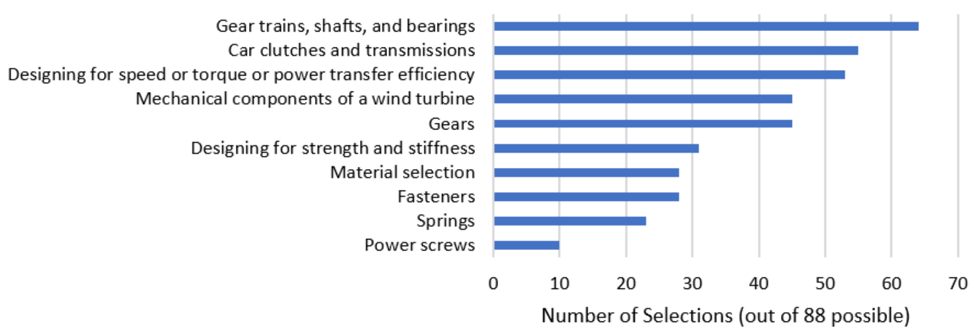

Figure 3. Responses from students indicating which topic they find most interesting.

The results of this question, illustrated by Figure 3, clearly show that students are most interested in activities related to gears and gear trains. 'Mechanical components of a wind turbine' also scored very high, supporting Dr. Cooper's desire for a wind turbine related activity.

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[2] 'Experimenting with concepts using products like Lego Technics or K'nex' was low scoring even though it is hands-on. This indicates student's interest in using higher quality parts and interacting with more 'real-world' systems.
[3] 'Passing around examples of real parts' also scored low even though students get to interact with real parts. This indicates that the interactive quality of a lab activity is especially important.
[4] A list of all of the responses can be found in Student Interest Survey Q3 Responses

2.2 Discussion of Existing Designs

We encountered some difficulty when exploring existing products applicable to our problem. During our research, we noticed that many of the products related to hands-on learning or early prototyping targeted electrical engineering and optics research. Despite hands-on learning products for mechanical systems being less common, we were still able to find four products and one company that make products similar to our project.

<u>1. PIC Design Educational Kits and Precision Tools / W.M. Berg Mechanical Breadboards</u>

PIC Design and W.M. Berg both produced similar products before. PIC Design tailored their product towards education with a product line showcasing a variety of electromechanical systems. W.M. Berg's breadboard system was designed for prototyping use in industry settings. Figure 4 shows a kit from PIC Design. The design of the product is very similar to W.M. Berg's breadboard system pictured in Figure 5. Both use a slotted base that allows modular components to be arranged as the user desires. [5, 6]

Figure 4. PIC Design's KE-120 kit, demonstrating the core design of their education kits [5]

Figure 5. W.M. Berg's mechanical breadboard system [6]

<u>2. Stokys</u>

Stokys is a German company that produces kits similar to Meccano's ERECTOR product line. Stokys is made with higher quality components and is aimed at a more mature user-base. Their kits contain various sizes of metal plates with a grid-work of holes in them, various mechanical components, and fasteners. The metal plates can be easily shaped by hand to create custom geometry. Looking through the Stokys community, members have gone beyond what is provided by Stokys and integrated more advanced components such as microcontrollers and motors to further customize their project. [7]

Figure 6. Stokys Basic set PRO Kit [7]

3. Tecquipment/PASCO

Tecquipment is a U.K. based company that produces testing and exploratory equipment for both higher education and industry. They provide a wide array of products related to engineering. Two products that we found when researching Tecquipment are their Gear Trains Kit and Geared Systems Unit. The Gear Trains Kit demonstrates the characteristics of spur and bevel gears as well as worm drives. The kit components can be mounted to a vertical metal plate with a grid-work of holes in multiple configurations. [8] The Geared Systems Unit is a more analytical product. The system allows the users to analyze the efficiency of different drive systems and comes with its own software to control and view power and efficiency readings. [9] Similarly, PASCO produces lab equipment and curriculum that cover a variety of STEM subjects at education levels from elementary to college. While PASCO does sell a lab that demonstrates mechanical systems, it is aimed at high school students rather than college students. [10]

Figure 7. Tecquipment's Geared Systems Unit [8]

2.3 Table of patent search results

In addition to researching existing products that attempted to solve our problem, we also researched patents that were relevant to our project. Our results are tabulated in **Table 2** and include the patent number, the year the patent was filed, and a brief description of the patent.

Table 2. Table of patents for related products

Patent #	Year Filed	Description
CN202145360U	2011	A teaching aid designed to improve understanding of different mechanical drive systems [11]
US4006538A	1973	An educational kit designed to help students understand the basics of switching and relay operations [12]
US3986278A	1974	An educational kit designed to teach the operation of an automobile transmission [13]
US9387411B1	2013	A toy car designed with an open frame that showcases a realistic drive train and steering linkage [14]
US5575660A	1994	An automotive maintenance kit that instructs users how to remove/maintain vehicles using a miniature scale model [15]

2.4 Summary of the relevant technical literature

During the existing product research, we found that multiple universities have tried to come up with activities for their machine design class. We evaluated each design and set aside the components that would be useful for our design.

2.4.1 Three-speed gearbox analysis and gear-box design

Griffith University came up with a 13-week semester machine design course for their undergraduate mechanical engineering students. In the first phase, a 3-speed gear box was the first lab activity they offered, shown in Figure 8 The goal of the first lab activity was to make students explore and examine a real world 3-speed gearbox. In small groups, students had to identify the following:

- The types of gears used.
- Count the number of teeth on all gears.
- Figure out the transmission ratios.
- Describe the power path through the transmission
- Determine the output shaft torque under a given input condition for different gears
- Develop a basic sketch of the gearbox layout

Teams were also given a specific set of input condition parameters, such as power rate and speed. By the end of the lab, each team had to record their findings so they could use it for their report. [16]

In the following weeks, teams had to apply their knowledge gained from previous lectures and labs to build their own gear box. The parameters used for the design were collected from an ASE small race car prototype. Later, students had to present their design and explain their calculations and decisions. The design was sent to an open system design in EXCEL where students were able to modify their design. The final product was transferred to SolidWorks and 3D printed. This is shown in Figure 9. Similarly, at Central Washington University, a 3-speed manual transmission from a 1950 F series pickup was analyzed. Students were able to become familiar with the main components, learned about their connections, and created a report with their findings. A survey was collected from students at the end of the semester. With a score 4.3 of 5, students thought that the lab activity increased comprehension of the operation of transmission. Even though students thought that the study of an old transmission was valuable, they were not sure on how to apply their knowledge from this lab to other styles of transmissions. [17]

Figure 8. Three-speed gearbox [16]

Figure 9. 3D printed gearbox components [16]

2.4.2 Gear lab activities

Multiple lab activities were introduced at Marquette University. These lab activities included a commercial gear box, a recreational vehicle leveler, a motorcycle engine transmission, and a small, geared motor. Figure 10 shows some lab activities used. At the first station, students learned about gear ratios, identifying the types of gears and the situation in which they will be used. They also sketched free-body diagrams with forces acting on the gear's teeth at different conditions. At the second station, students gained experience with the fundamentals of gears by learning the tradeoff between torque and speed to accomplish desired tasks. At the third station, students investigated the gear reduction in a geared motor assembly. Speeds of the motor and output shaft were measured with a laser tachometer. The geared motor was disassembled, and the train ratio was predicted by counting the teeth of each gear combination. Finally, the students were assigned to design a 5-speed constant mesh transmission for a motorcycle engine with spur gear and other design criteria. [18]

Figure 10. Lab activities. **A,** HVAC baffle. **B,** RV leveler. **C,** Transmission in motorcycle engine. [18]

2.4.3 Wind turbine design

A wind turbine design, shown in Figure 11, was incorporated at the University of Pittsburgh as a laboratory activity in their mechanical engineering machine design course. Students had to use knowledge gained from previous courses and laboratories. A DC motor and propeller were provided along with their performance curves. The task was to come up with the proper gear ratio, calculations, drawings, description of the design with justification for all decisions and assumptions, cost analysis, and a performance analysis. The laboratory was successful at providing students the opportunity to apply the design process. However, the project was not sufficient to require students to use all the knowledge they had learned in lecture. Force outputs from the wind turbine was relatively small and failure concerns were minimal. [19]

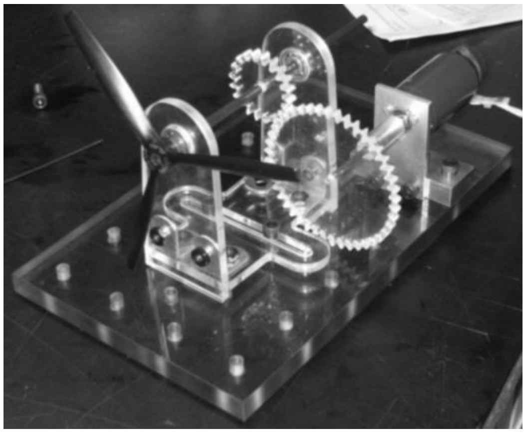


Figure 11. Student-designed wind turbine gearbox model [19]

2.4.4 Design and fabrication of planetary gearset

Students at the Rowan University were presented with a long-term project of a bench-scale hybrid electric power system. One of the modules in the hybrid powertrain was to design, build, and test a planetary gearset that combined two inputs into one output. One of the inputs came from an electric motor while the other one came from an air motor. The output connected to a chain sprocket. The complete built design and 3D drawing can be seen in Figure 12. At the end of the project, students had to submit the following:

- A five-minute YouTube video explaining the gear design and operation.
- A report showing the design decisions and calculations to obtain speed, ratio, and efficiency of the gear set.
- A 3D drawing of the CAD model included in the report.

Before students were sent to build their projects, an in-class assignment was given to help the understanding of planetary gear trains. They had to establish a relationship between the two inputs and the output shaft at various input shaft speeds. Based on the student feedback, an overwhelming 96 percent of the students felt that the hands-on project was valuable in the Machine Design course, and 80 percent of them enjoyed working on the project. [20]

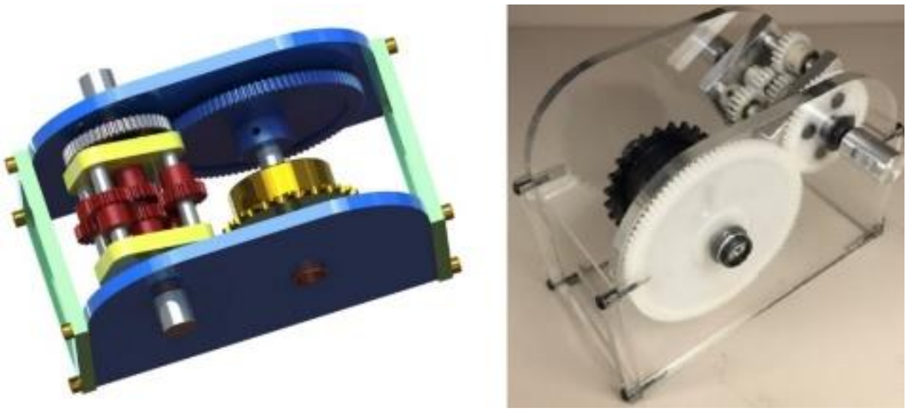


Figure 12. Spur and planetary gear set design [20]

2.4.5 Capstone powertrain project

The goal for this design was to make a group of students build something meaningful for them and the engineering department at United Arab Emirates University. They were assigned to build an inspiring capstone that integrated concepts learned in the machine design class. A powertrain system had to be designed and built to rotate the capstone at a certain rotational speed. Components for the powertrain are shown in Figure 13. The motor and gearbox were purchased from a source because the gear ratios had a very high reduction. All the other components were chosen from a catalogue based on calculations. In conclusion, this project made students enthusiastic because they were able to apply related concepts learned in class.

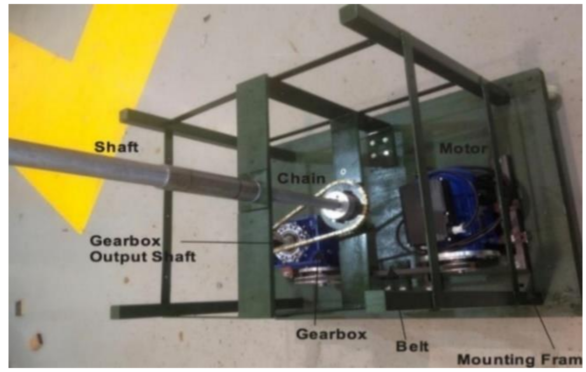


Figure 13. Powertrain components for capstone design [21]

3. Objectives

Having collected some background information from our customers and gathered research on previous solutions, the next step includes formalizing the problem and developing metrics against which we will measure the success of our eventual solution. To do this, we need to accurately define the problem, scope the solution space, and conduct a quality function deployment process using customer needs and wants to determine engineering specifications.

3.1 Problem Statement

Professor Cooper, and other ME 329 professors, need a way to teach students power train design concepts in an interactive, hands-on way that shows the application of the concepts to real-world systems. These laboratory activities should be easy to use, low in cost, durable, and provide students with an exploratory and learning experience using the highest quality parts that will focus on gears, shafts, and bearings. They should produce measurable results in response to changing parameters. It should also help them through a design activity that will model a real-world scenario.

3.2 Boundary Diagram

Upon defining our problem statement, we sketched the boundary diagram pictured in Figure 14. The diagram shows a visual representation of the goals of this project as well as the supporting context.

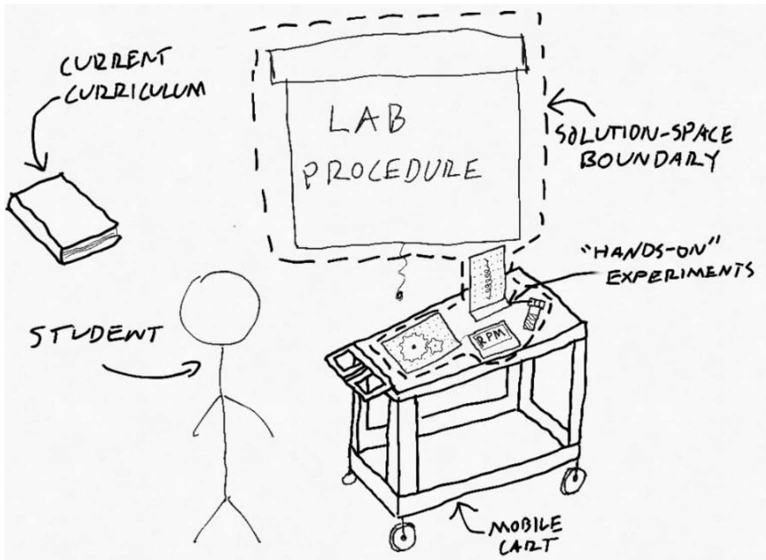


Figure 14. Boundary diagram for mechanical system lab activity

Everything within the dashed line is what we will be responsible for producing while keeping in mind everything outside the boundary. We will also be providing the cart for transportation of our solution.

3.3 Customer Needs and Wants

Having identified the boundaries of our solution space, we went back to the notes from our Primary Stakeholder Meetings and Secondary Stakeholder Interviews to compile a table of customer needs and wants[5]. The most important of these are:

- Safe and easy to use for students
- Interactive with measurable outputs
- Applicable to the real world

If possible, the solution should be:

- Manufacturable by student shop techs on site
- Composed of off-the-shelf, industrial level parts
- Robust and maintainable

Identifying these needs and wants is the first step in developing engineering specifications by which we will measure the eventual solution against. The next step is to work them into the Quality Function Deployment Process.

[5] For the full table see Table of Customer Needs and Wants

3.4 Quality Function Deployment Process

To make sure we are solving the right problem and meeting the engineering specifications for the project, we built a House of Quality by following the quality function deployment (QFD) process, The QFD process has multiple sections:

1. The "**Who**" section includes the parties that will benefit from this project, i.e. sponsor and students.
2. The "**What**" section contains the needs and wants of those in the "who" section and are ranked based on the importance to each party.
3. The "**How**" section states quantifiable specifications reflecting the customer's needs such as 'overall weight' or 'assembly time of the final product'.
4. Each specification is then correlated to each need/want it is related to using symbols representing strong, moderate, weak, or no relationship. This helps to determine the relative importance of individual specifications. The goal was to have no need/want without a specification, and no specification without a corresponding need/want.
5. The "**How Much**" section defines concrete targets for each specification, determines the relative importance of each, and allows a comparison with existing solutions.

The result of the QFD process is a strong understanding of the interaction between different elements involved in our project and allowed us to conclude that there are no existing solutions that fully meet the needs of our stakeholders. The specifications it helped to produce will also help us to determine whether the needs for the product have been met during the prototyping and testing phases. The full House of Quality can be found in Appendix D.

3.5 Specifications

Table 3 lists the engineering specifications for our project gathered from our QFD process. This table includes different parameters and a way to test them. For a successful final design, we will have to meet all the product's requirements and tolerances. Each parameter description is assigned a risk factor of high (H), medium (M), and low (L). One example is the size description assigned with a high risk because we thought it may be difficult to meet the requirement that the final product must fit within a shopping cart, and it cannot be taller than a door. Another example is the production price for our product. This was assigned as high risk because producing a solution that fulfills the needs of our customers within a budget of $1000 will be a challenge. Lastly, the compliance column describes the method by which each specification will be tested; analysis (A), test (T), similarity to existing design (S), and inspection (I).

Table 3. Engineering specifications

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Weight	500 lb	max	L	A, T
2	Size	45"x 25"x 47"	max	H	A, T
3	Production cost	$1,000.00	max	H	A, T
4	Production time	8 hr	max	M	T
5	Set up time	10 min	max	L	L
6	% of standard parts	80%	min	L	A
7	Ease of use	pass/fail	n/a	M	A, I, T
8	Measurable outputs	4±2	min	L	A, T
9	Noise	85 dBA	max	L	A, T

The following list provides a description of the engineering specifications and ways of testing them:

1. The combined weight of final products will be tested on a scale. This weight must be 500 lb or less.
2. The final height, length, and width of the product will be measured with a tape measurement. The specified parameters were gathered from a utility cart.
3. The production cost will include the total price for parts and manufacturing of the final product.
4. The assembly time of 8 hours includes machining and assembly for the final product.
5. Professor will usually have about 10 minutes to prepare for lecture between classes. The final product needs to meet this time constraint and will be measured with a timer.
6. The final product must be at least 80% made of standard parts and materials.
7. Cal Poly students will test the ease of use of the final product. They will assign it with a pass or fail.
8. The final product needs to have measurable outputs, i.e. speed and torque. A tachometer could be used to measure speed.
9. The noise from the final product must be less than 85 dB to prevent noise distraction in the classroom setting. This is based on OSHA defined noise limits in an 8-hour workday environment. This could be measured with a cell phone application. [22]

Our team felt that it was reasonable to take the vibration testing off the engineering specification because of the variation set ups and frequencies each design could have. It will be impractical to measure and calculate the frequencies for each possible design made by the users. Furthermore, the driving input speed will be low making the consequences of reaching the geartrain's natural frequency minimal.

3.6 Scope of Work

Having identified and researched the project stakeholders, their needs and wants, existing solutions, potential solutions, and budget/time restrictions, our team has settled on several decisions regarding the scope of our work for this project.

1. Our solution will focus on teaching the course concepts related to gears, gear trains, and power transmission systems as this subject matter is both a significant portion of the course curriculum and underserved by current lab activities.
2. We have determined that the best solution would be an integrated 3-step activity consisting of
    a. An Exploration Activity where students explore and discover gear and power train concepts.
    b. A Demonstration Activity where students are shown an example of how these concepts are applied in the real world (e.g. a manual car transmission).
    c. A Design Challenge for which students are encouraged to apply the concepts they learned from the previous activities to produce a working power transmission system.

    However, due to budget and time constraints we have decided to focus on producing just the <u>Exploration Activity</u> and the <u>Design Challenge</u> as deliverables for this senior project. We recommend that perhaps a future senior project group could produce a demonstration activity that would integrate well with our solutions, such as a manual car transmission with clutch intact that has been set up to allow visual access to the gear train as well as manual rotation of the shaft by students.

3. While our engineering team will primarily focus on producing the physical apparatuses used for each of the activities, we will also work with our sponsor to produce learning objectives, lab procedures, and other supporting documents that will assist professors with integrating our solution into their lab curriculum.

4. Exploration Activity Concept Design

The team used the concept ideation process to come up with a 'magnetic breadboard' as our final concept design. The process included:

1. Creating a functional decomposition
2. Ideating on solutions for each function
3. Modelling the best ideas
4. Evaluating through Pugh and weighted decision matrices
5. Selecting the scoring design components and compiling them into the best design

The final concept allows students to explore the fundamentals of powertrains by having many configurations. The best configuration ideas will be tested and shown to our sponsor to make sure they perform their required tasks. The magnetic breadboard configuration is shown in Figure 19.

4.1 Development Process

As a base to develop multiple ideas for our project we developed a function decomposition tree that focused on the most important functions our overall project should consist of. Each of our main functions contain a few sub functions to better describe the main function and serves as a steppingstone for the ideation process. The function tree outlines six main functions:

- the exploratory lab should provide quantitative measurements
- demonstrate qualitative properties
- engage the students
- prioritize safety
- the practicality of the overall apparatus should be considered
- be cost effective.

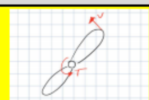
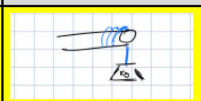
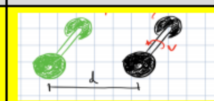
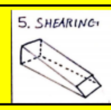
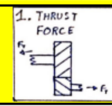
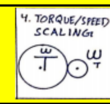
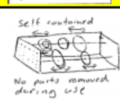
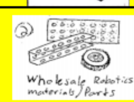
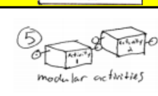
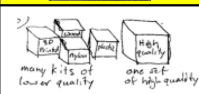
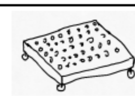
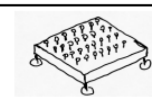
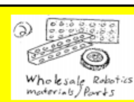
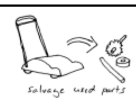
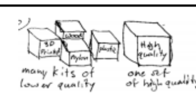
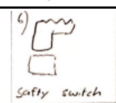
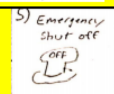
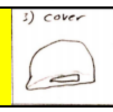
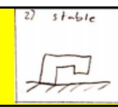
These functions and sub functions were utilized to fuel the ideation process and prototype building.

We started the ideation process by brainstorming our own individual ideas while taking into account the function decomposition tree we had created. This helped in the concept prototype building. Appendix E shows the prototypes that each member of the group created. These basic builds helped us improve our ideas and eliminate ideas that were unrealistic. We then compiled all of our ideas into a three-column table categorized by: what, how, and results. This table was used to create decision matrices that focused on the main functions of the function tree.

For each of the main functions from the function tree, an individual Pugh matrix was created and can be seen in Appendix G. The Pugh matrices we created also took into account the needs and wants of the customer, but only the ones that best fit the main function. They were then closely analyzed and given a proper score reflecting the need or want by using a +, -, or s. The top four ideas of all the Pugh matrices were compiled onto a morphological matrix.

The morphological matrix, seen in Table 4, helped us generate multiple ideas for meeting the functional requirements and combine those ideas into several different possibilities for concept designs. It includes the function requirements on the far-left column, and the top ranked functions from the Pugh matrix, on the other columns.

Table 4. Morphological matrix table for exploration activity

Function	Idea1	Idea2	Idea3	Idea4
Quantitative measurements				
Qualitative properties				
Practical				
Configurable				
Cost				
Safety				

Since one of the goals for our design is to provide students with multiple learning opportunities, the first two rows, quantitative measurements and qualitative properties, where included for all four design ideas. Additionally, the other four rows where used to combined different possibilities for a full design. The third row shows the practical applications for each design idea, i.e. modular or set activities. The configurable row included different ways to mount parts that will be configurable by students. The price and quality of the design is very important. Therefore, the fifth row shows difference sources of prices for parts. Lastly, we had to incorporate ways to keep our design safe for students by implementing safe measures as in safety switches or covers.

Each team member was responsible for coming up with one concept from the morphological matrix. In the end, four full concept design ideas where generated. Complete drawings and descriptions for the four concept designs can be found in Appendix H. One example is the 'magnetic breadboard' design which can be seen in **Figure 15**.

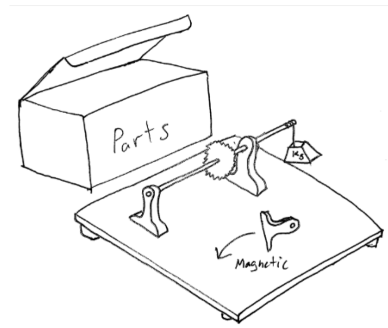


Figure 15. Magnetic base plate design concept.

It includes robotic wholesale parts that are practical and cost effective. These parts will be magnetized to a steal plate.

Our team used a weighted decision matrix, shown in Appendix I, to compare concepts to aid in deciding on a design. The QFD's specification and their relative weights helped with the comparison. Five design ideas were included in the decision matrix. Each element of the design idea was given an importance score value between one and five, one meaning the idea is relatively unimportant in the final decision, and five meaning it is very important in the final decision. Next, each score got multiplied by the specification' relative weight score. At the end, we combined those scores by adding them up. The option with the highest summed score should be the best choice.

The best concept design from the weighted decision matrix was the 'magnetic breadboard' design. We decided to take its recommendation because this design concept excels at being easily maintainable and machinable. Using a pegboard system, like in the other three designs, requires keeping track of all the fasteners and ensuring they are working correctly. The first design's components, seen in Figure 16, could stop locking properly if the mechanism were to be damaged or improperly maintained.

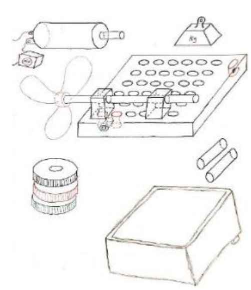


Figure 16. Design 1 with the horizontal baseboard covered in with holes that uses special locking peg components.

Designs 2 and 3, shown in Figure 17 and Figure 18 respectively, could lose their fasteners if a careful inventory is not kept.

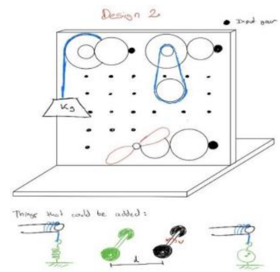


Figure 17. Design 2 with vertical baseboard.

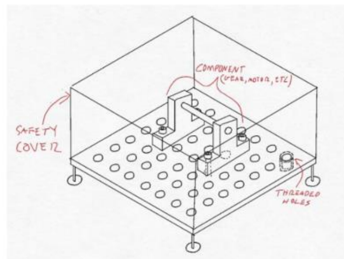


Figure 18. Design 3 with horizontal threaded base board

Additionally, although less likely, design 3 runs the risk of being cross threaded resulting in holes being damaged. The use of magnets avoids the need to drill or tap a large number of holes in the base plate which reduces manufacturing and maintenance time.

4.2 Description of Selected Concept

Our development process resulted in the team selecting the 'Magnetic Breadboard' solution for the Exploration Activity. It consists of a steel base plate and a collection of modular components that interface with the base using magnetic 'pillars' and can be easily configured into many different arrangements. Figure 19 depicts a variety of gear arrangements that could be produced with our system. We plan to use off-the-shelf parts for as many components as we can. For example, the only custom part in Figure 20 is the white block at the bottom of the U-channel. All the other components can be sourced from robotics parts suppliers. The white block contains the magnet used to secure the component towers to the metal base. We are considering 3D printing that component due to the low volume required. We also need to determine a way to fix the position of components relative to each other so that all components operate correctly and stay properly aligned.

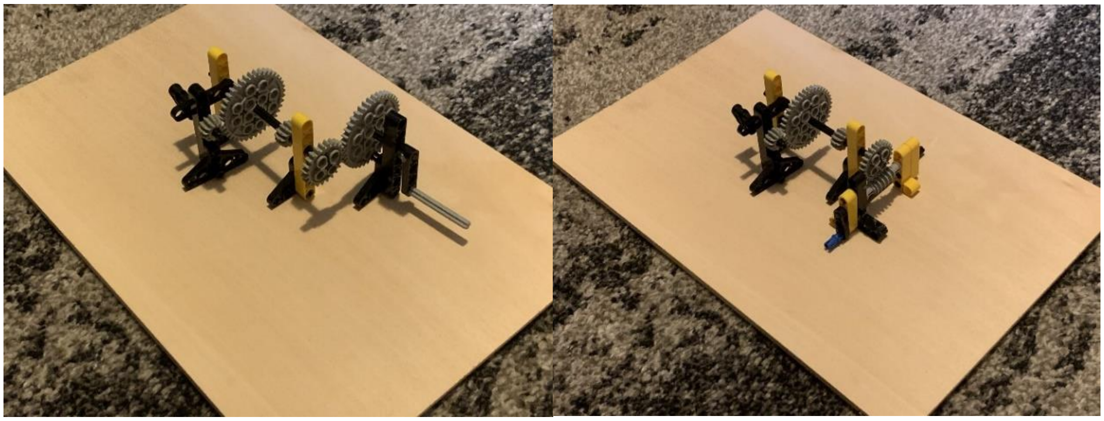


Figure 19. Concept prototypes showing different arrangements that students could experiment with using the breadboard design.

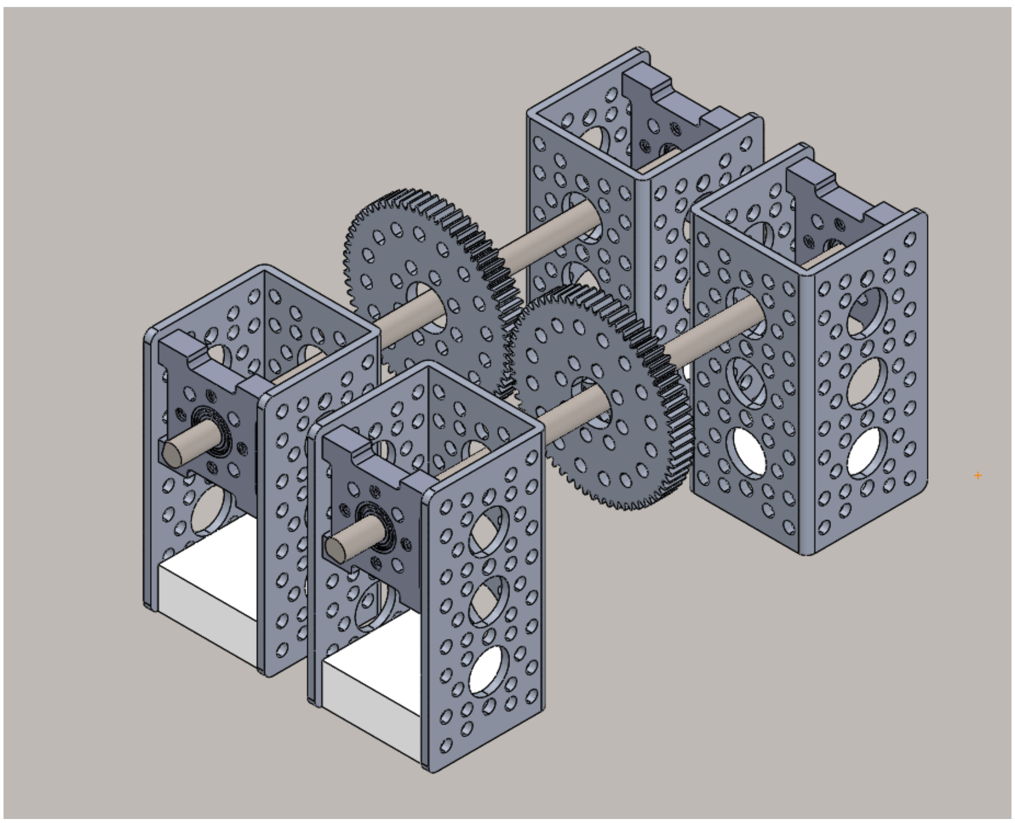


Figure 20. CAD of one system concept. The U-channels, gears, shafts, and bearing blocks are all standard parts sold by robotic part suppliers. The white block would be manufactured by us and has an embedded magnet.

4.2.1 Function

The base plate is a simple flat sheet of steel on rubber feet. It acts as the work surface that students can attach the other components to. Most components will attach to the plate by first connecting to pillars, which will have strong magnets in their bases. These pillars (with shafts, gears, motors, etc. attached) can be placed on the base plate and orientated in any configuration that students desire.

The biggest challenge to this method is maintaining the desired configuration once inputs are applied to the system and components experience opposing forces. We do not want gears to become unmeshed due to the pillars sliding or pivoting from the transferred forces. We can do several things to mitigate these movements. The bottom of the pillars, or the base plate, could have a surface with a high friction coefficient such as rubber to prevent sliding. But perhaps the best way would be to have a component that fixes the pillars and shafts in their places relative to each other. Thin beams with many holes along their length could be used to accomplish this by arranging them to span between pillars of parallel shafts. Doing so would contain all the system forces within the components and pillars, preventing any from being transferred to the base plate which would cause rotation and translation of the pillars.

Some of the components provided would allow students to produce inputs and measure outputs of the system. For example, a student could:

- Attach a crank to the input shaft and a motor to the output shaft of a speed increaser, then use a multimeter to measure the voltage produced by the motor.
- Use a tachometer to measure the output shaft speed.
- Tie a string attached to a weight to the output shaft to help measure torque output.

This activity is designed to be as modular as possible and give students the opportunity to explore the fundamentals of gear trains with some light guidance.

4.2.2 Materials and Geometry

As the activity is essentially a base plate and a box of parts, it will be easy to store and transport.

Figure 21. U-channel from ServoCity [23] with shaft and bearings

- **The base plate** itself will be steel and likely somewhere between 8.5”x11” and 11”x17”, though the only really limiting factor to its size is the cart that it will be transported on.
- **The pillars** will primarily be composed of 1.5”x1.5”x~3.75” aluminum U-channel, which will allow enough clearance for gears up to 7-inch diameter.
- **Shafts** will be standard 1/4” inch steel D-shafts of various lengths
- **Bearings, collars, couplings, brackets, beams etc.** will be mostly aluminum and attach either directly or indirectly to the pillars using bolts.
- **Measurement devices** such as multimeters and tachometers will be purchased and provided to students.
- **Motors** for both input and output will also be provided to students. Specific selection of motor will require further analysis of the forces and power required by the system. However, it will be a priority to select motors that can handle stalling regularly for short periods of time as students experiment with their setups.
- **The magnets** will be neodymium for highest strength, but the exact specifications will be determined through further testing and analysis.

4.2.3 Manufacturing and Assembly

A significant goal for this project is to perform as little custom manufacturing as possible, and to make the product as simple and easy to assemble/disassemble as possible. This means that we hope to be purchasing as many standard components as possible and assembly should be simple. Some of the structures, such as the pillars, will contains multiple parts pre-assembled to some extent. The rest of the parts will be provided to students as sold. A storage container will be provided for all the components that will make teardown and inventory as easy as possible for students and professors.

4.3 Preliminary Analysis

Our project does not have very many calculations at this stage of design. All the components being used will not be under very much stress due to the exploratory nature of our project. We want students to be able to observe changes in the system safely and easily. This results in a very “overbuilt” system with no danger of component failure. One preliminary calculation was performed to check the feasibility of using magnets to secure components. We used the motor specifications of a low power DC motor to calculate a maximum radial load on the gears to determine what magnet strength we would need to prevent slippage. We calculated a maximum required magnet strength to be approximately 80 lbs. to prevent slippage. This strength is divided between the two U-channels. The full calculations are included in Appendix K. This is a high magnet strength, but we were able to find off-the-shelf magnets that fulfilled this requirement. The typical holding force would be low as we assumed the highest power output possible from the motor. The primary hazard in our system will be pinch points. The focus is exploration of gears which requires easy access to be able to change parameters. This means that it will be more difficult to eliminate pinch points instead of providing warning labels and safety instructions.

4.3.1 Potential challenges

The design we selected presented a few challenges at this stage is the project.

- Further testing of the magnetic attachment method needed to be performed to make sure it is sufficient to handle the forces involved. If it is not, we could always use mechanical fasteners, though this will lower the ease of use and intuitiveness for students.
- The ‘box-of-parts’ approach tends to make inventory tracking difficult. We would explore ways to make this as easy as possible for students and professors.
- Cost could be a challenge as well. This design would require quite a few parts and while none of them should be extremely costly, it would all add up. Our budget would likely impact the number of units we are able to produce.

Our team also included a hazard checklist in Appendix J, which includes potential risks and preventative methods for this design. One potential hazard is the high magnetic force that connects the metal base plate to the pillar assembly. To reduce this hazard, the gap distance between the magnet and the place will be increased which will result in a lower magnetic force. Another concern is for loose items and hair getting caught on the rotating components. Some preventative methods that we are considering is adding a user’s guide, warning labels, and a shield cover over the rotating components.

5. Design Activity Concept Design

The team used the similar concept ideation process as the 'magnetic breadboard' to come up with the 'wind turbine design activity' as our final concept design. The process included:

1. Creating a functional decomposition
2. Ideating on solutions for each function
3. Modelling the best ideas
4. Evaluating through Pugh and weighted decision matrices
5. Selecting the scoring design components and compiling them into the best design

The final concept, shown in **Figure 22**,allows students to use knowledge gained in the exploratory activity and in lecture for a geartrain design project. Students will work in small teams to design and build a wind turbine drivetrain that will meet a set of performance and housing specifications. A report documenting design decisions and testing will be due at the specified due date.

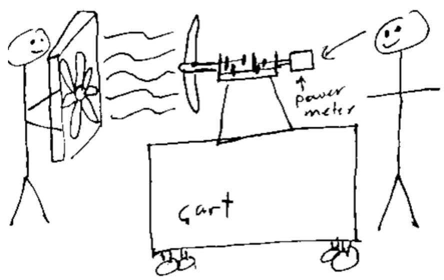


Figure 22. Sketch of selected concept, the Wind Turbine Design challenge

5.1 Development Process

The functional decomposition tree was created similarly to that of the exploratory lab and can be seen in 0. The main functions for the wind turbine design activity includes:

- Provide quantitative measurements
- Demonstrate quantitative properties
- Provide design opportunities
- Engage the students
- Safety features
- Cost effective.

As with the previous design we utilized these functions and sub functions to fuel the ideation process. We knew from our research of customer wants and student interest that the selected design should focus on a model of a real-world system. First, we needed to decide which system to model. We brainstormed many gear train systems to model and evaluated their potential against the functions that served as criteria for our selection, listed in Appendix P. Car transmissions and wind turbines quickly became front-runners because students would be familiar with both applications, both ideas had potential to highlight many course concepts, and both seemed safe and reasonable to implement. Ultimately, we chose to ideate on a wind turbine design activity because car transmissions are already so popular in engineering education and because our sponsor relayed both personal interest in such a topic as well as that of her students.

Once we selected the topic we needed to ideate on each individual function of the activity. Once we had done so for each main function, we moved on to create the Pugh matrices.

We created a Pugh matrix for each main function. They each took into account the needs and wants the customer specified. They were then analyzed just like the previous exploratory lab design concept. Pugh matrices can be seen in Appendix R.

Then, we compiled the top five ideas of all the Pugh matrices into a morphological matrix and weighted. An example of one of the combinations is shown in Table 5 highlighted in yellow. This concept idea required students to design a wind turbine geartrain with no size restrictions. The internal components will be acquired from a robotics website, and the gears will be covered with a photo elastic film to show qualitative properties. To prevent injuries the rotating components like the fan blades and gears will be covered. Finally, a tachometer and a multimeter would be used to gather qualitative measurements from the design.

Table 5. Morphological matrix table for design activity

Function	Idea1	Idea2	Idea3	Idea4
Quantitative measurements	① output Tachometer	② Measuring Torque lifting Stacked weights # weights lifted ⇒ torque	⑤ Input Measurement anemometer ⇓ plug-and-play fluid dynamics eqns	⑥ motor on output multimeter read output voltage/current
Design opportunities	OR • Gearbox housing size restriction. Students will have to build with considering the size of the box. Box will and blades will be provided.	• with calculations, students will have to identify the point of failure with fatigue analysis.	• Students have restriction on size but only the blades will be provided.	• Model design in SolidWorks including, shaft, gears, bearings, and casing.
Qualitative properties	⑦ photoelastic film on gears			
Engage Students				
Be safe	BLADE GUARD		E-STOP	!
Cost effective	• Have students 3D print their model.	Robotics • Shop from robotics supply sources rather than brand-name industrial suppliers.	• Students could re-use as many parts as possible form exploratory activity.	FREE Suppliers • Contact supplier to attempt to solicit donations or discounts.

From the morphological matrix four different combination ideas for concept designs were divided between each team member. After we each presented our individual fully detailed design, we decided that one more concept idea had to be made because there were some key features in the designs that were getting left out. This fifth concept design included all the positive aspects from the other four, making it a good candidate as the best one. The full detail drawings and description for the five concept designs are shown in Appendix S.

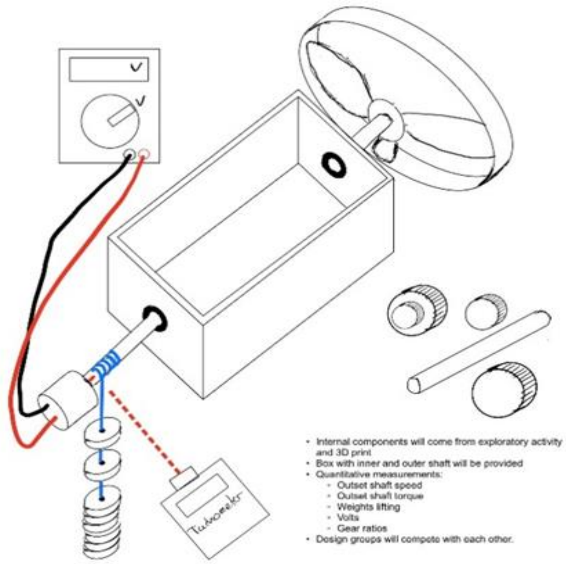


Figure 23. Concept design 5 for design activity.

The five candidates for the second lab activity were compared against each other by applying the decision matrix shown in Appendix V. Concept design 5, shown in Figure 23, ended up being the best one by having the highest score. One feature that made design 5 stand out were its internal components. Design 5 included geartrain components that could be 3D printed or reused from the exploratory activity. Being able to 3D print some components does not only give students the knowledge on how to 3D print, but it also engages students into the project by seeing the components that they have built. In the case that a part is missing from the previous activity, 3D printing parts can also be cheaper option than having to buy a real part for a source. This will reduce the total price for the design.

5.2 Description of Selected Concept

Our development process resulted in the team selecting a wind turbine design project that uses similar components to the exploratory lab. The basic idea is that teams of students will be asked to design the gearbox for a wind turbine with the goal of producing the most power output. They will be given design parameters/restrictions such as the dimensions of the gearbox housing which will be provided to them for testing. They will use some combination of force analysis, fluid dynamics, CAD modelling and more to apply what they learned in the exploration activity to this design challenge. In a following lab period, they will then test their designs by implementing them within provided housings, pointing a fan at the turbine blades attached to the housing, and measuring the output power generated. Figure 24 shows the concept we are trying to design for.

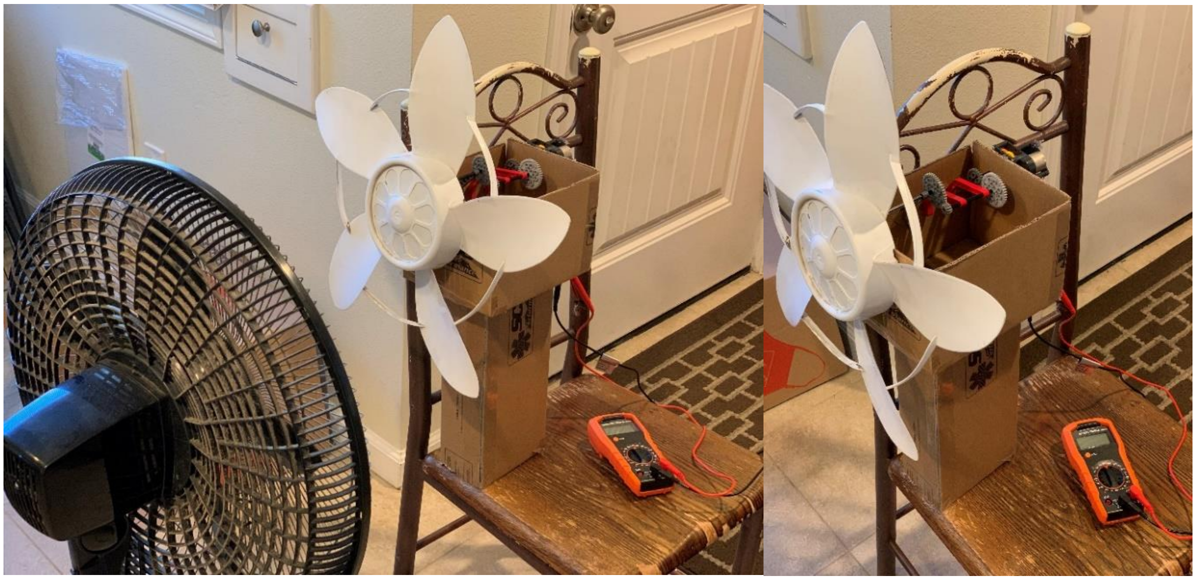


Figure 24. Concept prototype of wind turbine design. Fan, blades, housing and measurement devices would be provided to students while students would design and implement the gear train.

Figure 25 shows the configurable gearbox housing to be used in the lab. The brackets can be secured at different intervals along each plate allowing for control of the gearbox size. Additionally, the brackets are used on the outside of the plates to provide a tab for a clamp to be used to secure the gearbox to a table or other surface. The plates and brackets are specific to the design lab however, other components such as gears, motors, bearings, and shafts could be re-used from the exploratory lab. Additionally, students can be given the option to 3D print certain components if needed. Not pictured in Figure 25 are the propeller blades used to provide the input power for the gear box. All of the off-the-shelf components will be sourced from the same suppliers as the components in the exploratory lab.

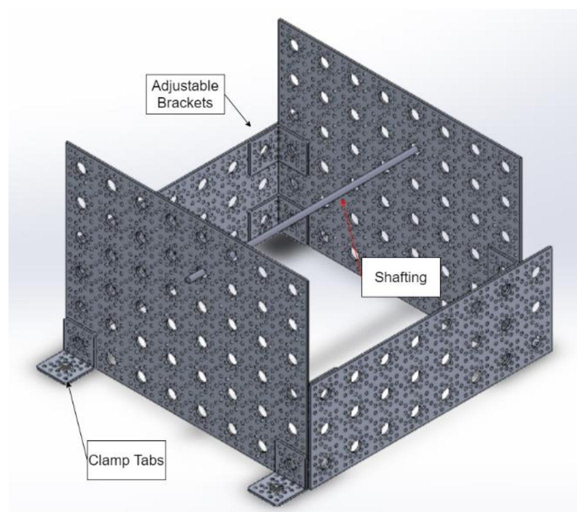


Figure 25. Housing for wind turbine activity gearbox, without input and output shafts shown.

5.2.1 Function

The wind turbine design activity is composed of three major systems, each with their own function.

1. **The gearbox**
    - The housing, shown in Figure 25, will serve as both a design constraint and a framework within which students will implement and test their design. It will:
        - Have an input shaft to which the turbine blades will attach
        - Have an output shaft connected to a motor that will produce electrical power for the students to measure
        - Be adjustable. The professor will be able to change the dimensions of the housing if desired in order to give students more or less space
    - The internal components will be re-used from the exploration activity in order to save on cost and make sure students are using parts they are familiar with. If students produce a design that uses gears which are not provided, they will have the option to 3D print those components. An optional collection of printed components each quarter will help to bolster the inventory of parts available to future students.
2. **The input**
    - A set of fan blades will attach to the housing's input shaft. They will have a protective rim/cage for safety and will detach easily for storage.
    - A large fan will plug into the wall and provide an input to the wind turbine. Students will be able to measure the incoming wind speed and use provided fluid dynamics equations to estimate the input power to their turbine.
3. **The outputs**
    - Measurement devices such as a tachometer and multimeter will be provided to students to measure the output power of their turbine. Potentially a light bulb could be attached to the motor to provide a visual representation as well.

In addition to these mechanical systems, there are also other 'components' to this activity. These other components describe how students will interact with the mechanical systems.

- **Design Opportunities** – We will be suggesting a number of opportunities for students to apply mechanical systems design concepts. We recommend that professors include the following in the execution of this activity:
    - Design requirements
        - Restrict the gear train footprint to the dimensions of the housing
        - Require inline input and output shafts
        - Request maximum power output, <u>make it a competition between teams</u>
            - Or, request maximum power per dollar (as if they were buying the drive train components) to encourage designs that use fewer/standard parts.
        - Place limits on forces produced
        - Allow 3D printing components that aren't available
    - Design analysis
        - CAD modelling proposed design
        - Identifying Point of Failure in design using force analysis
        - Calculating input energy and expected output and efficiency

        - FEA analysis of proposed design
        - Cost analysis of proposed design (as if purchasing all parts from industrial supplier)
    - Testing and results analysis
        - Calculating actual output and efficiency
        - Explaining failures (if any)

This activity, executed over a multi-week period, would be a fantastic opportunity for students to practice mechanical systems design concepts.

5.2.2 Materials and Geometry

Like the exploratory lab, the wind turbine lab will be able to be broken down into a box of parts. It will be easy to store and transport.

- **The wall plates** will be aluminum with pre-existing holes. The two taller plates measure 9”x12”, and the two shorter plates measure 4.5”x12”.
- **The propeller** will be plastic.
- **Shafts** will be standard 1/4” inch steel D-shafts of various lengths.
- **Bearings, collars, couplings, brackets, beams etc.** will be mostly aluminum and attach either directly or indirectly to the pillars using bolts.
- **Measurement devices** such as multimeters and tachometers will be purchased and provided to students.
- **Motors** for output measurements will also be provided to students. Specific selection of motor will require further analysis of the forces and power required by the system.

5.2.3 Manufacturing and Assembly

A significant goal for this project is to perform as little custom manufacturing as possible, and to make the product as simple and easy to assemble/disassemble as possible. This means that we hope to be purchasing as many standard components as possible and assembly should be simple. Unlike the exploratory lab, the design lab will not have many pre-assembled components. Everything inside the housing will be assembled by the students as part of the lab due to the difference in final designs. However, there is the possibility that students would be 3D printing some components which could take hours per team to complete.

We will have to provide and label storage containers for all the components that will make teardown and inventory as easy as possible for students and professors.

5.2.4 Undefined aspects and potential challenges

There were a few details of this activity that were yet to be defined at this point in the project, as well as some challenges we knew we may need to address.

- **Exact component attachment method**.
  - While we hoped to reuse as many internal gear-train parts as possible from the exploration activity, the magnetic pillar attachment system would not work for this one. We had not identified exactly which parts and methods we will use for this purpose, but there were many options available that we would explore in the future.
- **Size/source of turbine blades.**
  - The turbine blades would most likely be a few feet in diameter and come from either a cheap fan or some sort of kit. However, none of that was set in stone.
- **Overcoming friction in the drive train**
  - Until we decided on the exact parts available and were able to conduct some tests, the input required to stimulate the system sufficiently enough to create a significant output was unknown. We hoped the fan and blades we intended to use would be enough. If the turbine blades were not able to produce enough power to overcome the friction in the drive train, we were planning to switch the input device for a motor.
  - Keeping the components clean and lubricated long-term would also be a challenge.

5.3 Failure Mode Analysis and Safety

Our team developed a failure mode and effect analysis (FMEA) to identify potential issues that our design can encounter. It also helps us to identify how to detect and mitigate those issues to improve the safety of our design. Our FMEA can be found in Appendix X for the design activity. A potential failure mode that our design can experience is gears not meshing correctly with other gears creating poor contact. This could completely break the power transfer, have uneven wear on the gears, and have slippage if not corrected on time. This type of failure could defeat the whole purpose of the project since it will not provide good results to the user. Thankfully, our design is configurable, so we can simply adjust the connection to make them stronger. Just like the other failure modes, we will use team and customer feedback to determine if this failure mode is an issue.

This lab design activity shares similar potential risks as the exploratory activity. We included a hazard checklist in Appendix W. The only difference is that the design activity will potentially use high voltage levels to run a fan, which will be the input wind power for the blades in the design. This high voltage will be grounded at the connection outlet preventing electrical problems. One problem we see is students stepping or pulling on the power cord. One way to correct this is picking a bright color for the cord so students can be aware of it. Also, there is never a reason for the fan to be plugged in when testing is not in progress.

6. Exploratory Activity Final Design

The final design of the exploratory activity, shown in Figure 26, consists of modular components that can be assembled into a rigid frame and a gear train. Student's will be able to measure inputs and output such as shaft speed, voltage, and current. Our activity has no specific way to be arranged and is completely up to the user's curiosity and imagination, although some subsystems do require several components to function properly.

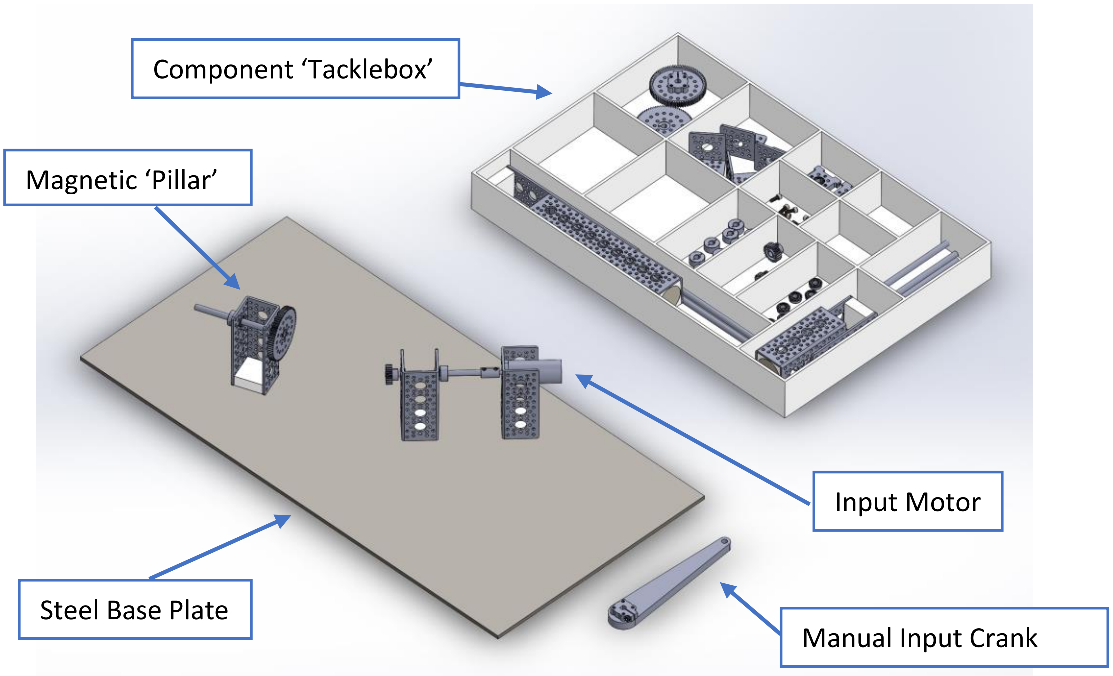


Figure 26. Exploration Activity Model. Note: Power supply for motor not pictured.

6.1 Exploratory Activity Configurations

We have illustrated some configurations of the type of designs one can make with our components, as well as described the possible learning opportunities for the users.

Below, we have a few models that can be created with our modular components. Most of the components have been ordered from a single supplier or outsourced to another vendor by the main supplier, ServoCity. These configurations were made to represent just a few examples of how they can be used and arranged. Figure 27 includes a 3D printed crank arm and uses the pillars positioned vertically. With this configuration the user can move each pillar independently to remove, reposition, or replace them.

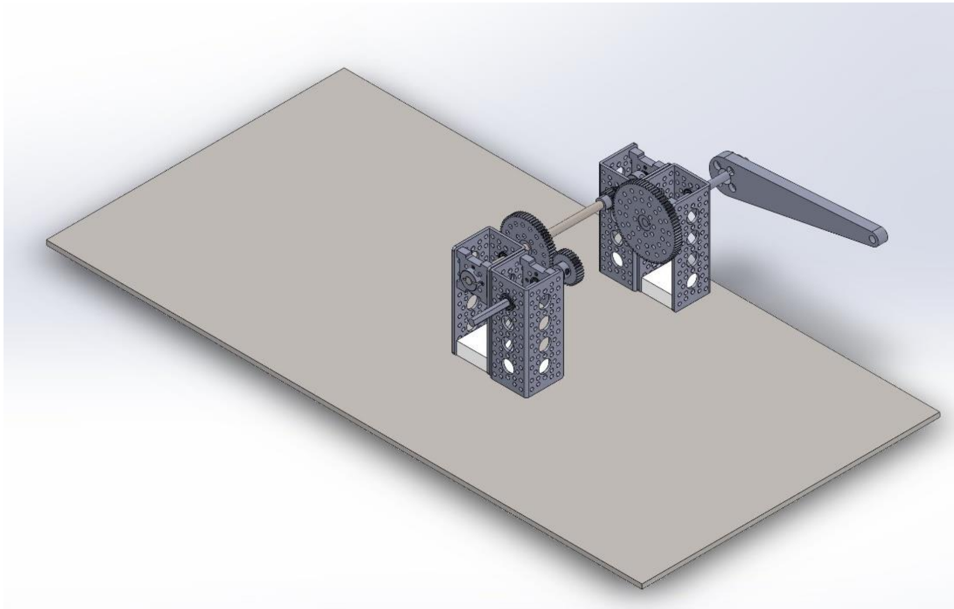


Figure 27. Crank arm and parallel vertical pillar assembly.

The next configuration, seen in Figure 28, uses the pillars vertically and stacks gears on top of each other while the input source is a motor that drives a pinion. This particular configuration is a speed reducer or torque multiplier, but this can be changed to a speed increaser by moving the motor to the other end of the model.

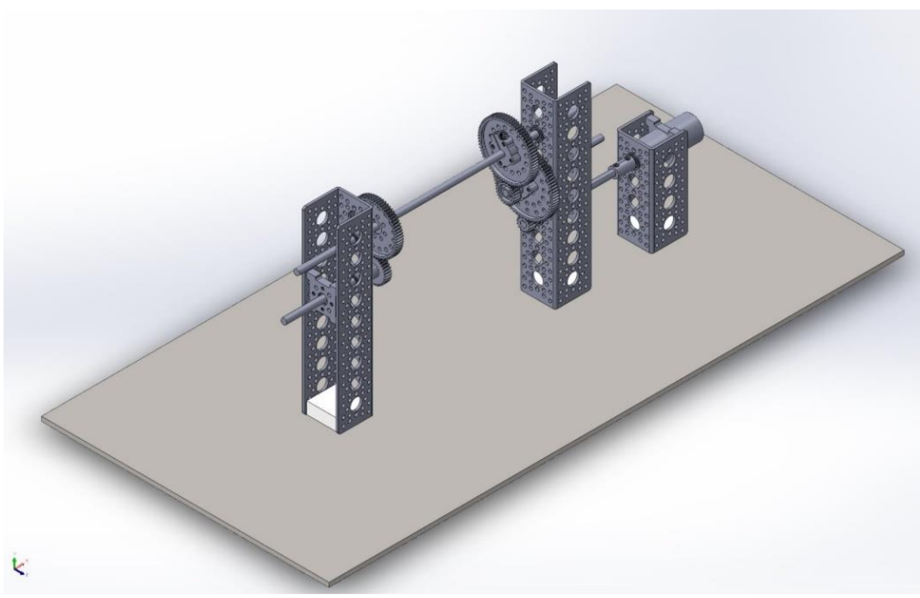


Figure 28. Motor input and stacked gears assembly.

The next configuration we wanted to model can be seen in Figure 29. This model demonstrates the U-channel placed in a horizontal position which would be held up with the vertical pillars. The pillars mention are not shown.

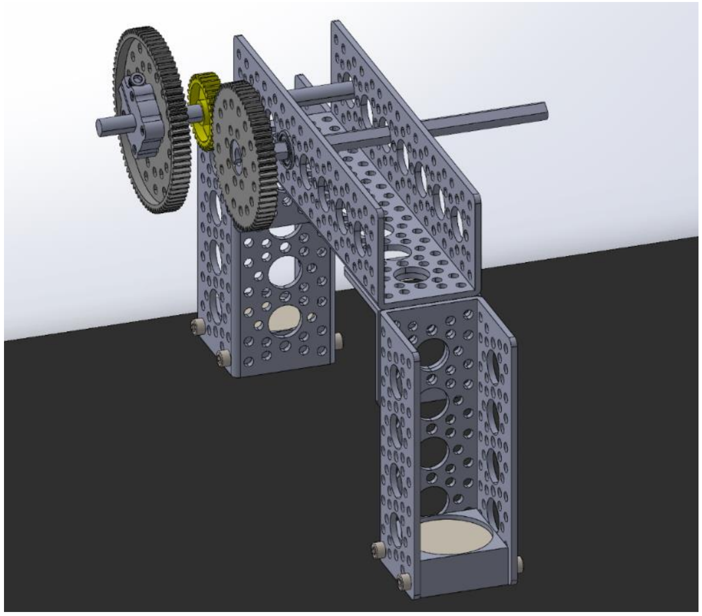


Figure 29. Gear train with U-channel in horizontal position.

These configurations do not illustrate all the designs one can make with our components. Rather, they are meant to show some basic arrangements that can be made with them in order to get started.

6.2 Components

We have many components that make up our project. We separated these items based on whether they are a system or a subsystem (used to make a single system). All the following components and instruments can be seen in Appendix Y which also gives the vendor information and price listed at the time.

6.2.1 Measurement components

The first system that is vital to our design can be seen in Figure 30(a), the tachometer. This instrument will be used to experimentally measure the input and/or output speed of the gear train configuration and compare it to the theoretical values calculated. To measure the input and output of both the voltage and current of the configuration, we included a multimeter which can be seen in Figure 30(b).

(a) (b)

Figure 30. (a)Tachometer 25-100,000 RPM capability, (b) Multimeter

To power the DC motor, we have a benchtop power supply similar to those used in the EE labs. The DC motors will be set up with leads that plug directly into the power supply and students will be able to adjust the input current and voltage and see how that affects the motors, Figure 31 shows this power supply.

Figure 31. Example benchtop power supply for input motors. Note: Not the same model that will be provided by the ME department for use with this activity. [25]

The ME department has power supplies available for checkout and we recommend taking advantage of that. However, if dedicated power supplies are required, a simple $50-$150 one should be sufficient. The biggest drawback to using a variable power supply aside from cost is the potential for damage. Our motors are rated for 12V and less than 4 amps. Most power supplies will be capable of much more, so proper warnings and procedures will need to be put in place to make sure motors are not damaged.

In order to adjust the voltage and currents, the unit needs to be on and this could lead to accidently frying the DC motor, so we will use a switch in conjunction to the power supply to cut power when adjusting. The unit will use banana plugs to connect to the leads, shown in Figure 32, which would then connect directly to the motor. This setup would provide a cut off switch to the motor reducing the risk of damaging motors.

Figure 32. Leads to easily connect power supply to DC motor board. [26]

6.2.2 Geartrain components

The next set of components are the pinion gears which do not need additional components to be mounted to the configuration. They slide onto the D-shaft and are secured by tightening the set screw that comes pre-assembled, Figure 33 shows the pinion gear set.

(a) (b) (c)

Figure 33. Pinion gears set, the (a) 16 teeth (b) 24 teeth and (c) 32 teeth. [26]

We are implementing two different lengths of ¼” D-shafts (4” and 10”) which allows for the user to create configuration that are more conservative in space, as well as allow them to reach far distances. Figure 34 shows a single shaft that represents both sizes in shafts that are to be implemented in our design.

Figure 34. ¼” D-shaft. [26]

Figure 35 shows the pillow block component. It is sized to fit between the U-channel passage but can also be attached on the outside sides of the channel. It comes with a bearing pre-assembled and is intended to be used as support.

Figure 35. Pillow block. [26]

6.2.3 Other components

Other assemblies in the exploratory activity will be mounted on metal base plate, shown in Figure 36. The 1X2' base plate is made out a magnetic material, mild steel A366/1008 C.R., that will attach to the magnetized U-channel assembly creating a firm connection between them, see Figure 45. To prevent rust buildup, the metal plate will be painted with a protective coating and covered by a layer of vinyl. Four or more little nonslip rubber feet will be glued to the bottom of the plate to prevent slippage of the system.

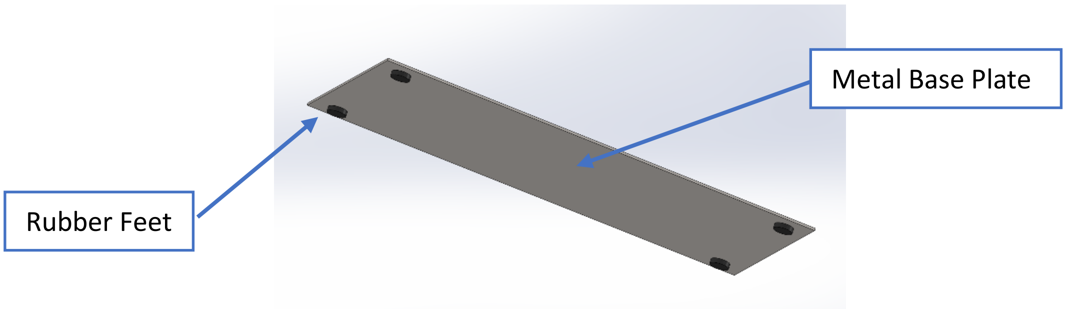


Figure 36. Metal base plate and rubber feet.

To allow the user more options for the exploratory activity we included an angle bracket, seen in Figure 37. This angle bracket could be used to connect a U-channel perpendicular to another U-channel making it possible for students to have a different geartrain configuration, see Figure 29.

Figure 37. Angle bracket. [26]

To attach the DC motor to the rest of the configuration we need a shaft coupler, shown in Figure 38. This image shows how the D-shaft attaches to the output shaft of the motor. The coupler comes with its own screws and only needs to tighten to be secured to the shaft and DC motor.

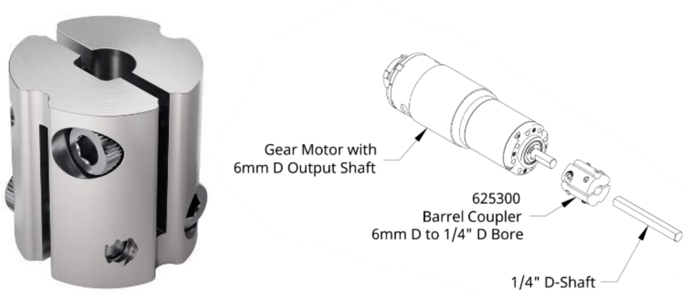


Figure 38. Shaft coupler assembly. [26]

In order to support our shafts but also allow rotation with negligible friction we will be using bearings, seen in Figure 39. These bearings fit perfectly in the many large holes of the U-channel assembly, see Figure 45. The drawback here is that they can easily slip out and need to be secured via shaft collar.

Figure 39. Bearings. [26]

The shaft collar, seen in Figure 40, is to be used whenever the bearing is implemented to restrict axial displacement. This collar allows for easy installation using only a screw to secure it to the shaft.

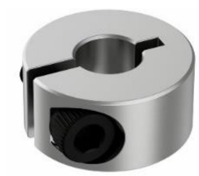


Figure 40. Shaft Collar. [26]

Figure 41 is a visual of the thumb screw we intend to use to secure the pillars, hub mounts, and any other component. It also has a hex head to tightly secure systems together that would not ever need to be disassembled.

Figure 41. Thumb screw. [26]

The wing nuts, Figure 42, secures to the thumb screw to help tightly secure components while also allowing for quick and easy disassembly.

Figure 42. Wing nuts. [26]

This exploratory activity consists of many large and small components. To prevent misplacement of these components, we will be including a tackle box with the kit, shown in **Figure 43**. Along with a checklist, having the tackle box will help the user in their inventory management.

Figure 43. Tackle Box.

To aid in the transportation of the kits between classroom and storage location, a utility cart will be provided. The cart, similar to the one shown in Figure 44, could also be used as a workbench area. It allows the user to move their kit with ease without having to lift them.

Figure 44. Utility cart. [27]

The utility cart is not part of our project budget. The ME department will either need to supply a cart or purchase one for this activity.

6.2.4 Pre-assembled components

Although we have covered components and how they are arranged to function properly, we do have a few components that do not need to be disassembled at all and will allow the user to create configurations faster. The following system, in Figure 45, shows a pre-assembled U-channel assembly. It represents every U-channel assembly that will be used as a pillar ranging between 4-hole all the way to the 9-hole assemblies. Each U-channel assembly will include a magnet and a magnet mount that will be screwed at one end. They are all assembled the same way. The idea to have these preassembled in the kit is to allow the user to quickly attach it to the base and not waste time screwing in and attaching each subsystem. The magnets have a magnetic force that provides a firm and secure attachment to the metal base plate.

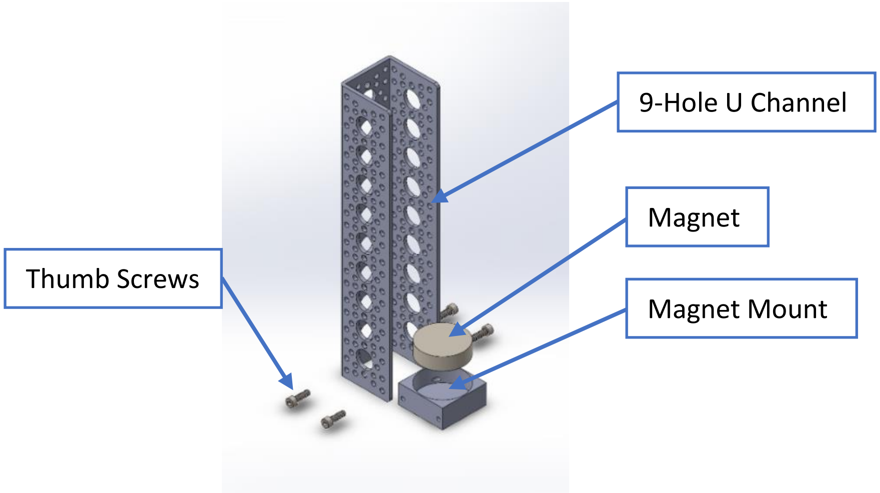


Figure 45. 9-Hole pillar assembly. A combination of a U-channel, magnet, thumb screws, and magnet mount block

The three large gears all require screws and hub mounts to secure to the shaft. For this reason, they do not need to be undone. Figure 46 shows how the subsystems are put together to make a permanent system.

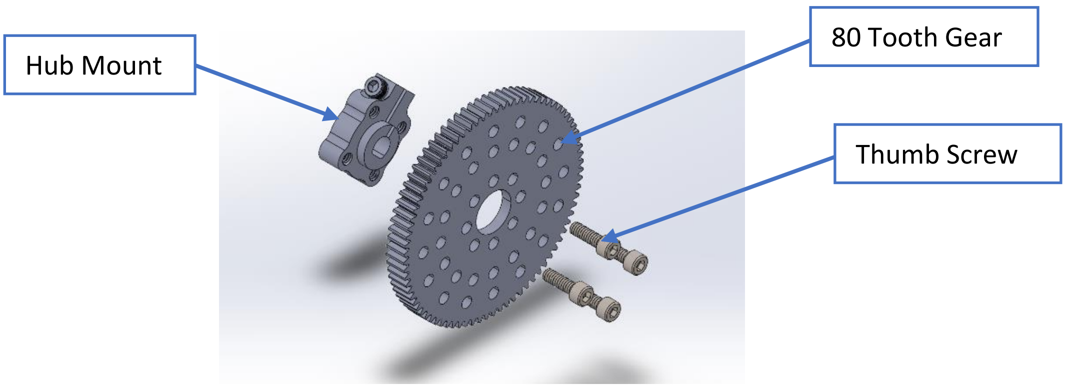


Figure 46. 80 Tooth gear assembly. A combination of a hub mount, a large gear, and thumb screws

To provide the user firsthand knowledge into the amount of force needed to drive their configuration we are providing 3D printed crank arms, Figure 47. This component was created with the purpose to be assemble with other existing components we intend to purchase.

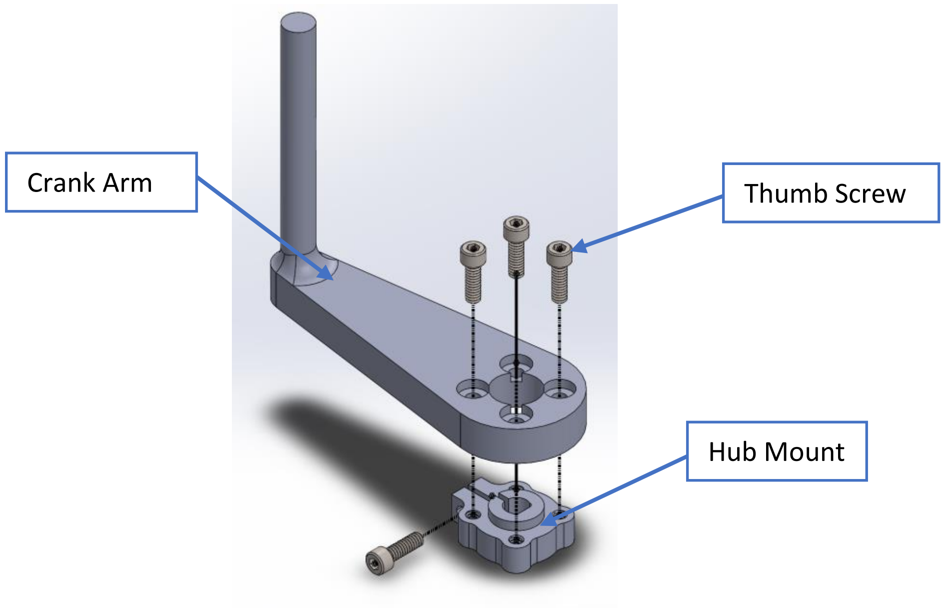


Figure 47. Crank arm assembly. A combination of 3D printed crank arm, hub mount and thumb screws.

To use the DC motor for our design, it will need to be assembled using various components. Figure 48 shows the components that will all be attached to the DC motor which includes the Figure 48 (a) motor mount that can be attached to a U-channel or an angle bracket, Figure 48 (b) the DC motor, Figure 48**Figure 48** (c) the motor board that attaches to the leads. We see in Figure 48 (d) how the motor mount attaches to the DC motor and in Figure 48 (c) how the motor board attaches to the DC motor, both the motor mount and board are simultaneously mounted together.

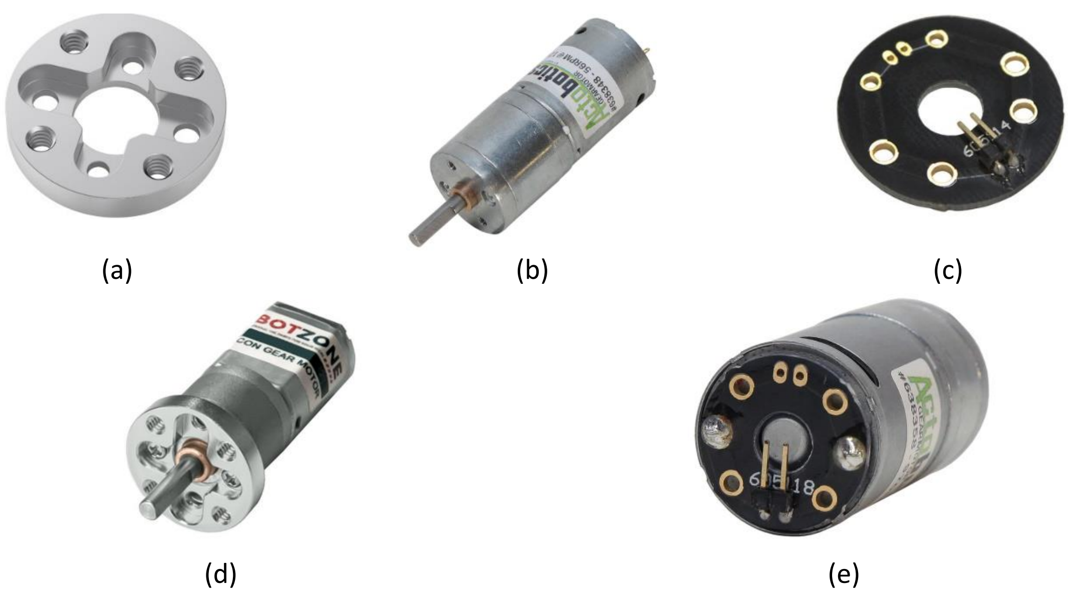


Figure 48. Subsystems of components to make motor system. (a) motor mount, (b) DC motor, (c) motor board, (d) motor mount & DC motor mounted, (e) motor board & DC motor mounted.

A list of assemblies and components can be seen in Appendix EE**.**

6.2.5 Extended Learning Kits

In addition to the standard components described above, we also plan to use any leftover money we have in our budget to provide a set of more advanced components for students to explore. Each activity kit would include a unique set of advanced components such as:

- Worm gears
- Helical gears and thrust bearings
- Bevel gears
- Belt drive components
- Chain drive components

In this way students will get exposure to some components that go beyond the class curriculum and they will be incentivized to interact with other groups, teaching and learning from their peers.

6.3 Function of Design

Our design uses the components listed in section 6.2 to give students experience in gear trains by setting up different configurations and observing the results. There is no right and wrong way on how to use this design. The intention is to bring all students up to a basic level of knowledge and experience of how gear trains work.

6.3.1 Learning Outcomes

This activity has several core learning objectives that students should achieve, such as:

- Practical behaviors of gears and gear trains
- Practical experience with spur gears
- Design and behavior of speed increasing and torque increasing systems
- Properties of forces between meshing gears
- Measurement of drive train system properties

In addition, there are several learning objectives that students can achieve with careful observation or by experimenting with the 'extended learning' components.

- Observe causes and effects of shaft bending
- Observe causes and effects binding of shafts and bearings
- Observe causes and effects of drive train friction
- Practical experience with worm gear systems
- Practical experience with helical gear systems
- Practical experience with bevel gear systems
- Practical experience with chain drive systems
- Practical experience with belt drive systems

6.3.2 Gear Configurations

Our design allows for a couple different configurations when it comes to gear meshes. All gears have the same pitch and can mesh together when supported by separate pillars, but students will need to count the number of teeth on each gear in order to figure out what gears can mesh with each other on the same pillar. Any pair of gears whose number of teeth sums to a multiple of 48 will mesh together when placed in a single U-channel or pattern plate. Once they figure that out, they can start by first taking the first half hour to an hour to explore and create a configuration. This will lead into following the direction of creating a certain configuration drafted in their lab manual.

6.3.3 *Recording Data*

The user will compare their intuition with their experimental results. The user will obtain readings utilizing the measuring instruments such as the multimeter to obtain values of power used and torque produced and validate speed reduction or increases with the tachometer.

6.4 Structural Prototype

Up to this point we had only theorized that these components would work for our purposes. So, we ordered a small set of components to test out our design, which consisted of:

- four U-channels
- two bearings
- two different pairs of meshing gears
- two D-bore barrel hub mount
- two four inch shafts
- four disk magnets
- and one pillow block

With these components we were able to mockup a simple configuration which can be seen in Figure 49. We were able to test out the pillar system and see if our magnet mounting idea would work.

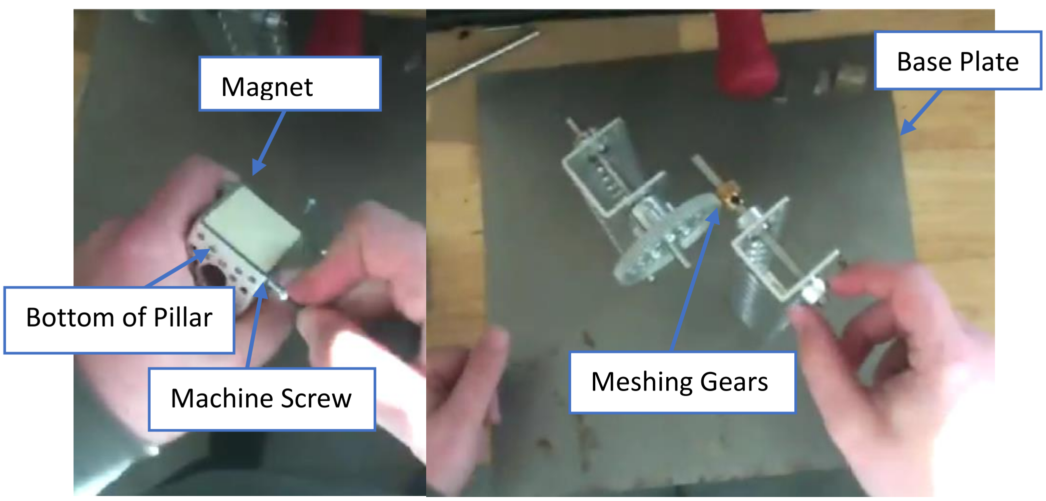


Figure 49. Exploration Activity Prototype Pillar Test

This configuration exceeded our expectation by securing itself strongly to the metal base plate. We then configured a model that looked similar to Figure 27. This configuration did mesh well together and so for our next implementation we decided to attach the crank arm assembly to the D-shaft.

We then tested the gears rotating at high speeds by securing an electric drill to the shaft to mimic a small DC motor, shown in Figure 50.

Figure 50. Hand drill test of exploration activity prototype

The drill spun the gears faster than we expect to ever get with the smaller DC motors we seek to implement and the components still behaved excellently.

This prototype also helped eliminate components, such as the D-bore barrel hub mount which did the exact same thing the hub mount did but slower and harder to use than the hub mount.

6.5 Documentation

We have created a lab manual for this activity that should be kept with each kit. It contains an overview of safety, operation, and maintenance for the activity, as well as a pre-lab activity and a few guided activities for students to follow. The manual should be provided to students electronically before coming to class. The full manual can be found in Appendix L.

We created a video walking through the first guided activity as an additional aid to students.

Additionally, we have created a brief lesson plan to guide professors through implementing this activity, shown in Appendix M.

Finally, we have created an inventory checklist, Appendix N, for students to use to make sure none of the components in the kit are lost.

6.6 Design Justification

Section 9 discusses how this activity and the next meet the technical specifications for the project. However, we must remember the more general problems this activity is meant to address. We needed a way to provide a hands-on experience for the numerous students that make it to ME 329 without ever having interacted with many of the components discussed in lecture. The solution also needed to reinforce lecture material and allow students to take measurements.

The potential for discovery of important concepts through exploration with a wide variety of drive train components makes us confident that our solution meets these goals. In addition to the guided activities provided in our lab manual, students can experiment with their own configurations and take measurements of shaft speed and input/output power to back up their observations.

6.7 Safety

Our team has placed safety for the user and the device as one the most important criteria in the design process. To review the safety of our design, we created a Failure Modes and Effects Analysis (FMEA) for the exploratory activity, which can be found in Appendix L. This process helps by anticipating potential issues that our design might have and allows us to build around those issues. Throughout this analysis, we found that most failures in the design are caused by a failure from the pillars. This can be caused by simple slippage between a pillar and the base resulting in loss of gear meshing, transfer of power, and finally defeating the whole purpose of the design. To address this concern, we are selecting the proper magnet size and magnet force that will be mounted at the bottom of the pillars. If slippage is still present during testing, we are planning to add a mechanism that will increase the coefficient of friction between the pillars and the base. For the other failures, included in Appendix L, further testing will be needed with a verification prototype to confirm that components selected are working properly.

The user must be mindful that this design will consist of multiple rotating components. He or she will be required to secure their long hair, wear safety glasses, and wear closed-toed shoes during this lab. They must also not wear loose-fitting clothing, chains, or other loose jewelry around the equipment.

When building our prototype, we concluded that the magnets were strong enough to keep the pillars and base connected. The forces created from our input device were not strong enough to create any tipping or sliding on the pillar. Even though one magnet by itself is not dangerous, some precautions should be considered when assembling or maintaining the magnets. The manufacturer should not put two magnets close to each other since there is a risk that both magnets can attract to each other and cause damage to part or the manufacturer. Users, like students or the instructor, will not encounter this magnetic risk because all magnets will already be secured and enclosed in a 3D-printed mount in a consistent orientation, preventing them from contacting another. Even though it is unlikely to happen we will warn the user about this risk. Students should not remove magnets or magnet mounts from pillars.

6.8 Maintenance and Repair

Proper care of the device is important to prolong the life of the components, which will reduce potential repairs. This includes not leaving the device alone while its running and properly cleaning it after use. The user must inspect the device completely before connecting to a power supply. They must make sure that all screws are hand tight and that all components are able to rotate freely by hand.

Since most of our parts are not custom, if any components are damaged beyond repair, they can be re-purchased from ServoCity. Exceptions include 3D-printed components and wiring, which require some manufacturing and/or assembly. See Section 8, Manufacturing, for more details on maintenance and repair.

6.9 Cost Analysis Summary

The cost of the exploratory activity is priced at around $615. This may seem high, but when considering that these components will be used again for the final design activity and that the course will be taught every quarter, the educational value is well worth the cost. Most of the components are relatively cheap with the cost of the magnets ($100) making up about 16% of the overall cost. Also, some components in the kits could be recycled from other lab kits such as the multimeter as there are many of these around campus.

Table 5. Cost of exploratory activity

Subassembly/Major Component	Cost
Pillars	$ 146
Base Plate	$ 30
Drive Train Components	$ 230
Motorized Input/Output Assemblies	$ 53
Measurement Tools	$ 27
Tools	$ 24
Tacklebox	$ 35
Advanced Components	$ 70
Total	**$ 615**

The price of the pillars should not scare anyone away from the design either. The magnetic, easily maneuverable design can make quick work of the reconfiguration on any model, there is no other product on the market that uses such an idea.

6.10 Remaining Concerns

The cost of the magnets was still a small concern. If we were able to find a vendor that sells the same size magnet without sacrificing the pulling strength that we need at a cheaper price our design would be more ideal.

Also, this kit relies heavily on some very specific components from ServoCity. If they decide to discontinue some of these parts, as we have observed in some cases, the design may need to be adjusted significantly.

7. Design Activity Final Design

The Design Activity is a wind turbine power train design challenge for which students will be provided a model wind turbine (minus the power train) that can be wheeled into the classroom on a cart. The apparatus will include a fan and turbine blades for input, and a generator set up to produce an output voltage which students will measure with a multimeter.

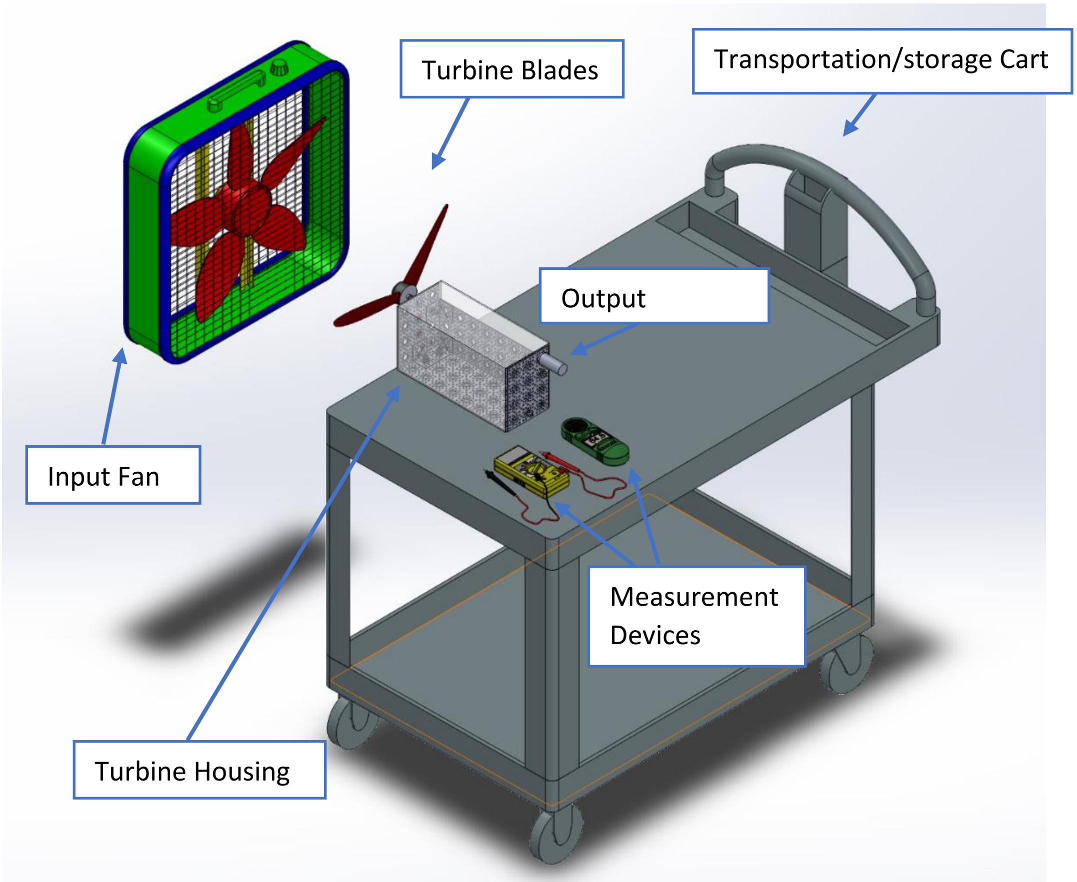


Figure 51. Model wind turbine final design.

Student teams will be challenged to design a power train within the apparatus to produce the highest power output. Then, teams will take turns building their design within the supplied housing and testing it to see who had the best design.

7.1 Subsystem Descriptions

The model wind turbine will consist of three subassemblies: housing, input, output.

7.1.1 Housing

The housing will be a rectangular prism with two open sides and enclosed by an acrylic cover, providing both constraints for the gear train design as well as a framework to support it.

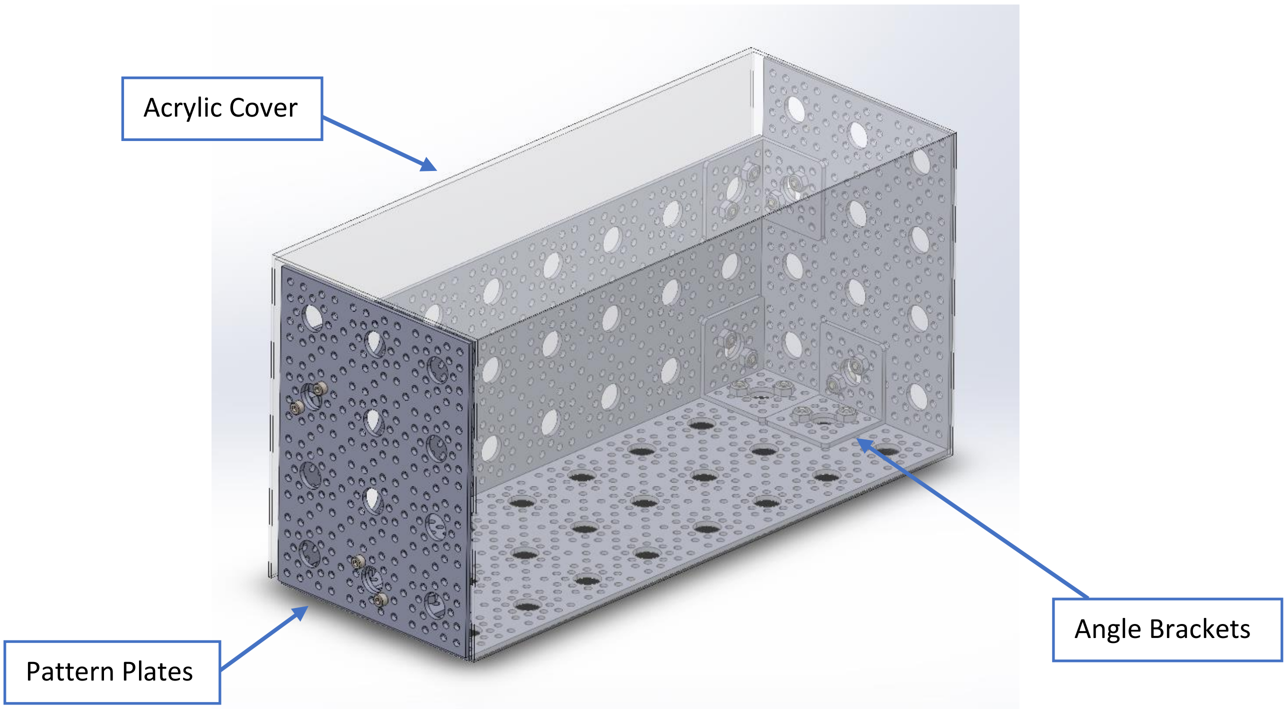
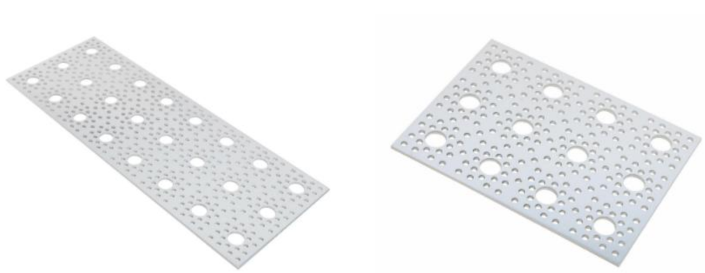


Figure 52. Model wind turbine housing

Two 3x8 hole pattern plates make up the side and bottom and two 3x4 hole pattern plates close off the ends. We considered closing off a third side but decided that it would be easier for students to access the housing if we left it off. If it turns out a third side is needed it can be added on hinged to maintain the easy access.



(a) (b)

Figure 53. (a) 3x8 hole pattern plate. (b) 3x4 hole pattern plate

The pattern plates are attached via 90 degree pattern brackets, machine screws, and Nylock nuts that will prevent the housing from coming undone due to vibration. This housing only needs to be assembled once by the manufacturer, though professors can easily make adjustments to it to change the housing size constraint if desired. An acrylic cover will fit over the open top during use to protect users from rotating parts while enforcing the housing size constraints and allowing observation of the power train during operation.

(a) (b) (c)

Figure 54. (a) 90 degree angle bracket, (b) Machine screw, (c) Nylock nuts

The use of pattern plates will allow easy modular configuration of different drive trains using components from the exploration activity kits as well as any components students chose to print or purchase[6].

7.1.2 Input

The input assembly shown in Figure 55 consists of a set of turbine blades and a fan that will be held a short distance away to power them.

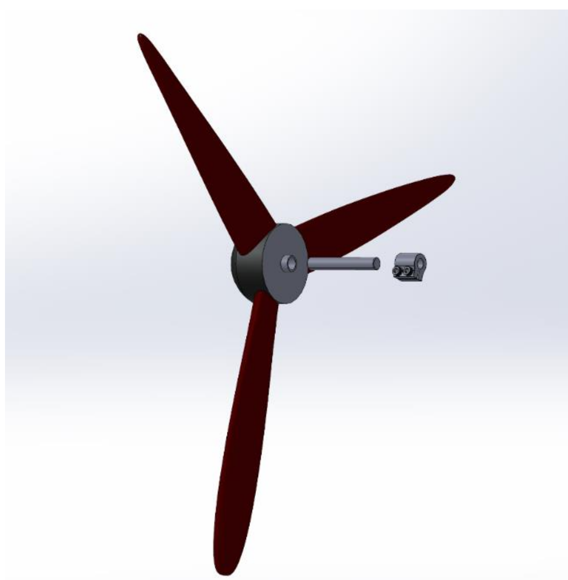


Figure 55. Input assembly for model wind turbine

[6] See near the end of section 7.2.1 for discussion about what components students can use.

The 18” diameter turbine blades will be attached to a 2” 5/16 shaft via interference fit and a 5/16”-1/4” shaft couple will allow attachment to any input shaft protruding from the housing.

(a) (b) (c)

Figure 56. (a) 18" dia. blades, (b) 2" long 5/16” dia. round steel shaft, (c) 5/16"-1/4" shaft coupler

Further testing of our structural and verification prototypes will help to determine how powerful of a fan we will need, what model of turbine blades work, and whether or not a guard for the turbine blades will be required.

(a) (b) (c)

Figure 57. (a) Option 1: Consumer box fan, (b) Option 2: Lower end industrial fan, (c) Option 3: high volume blower

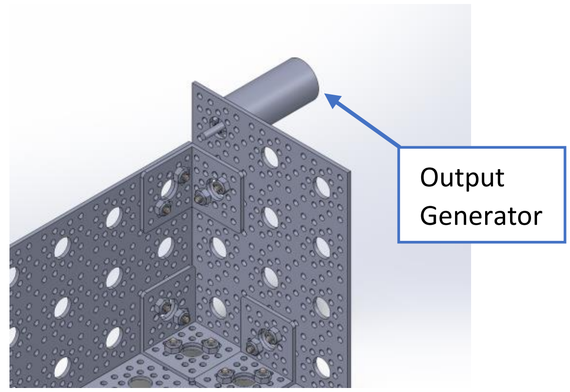
An anemometer will also be included for students to measure the speed of the ‘wind’ produced by the fan in order to calculate the input energy to the system.

Figure 58. Anemometer from Amazon

7.1.3 Output

The output assembly of the system will be an electric motor serving as a generator attached to the housing. The exact location of the generator on the housing can be determined by the professor to change design constraints quarter to quarter. Any sized gear can be attached to the motor shaft.

(a)



(b)

Figure 59. (a) 970 RPM motor acting as generator, (b) Motor mounted on housing

Students will use the multimeter supplied in each exploration activity kit to measure the output from the generator during testing.

7.2 Design Function

The apparatus described so far is just the physical aid to the design activity. It is part of the last step when students will get to test their final designs. But what about the activity as a whole?

7.2.1 The Activity

Challenge teams of 3-5 students to design the drive train for the model wind turbine apparatus with the goal of producing the highest power output.

- Alternative challenges could include maximizing torque (i.e. wind powered lift) or maximizing output speed. However, we feel that both of these are less applicable to the real world and more likely to have a single, easily identifiable optimal solution.
- The challenge for producing the highest power output will likely lie in finding the right balance between speed and torque, not just increasing one as high as possible. This will require students to calculate many things such as required torque and expected power losses in the system.

Recommended project requirements/constraints:

- Power train must fit within housing.
  - This one is highly recommended and naturally enforced by the testing apparatus.
  - The housing size will be configurable allowing professors to adjust constrains quarter to quarter.
- In-line input and output shafts
- A CAD model of their final design
  - Nearly all drive train components are sourced from Servo City which provides spec sheets and CAD files for most of their parts. Students should find and use these.
- Force analyses

    - FEA of their design.
    - Calculation of all forces within their power train.
    - Identification of point of failure in their design.
    - Calculation of expected shaft bending.
- Calculation of expected input power
    - Students can measure the speed of the 'wind' created by the fan using a provided anemometer and will be provided with relevant parameters such as frontal area of turbine blades.
    - Since Fluid Dynamics is not a prerequisite for this course, appropriate equations will be provided to students.
- Calculation of expected power losses, output power, and efficiency
- Design review presentation including all of the preceding items in this list.
    - This serves not only as good practice for teams and a chance for them to get feedback, but also to verify that they have done the calculations necessary to ensure their design is safe and not likely to fail in a dangerous or catastrophic way.
- Calculation of actual efficiency using expected output power and output power measured during testing.
- Post-testing report/presentation explaining suspected reasons for variation between expected and actual results.

Professors could require anything from an informal "here's the challenge, see you next week for testing" process with only a few of these requirements to a much longer formal design process that even includes design reviews. The number of weeks allocated for this lab should of course be adjusted accordingly.

Drive train components will come primarily from the core components of the exploration activity. However, there are additional options that may add to the learning experience:

- Professors can choose to allow extended learning parts such as chain drives if they wish. Doing so will reduce the competitive integrity of a contest between teams but it may also produce a wider variety of results.
- We also recommend allowing students to design and 3D print components if they would like to use something that is not supplied in their kit.
- Students could also be allowed to purchase components from Servo City for their final design. This would provide experience with researching and sourcing existing parts for a design from a supplier.
    - We recommend setting a budget if this option is used. Maybe $10 per team member or $50 per team. This would be enough for anywhere from 3-6 components probably.
    - If students are willing to donate their purchased components after the project, a pool of useful components will build up over time for future groups.
    - Lead times for part delivery can be 1-2 weeks, so professors will need to build this into their lab schedule.

On test day student will take turns implementing their design in the model turbine and testing it by directing a fan at the input and measuring the output with a multimeter. Only one apparatus is necessary for the class, but two would be ideal so that the group that is up next can be setting up while the previous group is testing. Another solution is just to provide a housing assembly to each group for them to build their design in ahead of time and then transfer then input and output assemblies to each housing for testing.

Possible ideas to take this lab even further:

- Provide several types of turbine blades with different diameters, profiles, number of blades, etc.
- Have students design and manufacture their own blades entirely.

7.2.2 Learning Objectives

This activity has several core learning objectives that students should achieve with anything but the most basic implementation of this activity.

Core Learning Objectives (* = direct from class syllabus):

- Generate ideas and concepts for mechanical designs*
- Select appropriate machine elements, components, and materials for mechanical systems*
- Analyze and size selected machine components for appropriate strength, stiffness, or fatigue life*
- Apply computer-aided engineering techniques to component and system design*
- Kinematic analysis and design of gear trains*

In addition, there are a number of learning objectives that students will achieve if most or all of the recommended requirements are requested.

Extension Learning Objectives:

- Predict and measure power losses in drive trains
- Measure efficiency of a mechanical drive train system
- Integration of fluid dynamics with mechanical systems
- Selection of optimal electro-mechanical components

7.2.3 Inventory System

The inventory system for this activity is actually quite straightforward. Most of the drive train components will come from and go back to the exploration activity kits. The rest of the components are large enough to be easily accounted for but still easily stored on the utility cart for transportation and storage. For any custom or purchased items, a simple box that students can look through will be sufficient.

7.3 Structural Prototype

As of this CDR we have not been able to construct a prototype of the model wind turbine apparatus due to some delivery delays. However, we were able to print out some smaller scale turbine blades and construct a structural prototype of the input system. This was the area of most concern and the results of the prototyping were very encouraging.

Figure 60. Input assemblies for wind turbine structural prototype

The turbine and fan blades that you see pictured in Figure 60 and Figure 61 are about 6” and 8” in diameter which is much smaller than the 18” diameter turbine blades we plan to use. Additionally, the motor being used to generate the airflow in our testing was not particularly powerful that we happened to have on hand and was underpowered by a pair of 9 Volt batteries. The airflow in the actual activity will be produced by a much larger commercial or industrial strength fan.

Figure 61. Testing of wind turbine structural prototype

Even so, we were able to us the larger set of blades mounted to the motor and the smaller blades mounted to a pillar to test the potential of this input system. The pillar was set up with a simple torque increaser and we were able to get the turbine blades spinning quickly and with enough torque that we are confident the larger scale components will be able to produce a useful output from a fully configured gear train.

7.3.1 Takeaways

- We are reasonably confident that using a fan to power the model turbine will work.
- It is quite possible to print functional turbine blades if future expansions of the activity wished to include something like that.
- The drive-train components performed very well once again with very little drag and no indications that they will have safety or durability issues.

7.4 Documentation

This activity has its own lab manual[7] and lesson plan[8] as well, along with a folder of CAD files for all of the individual components to make it easier for students to create their designs in SolidWorks or Fusion 360.

7.5 Design Justification

Aside from the technical requirements, which will be covered in section 9, we must remember that the overall goal of this design is to convey course concepts to students in a way that is both interesting and effective. We are confident that this apparatus, with its application to a real-world scenario, use of high-quality parts, and potential to include many forms of engineering design, will do just that.

7.6 Safety and Upkeep

Safety and upkeep are some of the most important things in any design, but especially so for an academic lab activity. Therefore, we made sure to look at these areas closely when developing this design. It has been designed not to have many inherent hazards, and the fact that it is composed of relatively cheap off-the-shelf components makes it easy to maintain.

7.6.1 Safety

As with the Exploration Activity we conducted an FMEA[9] analysis and Risk Assessment[10] for this activity, and it had similar hazards to consider. Most of these hazards come from rotating parts in the fear train. We were able to mitigate much of these risks by adding an acrylic cover to fully enclose the gearbox housing during operation. Even so we will also be requiring closed toed shoes, safety glasses, and all loose hair/clothing to be secured during this lab.

The only remaining significant safety concern is the rotating turbine blades during operation. We will need to perform testing with the final parts to see if the spinning blades are in fact dangerous. If they are we plan to add a blade guard the is essentially a circle arcing between the tips of the blade, preventing anyone from entering their path. If this is not enough, we can consider a full cage as well, although this will block some airflow and decrease resemblance to a real turbine.

7.6.2 Maintenance and Repair

Maintenance and repair of this apparatus should be straightforward, as with the Exploration Activity. There are no custom components, and no parts are particularly complex, fragile, or expensive. Additionally, almost all of the parts should be fairly durable. However, if any are lost or broken a

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[7] Appendix S - Design Activity Lab Manual

[8] Appendix T -

Design Activity Lesson Plan

[9] Appendix X - Design Activity FMEA

[10] Appendix W - Hazard Checklist for Design Activity

replacement can easily be ordered. Most of the parts come from Servo City, with a few parts such as the turbine blades and measurement devices coming from other vendors. The biggest risk would be in losing the output generator, but even this is not expensive to replace. Batteries in the measurement devices will need to be kept fresh.

7.7 Cost

Using parts from the Exploration Activity as the drive train components is this activity helps to keep costs down, resulting in an apparatus sitting at around $230.

Table 6. Cost breakdown of design activity apparatus

Subassembly/Major Component	Cost
Housing	$ 105
Input	$ 25
Fan	$ 50
Anemometer	$ 30
Output	$ 30
Total	**$ 240**

The input row includes all input assembly components other than the fan and anemometer. The output row contains all output assembly components including the generator. It does not include a multimeter as students will be able to use the one from their Exploration Activity. See The iBOM in 0 for a detailed list of components and cost breakdown.

7.8 Remaining Concerns

Initial testing of our design has led us to conclude that power losses in the system are higher than expected and that a torque increaser is likely to be necessary. This is not a huge problem but is different from real wind turbines that function as speed increasers.

8. Manufacturing

This section describes the procurement, manufacturing, and assembly of our Verification Prototype, as well as identifying challenges faced, lessons learned, and recommendations for manufacturers of future activities.

8.1 Procurement

We placed several orders for parts and materials over the course of building and testing our prototypes. We kept track of all our materials in our Materials spreadsheet, adding items as needed. The final version of this spreadsheet can be found in Appendix Y.

Whenever we planned to do some building and testing in the near future and didn’t have all of the parts we needed, we would put together an order form containing all of the parts that we were sure we would need and didn’t have yet. The order form fields consisted of vendor, full product name, part number, hyperlink to part, quantity, price per each, and total price, along with information about where to have them delivered and what shipping option to use. Whenever possible we used in-store pickup.

Then, we set this order form to our advisor, Professor Schuster, who would then forward it to the department staff member overseeing all ME senior project material ordering. She would place the orders and send the receipts and tracking information back to us.

Below is a summary of our budget and the orders we placed, along with our final budget status:

Table 7. Project Budget and Order History

Assets/orders	Vendor	Date	Amount	Notes
Project Budget	ME Dept	Initial	$ 1,000.00	
Order 1 - Initial Prototyping	Servo City	1/15/2021	$ (118.67)	
Order 1 - Initial Prototyping	Actobotics	1/15/2021	$ (19.13)	
Order 1 - Initial Prototyping	K&J Magnetics	1/15/2021	$ (60.14)	
Order 2 - Wind Turbine Prototyping	Amazon	2/18/2021	$ (49.54)	
Order 2 - Wind Turbine Prototyping	Servo City	2/18/2021	$ (97.43)	
Order 3 - Verification Prototypes Main	Online Metals	3/17/2021	$ (44.52)	
Order 3 - Verification Prototypes Main	K&J Magnets	3/17/2021	$ (94.95)	
Order 3 - Verification Prototypes Main	Home Depot	3/17/2021	$ (22.52)	
Order 3 - Verification Prototypes Main	Granger	3/17/2021	$ (20.14)	
Order 3 - Verification Prototypes Main	JLC	3/17/2021	$ (25.00)	<- not exact , but it shouldn't have been more than this
Order 3 - Verification Prototypes Main	Servo City	3/17/2021	$ (186.67)	
Order 3 - Verification Prototypes Main	Amazon	3/17/2021	$ (13.57)	
Budget Extension	ME Dept	5/6/2021	$ 100.00	Approved by Prof. Schuster
Order 4 - Spare Parts, Advanced, etc	Servo City	5/11/2021	$ (118.60)	
Order 4 - Spare Parts, Advanced, etc	Harbor Freight	5/11/2021	$ (61.35)	
Order 4 - Spare Parts, Advanced, etc	McMaster Carr	5/11/2021	$ (53.01)	
Order 4 - Spare Parts, Advanced, etc	Michael's	5/11/2021	$ (37.39)	
Total Remaining			**$77.37**	

After completing our core Verification Prototype and receiving a small extension to our budget, we had enough money to purchase a few more 'advanced' components to really boost the educational potential of our kit. This left us just about at our budget, but not over.

8.2 Manufacturing and Assembly

The following subsections describe each of the manufacturing and/or assembly processes required to construct our Verification Prototype.

8.2.1 Exploration Activity

These subsections describe the manufacturing and assembly for components used in the Exploration Activity. Many of these components are also used in the Wind Turbine Design Activity.

8.2.1.1 Base Plate

The base plate purchased from Olinemetals.com came as a plain 1'x 2' and 0.125" thick plate with a small amount of oil on the surface to protect it from rust. To prepare it for the activity we:

1. Round out all of the edges and corners using a file
2. Cleaned the metal to remove all oils in preparation for a thick layer of paint.
3. Applied a couple coats of Rust-oleum spray paint and allowing a suitable amount of time to dry.
4. Applied the 1' by 2' thick vinyl sticker to one side of the surface.
5. On the other side of the plate, we then added 6 rubber foot pads on each corner and middle portion of the plate.

a. We glued on some pieces of a rubber sheet we had lying around, but in the future the non-slip rubber pads with an adhesive side specified in the materials list should be used instead.

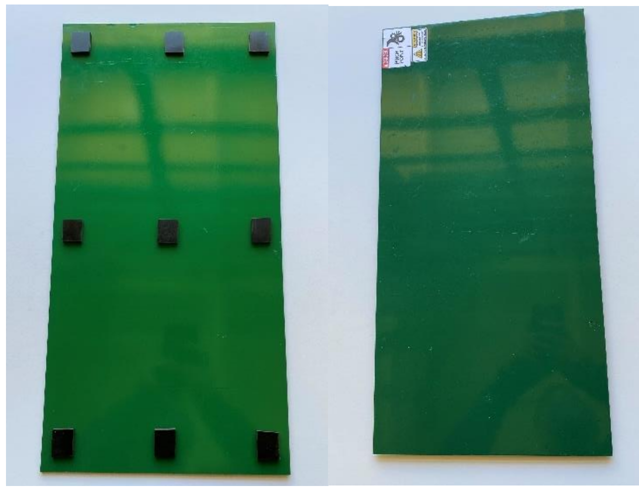


Figure 62. Front and back visuals of metal base plate.

8.2.1.2 Pillar Assemblies

The pillar assembly is similar for all U-channel sizes and one will describe that of the rest of the components.

Magnet Mount

Manufacturing:

1. The magnet mount is modeled in SolidWorks and sized to fit both within the U-channel space and allow the magnet itself to fit snug within the mount.
2. The model is then exported as an .STL file type.
3. It's imported to a slicing software to be converted into a '.gcode' file.
4. The file is then opened in a suitable printer that is configured for it within the slicer software, and after a couple hours the magnet mount is retrieved.

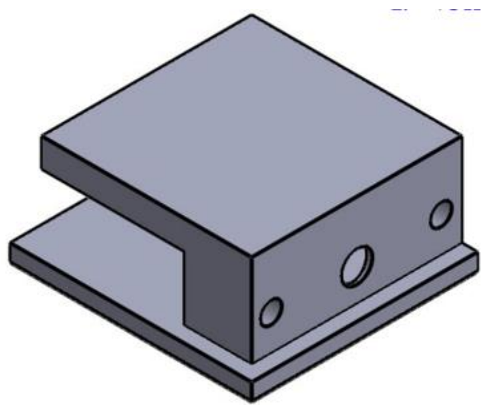


Figure 63. Magnet mount model

Pillar Assembly

Components:

- (1) Magnet Mount
- (1) Magnet
- (1) U-Channel
- (3) 3/8" Painted Torx Screws

Assembly:

1. The magnet that was purchased from Kjmagnetics.com is inserted into the slot in the magnet mount made for the magnet.
2. Select a channel that does not yet have a magnet mount attached.
3. Slide magnet mount into one end of the channel making sure the holes on the side of the mount align with the holes on the channel.
4. Insert and tighten the 3 torx screws into U-channel and magnet mount with a hex key

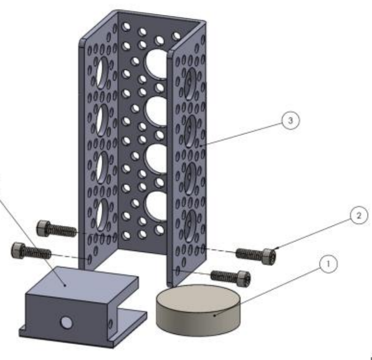


Figure 64. Pillar Assembly

8.2.1.3 Drive Train Components

All the components come from a single vendor, Servocity.com. A few of them require some assembly which is described in the following subsections.

Hub Gear Assemblies

The larger aluminum gears in the kit are all assembled in the same following manner.

Components:

- (1) Hub Gear
- (1) Clamping Hub Mount
- (3) 3/8" Painted Torx Screws

Assembly:

1. Insert a hub mount into the hole of one of the aluminum gears, making sure that the screw holes in the hub mount align with four holes in the gear.
2. Using three of the torx screws secure the hub mount and gear.
    a. Note: two torx screws should be placed the end of the hub mount opposite of the tightening screw, this will ensure that the hub mount will tighten on the shaft.

Figure 65. Hub Gear Assembly

Shaft Collars and Couplers

The shaft couplers and collars are a good location to get rotational velocity measurements. To get a rotation velocity from the tachometer a reflective tape must be added to them.

Components:

- (1) Black Electric Tape
- (1) Reflective Tape
- (1) Coupler

Assembly:

1. Install a dark color tape onto the coupler/collar. A good option for this could be electrical tape. This will serve as a background color contrast between the color of the coupler and the reflective tape.
2. Then, install at least ½'' of reflective tape onto the shaft coupler.

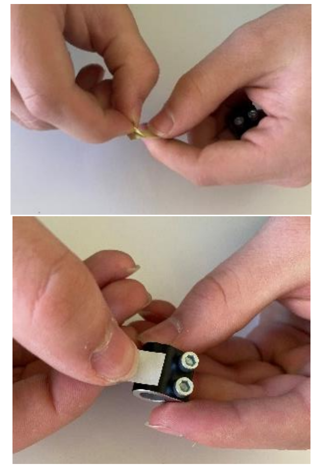


Figure 66. Application of reflective tape.

8.2.1.4 Input and Output Systems

Manual Crank Arm

Components:

- (1) 3D printed crank arm
- (1) Hub Mount
- (3) 3/8" Painted Torx head screw

Assembly:

1. Attach hub mount to crank arm using 3 screws leaving one of the threaded holes near the clamping screw free to allow easier clamping.

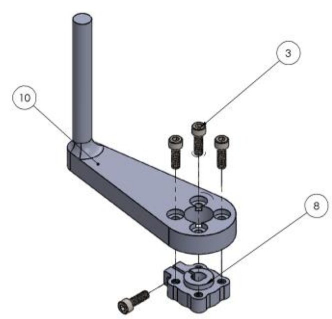


Figure 67. Crank Arm Assembly

Motor Board

The motor board was designed using the EasyEDA software recommended by JLCPCB.com, and manufactured by JLC.

Components:

- (2) Header Pins
- (1) PCB

Assembly:

1. Break two header pins off of the rack of pins and place in the small holes on the board.
2. Solder the pins to the board.

Motor

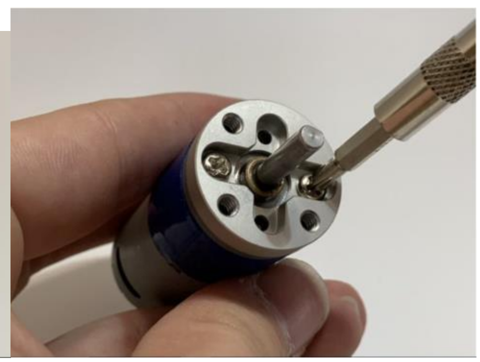
All DC motors were assembled the same way.

Components:

- (1) Electric Tape (Red and Blue)
- (1) Motor
- (1) Motor Board
- (1) Motor Mount

Assembly:

1. Apply colored electric tape to the diameter of the DC motor.
    a. Note: Blue with 970 RPM and Red with 124 RPM
2. With the two screws that come with the motor mount, secure the motor mount onto the DC motor.
3. Using the assembled motor board, solder the pins of the motor to the two large holes of the motor board.

Input Motor Assembly

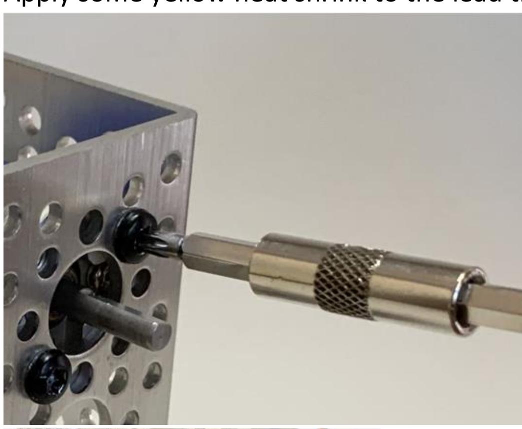
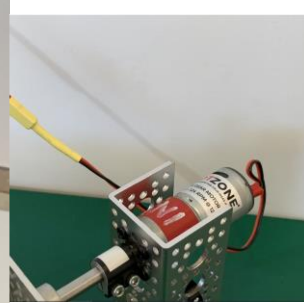
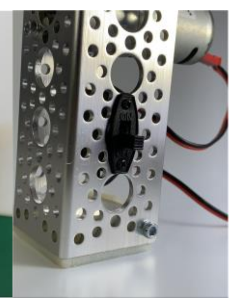
The input motor assembly is the red taped DC motor with the yellow colored heat shrink on the RCY plug.

Components:

- (1) Input Motor
- (1) 4-Hole Pillar
- (1) Switch
- (4) 3/8” Painted Torx Screws
- (1) White Paint/Whiteout
- (1) Yellow Heat Shrink

Assembly:

1. Start by positioning the correct motor to the hole within the U-channel furthest from the where the magnet mount is located.
2. Use the 4 painted torx screws to attach the input motor to the top hole of the pillar.
3. Place the I/O switch on the side of the pillar below the motor with the ‘ON’ position on top, make sure the two holes on the switch align with two small holes on the pilar.
4. With the two screws that came with the I/O switch tighten the switch on to the pillar.
5. Connect one lead from the switch to the motor.
6. Using some white paint, whiteout, or other appropriate substance, paint the raised letters of ‘ON’ and ‘OFF’ on the switch. Paint the head of the screw next to ‘ON’ white as well.
7. Apply some yellow heat shrink to the lead that is not connected to the motor.


Electric Current Measurement Adapter

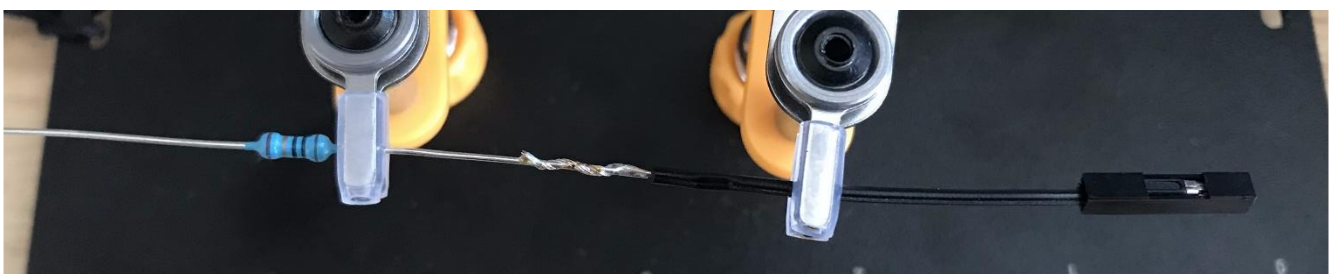
In order to measure the current produced by the motor, a load was needed. We used a 10 ohm resistor as our load and created an adapter that can be removed when a voltage measurement is needed.

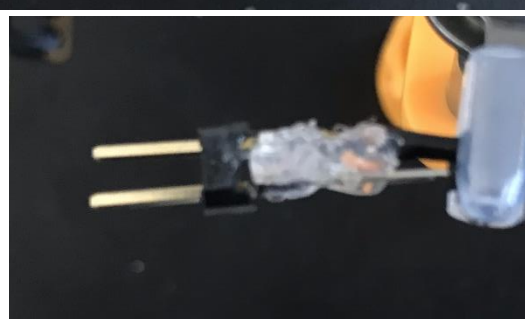
Components:

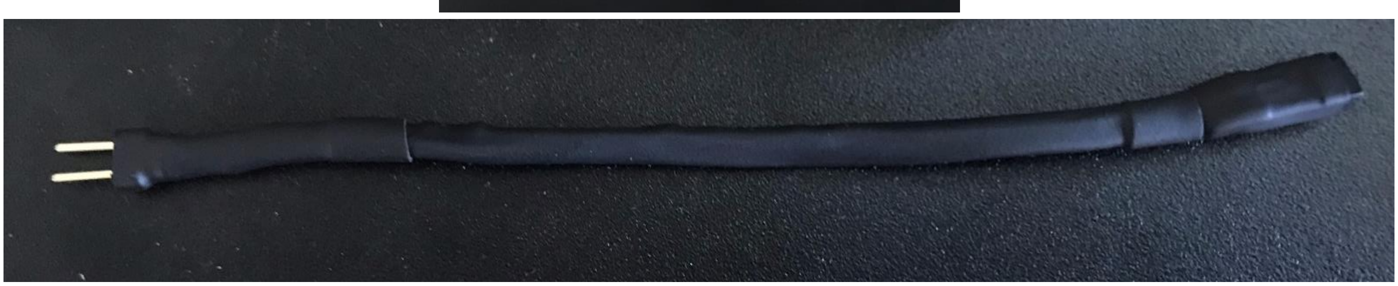
- (1) 10 ohm Resistor
- (2) Header Pins (Connected)
- (1) Female-Female Jumper Wire
- Assorted Heat Shrink Sizes

Assembly:

1. Cut approximately 1 inch off of one end of the jumper wire.
2. Strip both ends of the jumper wire pieces.
3. Solder the short jumper wire piece to one lead of the resistor.
4. Tin the other resistor lead, the other piece of jumper wire, and the header pins.
5. Solder the resistor lead to one header pin, and the other jumper wire piece to the other header pin.
6. Apply hot glue or epoxy on the header pin connections to prevent a short as well as to strengthen the joint.
7. Use heat shrink to secure the two female jumper ends together.
8. Apply more heat shrink as needed to cover any exposed wire and to secure the two wires together.







Generator Assembly

The input motor assembly is the blue taped DC motor with the white heat shrink near the header pins.

Components:

- (1) Output Motor
- (1) 4-Hole Pillar
- (4) 3/8" Painted Torx Screws
- (1) White Heat Shrink

Assembly:

1. Start by positioning the correct motor to the hole within the U-channel at the end opposite from the where the magnet mount is located.
2. Use the 4 painted torx screws to attach the output motor to the top hole of the pillar.
3. Apply the white heat shrink to the base of the header pins where it will not interfere with operation.

Figure 68. Generator Assembly

Warning Labels

A set of warning labels were printed onto a white sheet of shipping label. This sheet, shown in Figure 69, has labels that warns for pinch points, sharp edges, high magnetic forces and lasers.

1. Cut the desired warning label outside of the figure's shape.
2. Peal the back side of the label off. Keep the sticky side.
3. Place the sticky side onto a flat surface.

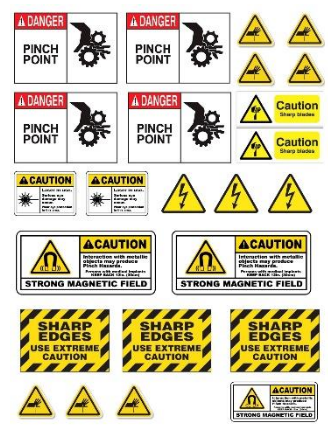


Figure 69. Warning labels

8.2.1.5 Measurement
All measurement devices are gathered from vendors and require minimum set up to be used.

Multimeter Leads
To get a voltage reading in the multimeter from a generator, two wire leads are needed. The following steps are required to have a safe and easy-to-use wire connection between the multimeter and the generator.

1. Cut the probes off of the wires that came with the multimeter. Strip a small amount of insulation from these ends.
2. Solder these ends to the RCY male connector by using a wire splice.
3. Use a heat shrink that matches the same color of the wire and surround the spliced connection with it.
4. Heat up the heat shrink until electrical wire is completely covered.

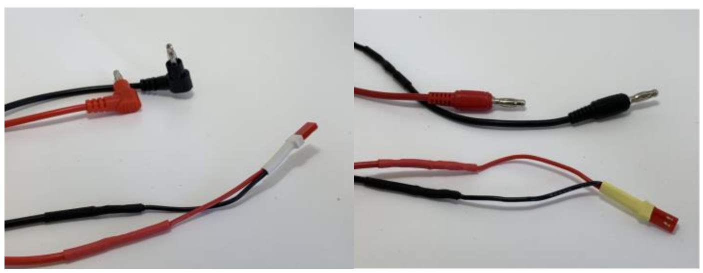


Figure 70. Modified Multimeter Leads

8.2.1.6 Inventory
An inventory check list and a tackle box will be provided to the users to prevent misplacement of components.

Checklist
We have prepared a checklist of all the components in both activities shown in Appendix A. This checklist displays a name, quantity, figure for each part.

This checklist should be printed out, laminated, and included with every kit.

Tacklebox
The tacklebox should not require any adjustment.

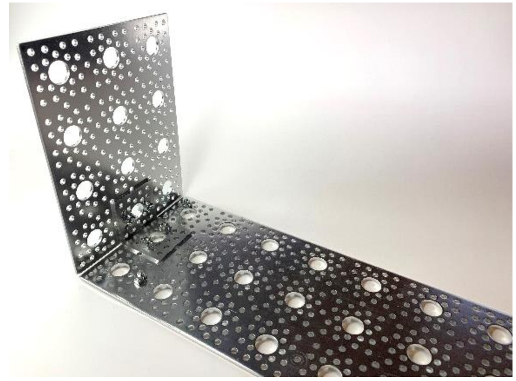
8.2.2 Design Activity
The design activity consists of input blades, output generator, housing, and geartrain assemblies. All the assemblies, except the geartrain, will be assembled by us.

Housing
Components:

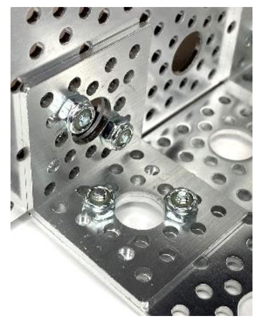
- (2) 3x8 hole pattern plates
- (4) 3x4 hole pattern plates
- (10) Angle Brackets
- (40) 3/8” Hex Head Screws
- (40) Lock Nuts

Assembly:

1. Match up the short sides of a large pattern plate and small pattern plate so that the two are perpendicular. Connect them using one angle bracket aligned with the middle row of holes on both plates.

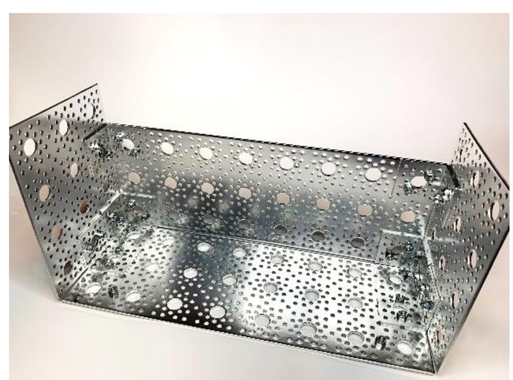


    a. Use two screws on each tab of each angle bracket (4 total per bracket) positioned in some fashion across the large middle hole from each other.

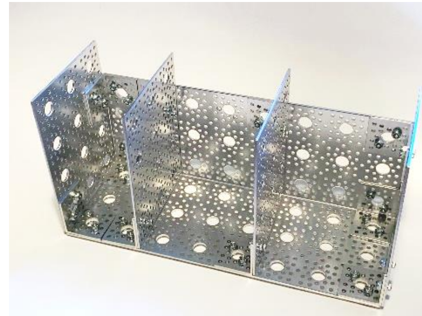


2. Repeat step 1 with another small plate on the other end of the large plate.

3. Align the long edge of the second large pattern plate with the long edge of the first pattern plate so that its short edge meets with the long edge of the small plates. Connect it to both small plates using two angle brackets spaced apart



4. Attach the last two small plates in a similar fashion to the first at somewhat even intervals between the other two small plates.



Safety Cover

The safety cover consisted of a single sheet of two by one foot Plexiglas.

Components:

2’ x 1’ sheet of Plexiglas

Assembly process:

1. The plastic sheet was measured to fit just outside the boundaries of the housing.
2. Sheet was aligned to the edge of a worktable using a square, then brought up to the marked line.
3. The sheet was clamped to the table to prevent any misalignment.
4. Both sides of the protective paper on the Plexiglas was peeled back.
5. A small blow torch is used to heat up the sheet off the corner of the work table.
6. The sheet softens on the edge and is pushed downward while heating along the edge along the entire length of the corner.
7. This process is followed until hanging edge is at a 90 degree angle with table.
8. Steps 1-7 is repeated for the other corner resulting in a housing structure resembling figure xx

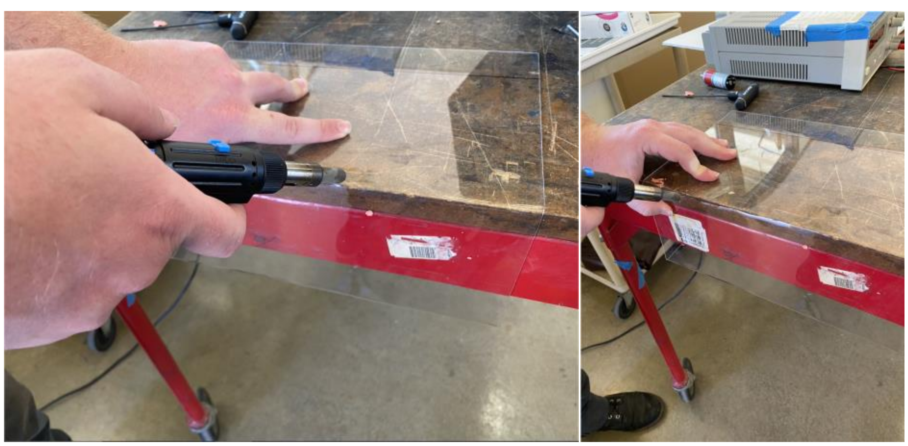


Figure 71. Bending acrylic for turbine housing using butane torch

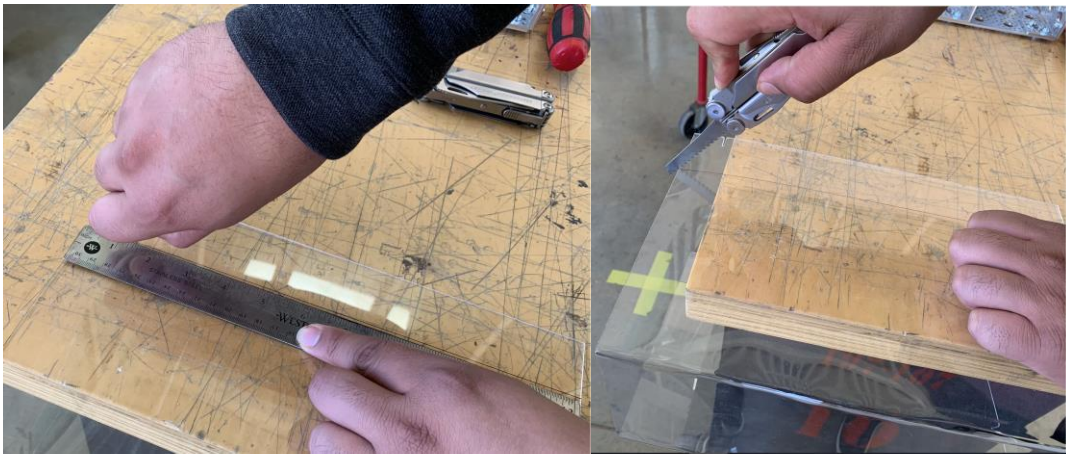


Figure 72. Cutting Acrylic to size

Turbine Blade Assembly

The turbine blade assembly is composed of 3 pieces:

- Master Airscrew 18” Propeller
- 2” 5/16 Round Shaft
- Shaft coupler

Assembly process:

1. Lightly sand one side of the 5/16” shaft in order to provide better grip for the adhesive.
2. Apply adhesive (JB Weld was used in our project) to both the shaft and the bore of the blades.
3. Insert the shaft into the bore of the blades and allow adhesive to fully cure.

8.3 Challenges and Lessons

- The trailing edges of the propeller blades are sharp, be careful removing them from packaging.
- Getting the tachometer to give steady readings was challenging. It turned out the reflective nature of the metal components was difficult to differentiate from the reflective tape. The black tape completely surrounding shafts and collars underneath reflective tape was our solution.
- There have been occasions where readings from some of our measurement equipment was inconsistent or seemingly inaccurate. We suspect this to be because they are super cheap models, and in the future it may be better to buy higher quality equipment.
- The hub mounts we chose to use require a lot of force to fully clamp to the shaft. We chose it because it only had one clamping screw instead of our initial hub that had two clamp screws. We thought that would make it less work for the students. However, it turned out the excessive force need to tighten the single-screw version is less than ideal and has caused issues with student testers.
- ServoCity is not entirely consistent with their offerings. Various components are out of stock periodically and on more than one occasion they discontinued a component we were using or planning on using (motor board and 3x8 hole pattern plate). For some components, this is not a big deal as they are non-critical or have alternatives available. However, there are some components that would require significant changes to the lab activities or kits if they were unavailable. This is the downside to relying on a single supplier like ServoCity.

8.4 Recommendations

We have the following recommendations for the manufacturers of future kits:

- Apply two or three layers of vinyl to the exploration activity base plate, rather than just one, to make this protective layer more robust.
- Print a large Cal Poly logo on the top vinyl sheet applied to the top of the exploration activity base plate.
- Print base plate warnings onto the top vinyl sheet instead of applying stickers, or place a protective layer such as clear tape over the stickers.
- Parts and Inventory:
    - We also recommend having a couple of extra motors, shaft couplers, and RCY leads on-hand. If any of these are lost or broken a significant portion of the activity becomes impossible.
    - Order the hub mounts with two clamping screws for future kits.
    - Order two 1-foot lengths of chain for the chain and sprocket set.
- Stamping components with kit number or letter will ensure all components stay within their intended kit.
- Adding some labeling within the tackle box compartments will make clean up a faster process when students know where each components go.
- Laminating the inventory check list to prevent damage and extend the life of the list.

9. Design Verification

In order to verify that both of our designs met our project specifications and could be used in a classroom for teaching purposes, we performed a series of verification tests. We started with our project specifications and developed a list of tests that would serve to verify them. Then, we generated procedures for each test identifying measurements to take, facilities and equipment required, level of prototype needed, and more[11]. We recorded data and observations during each test and summarized the test details and results in a Design Verification Plan and Report[12]. The rest of this section highlights the important notes about each test.

9.1 Testing to Meet Project Specifications

In order to confirm that all of our engineering specifications have been properly met, we performed a number of tests. The results of our verification are shown in Table 8.

[11] Appendix AA -
Test Procedures

[12] Appendix Z - Design Verification Plan and Report (DVPR)

Table 8. Specification Verification Testing Summary

Test #	Specification	Criteria	Numerical Results	Pass/Fail
1	Weight	< 500 lbs	46 lbs	Pass
2	Size	< 25" x 45" x 47"	12"x24"24"	Pass
3	Production Cost	< $1000	$881.73	Pass
4	Assembly Time	< 8hr	~6 hours	Pass
5	Set up Time	< 10 min	~ 2 min	Pass
6	% of Standard Parts	> 80%	~90%	Pass
7	Ease of Use	> 80% Positive Feedback	93% Positive	Pass
8	Measurable Inputs and Outputs	>= 2	4	Pass
9	Noise	Original: < 60 dB, Final: < 85dB	~65dB	Re-assessed -> Pass

All our project specifications passed testing. The following subsections describe each test in more detail.

9.1.1 Weight

The combined weight of both design systems needed to be less than 500 lb. This number was calculated from the maximum weight capacity of a typical utility cart which is what the activity will be stored and transported on.

All physical components for both activities together came in at 46 lbs., well under our 500 lb. limit.

9.1.2 Size

The size of both activities must not exceed 25"x 45"x 47". This is to ensure that both designs fit through a classroom door while being transported on a utility cart.

The widest component we have is the turbine blade assembly at 18”, the longest component is the base plate at 24”, and the tallest is the wind turbine housing at 12”. All of these meet spec.

9.1.3 Production Cost

The goal was to have a maximum production cost of $1000 as this was our project budget. The cheaper each kit is, the more kits can be purchased for a lab and the smaller the lab groups can be.

The total cost for both kits came to about $880, which is within budget. This also includes a few extra components such as motor boards, advanced components, and some screws that could be used in future kits, reducing the cost to acquire them.

9.1.4 Production time

To make fast replicas of this kit, the production time must stay below eight hours, assuming that a skilled shop technician will be the one manufacturing and assembling. While we did not formally time the entire production process form start to finish, we conservatively estimate a kit can be assembled in less than 6 hours, and an efficient manufacturer could probably do it even faster.

9.1.5 Set up time

The set-up time should be less than ten minutes starting at the moment the professor rolls the cart with the kits into the classroom until the kit is completely set up on a workbench. Ten minutes is usually the time instructors have between classes.

The only setup necessary is to pick up each kit from the cart and place them at each group’s work area, which should take no more than a couple of minutes.

9.1.6 % of standards parts

The percentage of commercially available parts for the kit should be greater than 80%. This is to keep the manufacturing time down.

93% of all our parts are either off-the-shelf or only slightly modified. The rest are easily 3D printed.

9.1.7 Ease of use

It was important to make the activities we designed as intuitive and easy to use as possible so as to not get in the way of student learning. We aimed to get greater than 80% positive feedback from current and former students as well as ME 329 professors through a survey during user testing.

We were not successful in acquiring user testing from any professors other than our sponsor and advisor, but their feedback and that of the 14 student volunteer testers was very positive.

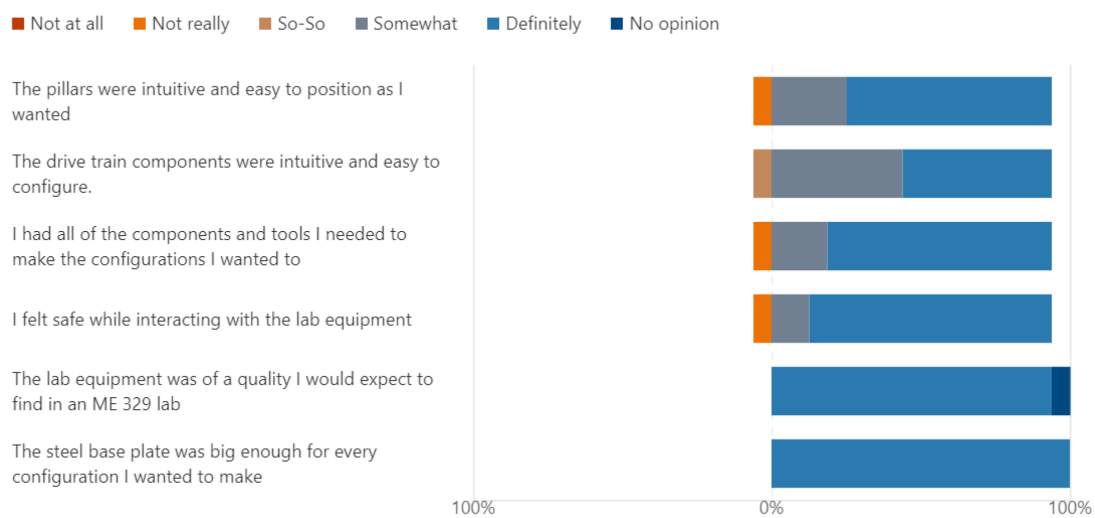


Figure 73. Ease of use feedback

As shown in **Figure 73**, the majority of users (~93%) found the pillars and drive train components somewhat or definitely intuitive and easy.

9.1.8 Measurable outputs

It was important for our activities to provide opportunities for taking measurements. Our specifications called for at least 2 measurable inputs and/or outputs.

Using the voltmeter, tachometer, and anemometer provided with each kit, students are able to measure four values; wind speed, shaft speed, voltage, and current. From these measurements, other quantitative conclusions like power and torque can be calculated.

9.1.9 Noise

The maximum noise specification was put in place to ensure sound levels were both safe and did not interfere with conversation. We started with a maximum limit of 60 dB as this was the level at which normal conversation starts to become affected according to our research. However, upon testing our motors, which give off ~65dB at one foot, we noted that the noise levels were not uncomfortable and did not interfere with our conversation. We decided to adjust our noise specification criteria to a max of 85dB which is the OSHA limit for safe exposure over an 8-hour workday without hearing protection.

9.2 Additional Performance Testing

In addition, we performed several tests to verify some aspects of performance that were not directly related to a specification. These are summarized in **Table 9** below.

Table 9. Additional Performance Testing Summary

Test #	Characteristic	Purpose	Results
A	Magnet Power	Magnets are strong enough to suport pillars and forces between gears	Pass
B	Drive Train Component Integrity	Components are able to perform well in high stress/speed configurations	Pass
C	Fan as Input Method	Fan is powerful enough to power turbine gear train implementations	Pass
D	Wind Backwash	Determine minimum distance between housing and blades to avoid signicant loss in efficiency	RPM of input shaft at minimum distance only 2.3% lower than average RPMs across all distances
E	Generator Power Losses	Identify amount of power lost within generator.	Data Collected

The following subsections provide more detailed information on each test.

9.2.1 Magnet Power

The entire concept for our Exploration Activity relied on the magnets being strong enough to keep the pillars from translating or rotating too easily when forces are applied to the gear train.

Upon completing manufacturing of our base plate and pillars, we were able to set up some sample configurations and observe whether the forces applied were enough to overcome the magnets.

As it turned out, the magnets were a little bit too strong for our liking and presented a pinching hazard. We increased the thickness of our magnet mounts to hold the magnets farther from the base plate. Further user testing revealed that the magnets were still plenty strong to do their job.

9.2.2 Drive Train Component Integrity

Students will be given free rein to configure the components we provide them in any way they want, and we need to be sure the parts can take the abuse they will undoubtedly experience.

To test this, we set up some of the most extreme configurations we could think of including max speed increasers and max torque increasers and applied plenty of force to them. In one test we even hooked up an electric drill to a shaft to simulate more input power than students should be able to provide, see Figure 66.

Figure 66. Drill connected to a shaft

None of our components showed any sign of failure from any of these tests and we are confident they will be able to last through many groups of students.

9.2.3 Fan as Input Method

One of our major concerns for this project was not being able to power the wind turbine implementations using a fan. We did not know if a fan would be able to overcome the friction in the gear train.

Our first preliminary test included small scale 3D printed fan blades and turbine blades powered by a small electric motor shown in Figure 67. This was able to power a small gear train with no resistance, which was encouraging.

Figure 67. Input wind turbine test

For our next test we needed to know how powerful of a fan to get. We set up a medium sized configuration in the housing with the actual turbine blades on it and used a leaf-blower to see if that produced enough force to generate power. It did, and we were able to get measurements. However, it only just barely worked. Luckily, the leaf-blower only had a small area it was affecting, and we knew a larger diameter fan would perform better, but we had learned it would have to be a pretty powerful fan.

Once we received the fan, we set up a full configuration with multiple sets of meshing gears and used our fan to power it, see Figure 68. The fan performed very well and was able to turn the turbine blades at high speeds despite the resistances from the gear train and generator.

Figure 68. Wind turbine and torque increaser geartrain test

We do not believe the fan is powerful enough to power a maximally speed-increasing configuration, but this is a good thing as that would make the design challenge too easy.

9.2.4 Motor Input and Outer Power

For this test we simply had to confirm that we could power an input motor with a power supply and use another motor to generate measurable output. To do so, we simply connected our input motor assembly directly to our output motor assembly using a single shaft. Then, we connected the input motor to a power supply, the generator motor to a multimeter, and turned the power supply on.

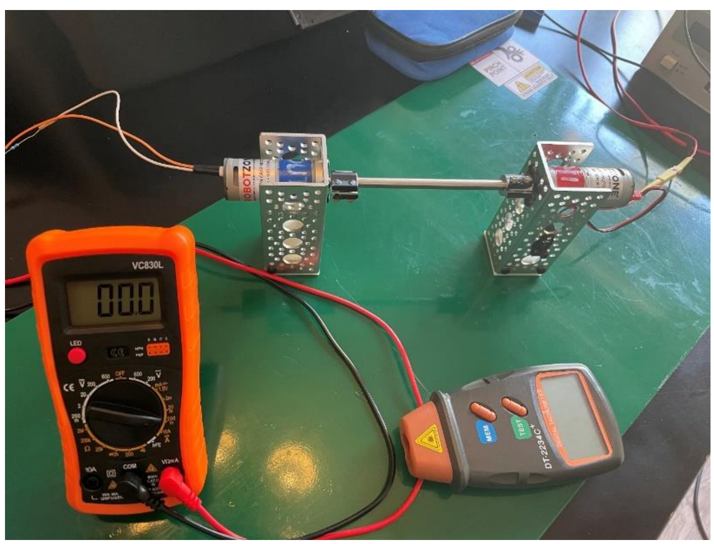


Figure 74. Motor input and output power test setup

Everything worked as expected, including doubling the input power and approximately doubling the rotation speed and power output.

9.2.5 Effects of Backwash

Our concept for the Wind Turbine activity allows students to attach the turbine blade assembly to their gear train with only a few inches between the blades and the housing. We needed to know if doing so would significantly reduce the potential power input to the system due to the housing interfering with the backwash of the turbine blades.

To find out, we set up a test for which we set up a simple drive train with very little resistance in the housing, kept the turbine blades a set distance away from the fan, and varied the distance between the fan blades and the housing. Figure 75 summarizes the results:

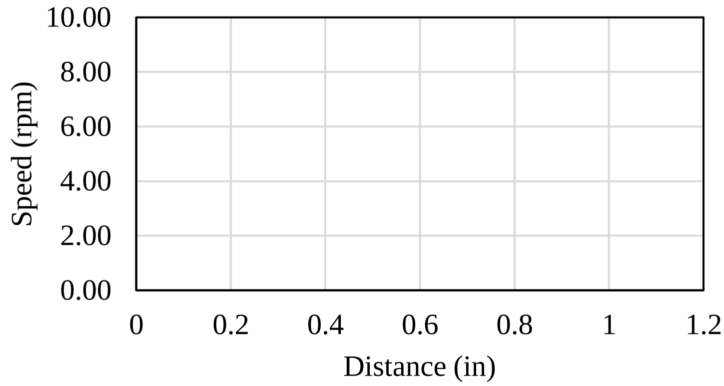


Figure 75. Effect of Distance Between Housing and Blades on Input Speed

As you can see, the speed of the shaft decreases only marginally as the blades get closer to the housing, and the closest position possible they spin only about 2% slower than the average speed across all distances.

9.2.6 Generator Power Losses

For this test, we wanted to find out what the power losses are in the generator while operating. We connected the generator straight to an input motor by a shaft similar to Figure 74. The input motor connected to a power supply with a set amperage of 0.5 and a variable voltage. We varied the input voltage from 4V to 12V with 1V increments. Measurable outputs like shaft speed, current, and voltage were measured with a multimeter and a tachometer. With these values, we calculated the output power at the generator. Finally, the power loss was found by subtracting the power out from power in and the efficiency of the generator can be calculated dividing the output power over the input power.

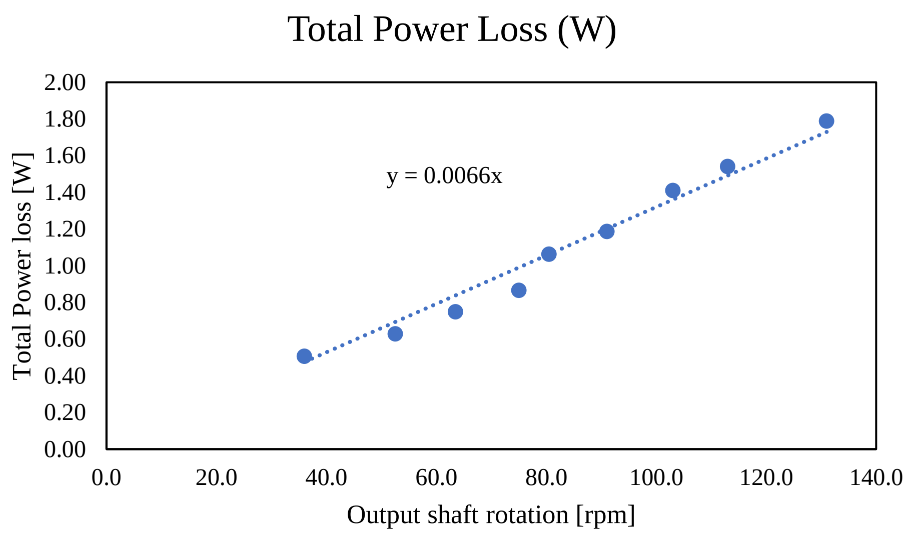


Figure 76. Power losses in generator

As shown in **Figure 76**, the relationship between power in/shaft speed and power lost is linear. This makes sense as back-emf resistance in a motor increases with speed.

9.3 Testing Challenges and Lessons

Throughout our testing, we found a number of challenges and learned a few lessons, too.

- We found that if the housing does not have enough structure, the pattern plates that make it up may be slightly warped which can cause shafts of any implemented drive trains to bind up. Adding the two middle pattern plates acting as baffles in the middle seemed to help.
- We encountered a problem with the amperage measurements. It was difficult to connect the multimeter in series with the generator with our current set up and get measurements. To correct this, we are implementing a resistor assembly that will create a load in the circuit and will allow to have an easy connection at the back side of the generator to the multimeter.
- We learned from our user testing that good pictures, backed up by very specific text, is the best form of instructions for students. We also got multiple requests to create videos of how to use the components.

10. Project Management

Good organization is essential for a large project like this one to be successful. Many layers of processes must be followed at a time from tracking overall progress to creating, reviewing, and submitting a single document to handling disagreements during team meetings. This section describes and reflects on some of the processes we used during this project.

10.1 Team Contract

The first thing we did as a group was create a team contract[13]. This contract specified team roles, commitments, and set expectations for matters such as participation, communication, decision making, and handling conflict. It also provided guidelines and procedures for team meetings. Each topic was discussed and agreed upon as a group. Every member signed this contract.

While we never had any incidents requiring us to refer to this team contract, the exercise of putting it together was important for setting expectations early. Also, if any disputes had occurred, we would have had something irrefutable to fall back on and guide us. We would recommend implementing team contracts for all long-term team projects.

10.2 Documentation

A project like this results in the creation of many types of documents that must be stored, organized, and shared between group members. This includes reports, spreadsheets, sketches, pictures, presentations, notes, references, surveys, contacts, and more. We kept track of all documents for the project in two shared tools, OneDrive and OneNote.

10.2.1 OneDrive

We kept all files in a team OneDrive. This included text documents, spreadsheets, slideshows, and pictures. OneDrive allowed multiple members to edit these documents at the same time which proved to be incredibly useful. It also meant that there was only ever one version of a file rather than each of us working on local versions and then trying to combine changes into a final document.

We did find that the online version of many Microsoft tools were either buggy, more limited, or less intuitive than their desktop app counterparts. However, barring these online versions, OneDrive worked very well for us and we would use it again.

10.2.2 OneNote

OneNote served as a digital project notebook. We put notes, links, reminders, photos, sketches, drafts of pieces of deliverables, and meeting minutes in the notebook. OneNote's automatic referencing feature when pasting anything copied from the internet was especially helpful.

It was requested by our advisors that we log hours spent on each task in our notebook throughout the project, but this proved to be impractical without very strict discipline.

Given the virtual nature of our work as this project took place during the COVID-19 pandemic, OneNote was an obvious choice. However, we found that the digital format worked exceptionally well. It allowed easier addition of more types of notes (such as links) than a physical notebook would, and we could stil easily add sketches to this as well. Add to that the shared nature of it rather than a separate notebook for each group member and the advantages are clear. We would definitely choose OneNote again for future projects.

[13] Appendix CC - Team Contract

10.3 Meetings

With the virtual nature of our project communicating with each other, our advisor, and our sponsor was especially important for sharing updates, receiving feedback, and planning. The majority of our meetings were conducted over zoom until late in the project when we mixed in a few in-person meetings to physically interact with our project.

10.3.1 Team Meetings

In addition to individual work, we met four times a week as a team for a total of about 7.5 hours to make sure we stayed on track and up to date. Every meeting was a chance to discuss decisions and ask for advice or feedback on individual work, but each meeting also had its own general purpose which is summarized in **Table 10**.

Table 10. Team Meeting Schedule

Day	Duration	Purpose
Tuesday	3 hours	Work on items requiring full team participation. Finish/delegate tasks to be completed by Thursday.
Wednesday	1 hour	Prepare Weekly Status Review for Thursday morning meeting with advisor.
Thursday	2.5 hours	Assess work to be done in the next couple of weeks. Make plans, delegate, and begin work
Saturday	1-2 hours	Check in on progress, provide feedback to each other, and answer questions

Later in the project we began conducting some of these meetings in person to interact with our activities, perform testing, and gather user feedback from volunteer testers. We also took these opportunities to hand the activities off between group members, giving everyone opportunities to play with it on their own time.

This meeting schedule worked very well for us. We found that having many meetings prevented members from getting stuck on any issue for too long and having a couple of longer meetings allowed us to be very productive on tasks that required the entire group.

10.3.2 Asynchronous Communication

Outside of meetings, we primarily used E-mail and GroupMe to communicate. Email as used for communicating with our advisor and sponsor and whenever files were shared. General questions and planning took place in a group chat over GroupMe with more specific coordination occurring in direct messages.

This system worked well for our team and project. GroupMe in particular was simple, easy, and allowed members to acknowledge they had seen a message which proved to be quite convenient.

10.3.3 Weekly Status Reviews (WSR)

Along with occasional e-mailed questions or updates we met weekly on Thursdays with our project advisor. In preparation for these meetings we would prepare a document that highlighted successes, insights, and concerns and discussed progress on goals from the previous week as well as goals for the following week. We would then review this document with our advisor and ask any questions we had gathered since the last meeting.

Overall these WSRs were helpful as they motivated us to stay on track and provided an opportunity to gather feedback and ask questions. On a couple of occasions it also served as an opportunity to discuss adjusting deadlines for certain deliverables with our advisor when the structure of our project called for that.

10.3.4 Sponsor Meetings

After the first few weeks of gathering 'needs and wants', meetings with our sponsor were primarily opportunities to present our progress and ask for feedback on our recent deliverables. We had a loose bi-weekly schedule for these meetings though we often postponed or cancelled a meeting when there wasn't too much to discuss or a big deliverable was approaching. Later in the project we met in person with our sponsor as well to gather her feedback on the prototypes we had produced.

10.4 Design Process

As this was a design project, we followed an engineering design process. This process is shown in **Figure 77**. All senior project groups followed this general process, and there were specific due dates for deliverables related to each step.

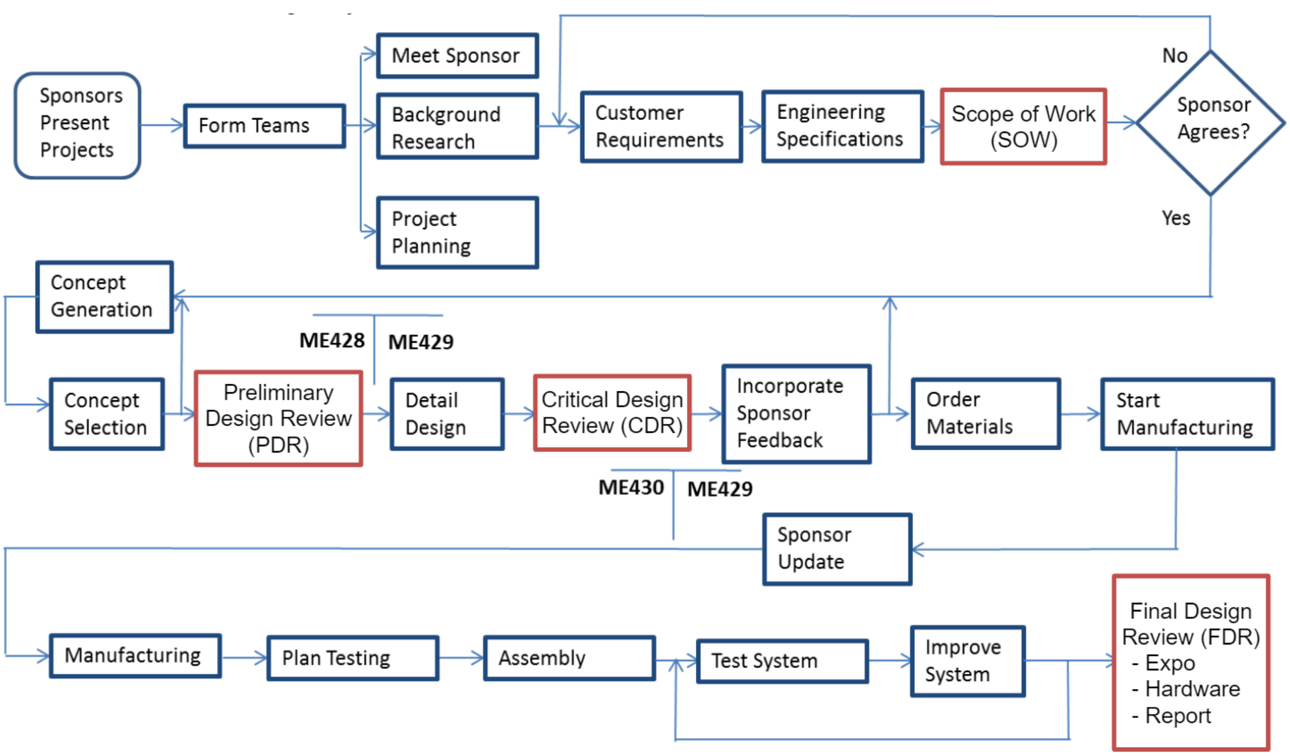


Figure 77. Senior Project Design Process

The process itself worked quite well. We are proud of the solution we ended up with and the deliverables we will be providing to our sponsor. However, the timing of the execution of some portions of the process could have been better. Often, the steps requiring iteration would be rushed due to a deliverable coming due in a short period of time and the real iteration would occur in parallel with later steps in the process. This led to previous deliverables becoming outdated and needing significant revisions in preparation for a design review or presentation on more than one occasion.

A similar problem occurred once we decided to produce two separate activities. This essentially meant we were working on two projects and basically doubled the number and/or size of deliverables we had from that point on. This didn't mesh well with the pre-determined intermediate deadlines.

In future projects, we would make a stronger effort to discuss the schedule of deliverables with our advisor, tailoring it to our specific project.

10.5 Planning and Prioritizing

Keeping track of past, present, and future tasks during a project like this is always a challenge. A Gantt Chart is a common solution used by many professional engineering teams. We created an maintained one ourselves[14], but we never really relied on it the way a professional project would. Since we had so many due dates and a calendar through our class portal and weekly meetings with our advisor we ended up keeping track of things using these methods instead. We also made notes to ourselves in our OneNote.

11. Conclusion

Our challenge was to expose students to ME 329 concepts and real-world applications with activities that use high quality components at a low cost.

After a thorough investigation of what students and faculty would like to see in a lab we decided to develop a lab that provides students will a better experience and understanding of gears, shafts, and bearings. Our solution is two activities with the second one building on the first: a one-lab exploration activity and a multi-week design challenge.

The exploration activity includes quality aluminum and steel components from a robotics vendor which can be assembled by students to model real-world gear trains. The gear trains are configured on top of provided magnetic 'pillars' and lows speed/torque motors are provided for input and output. This keeps forces and speeds low enough to maintain a safe environment while allowing students to learn using high-quality equipment. Multimeters and laser tachometers are supplied for taking measurements.

The design activity challenges students to design a power train for a model wind turbine using the parts from the exploration activity. A fan, turbine blades, and housing of our design will be provided for student teams to implement their designs and test them, competing to produce the highest power output.

We hope our confidence in capturing our sponsor's vision is not unfounded, and we look forward to positively impacting the education of many future ME 329 students.

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[14] Appendix DD - Gantt Chart

11.1 Achievements

In addition to prototypes of the two activities, we developed lesson plans to guide professors through implementing the labs and lab manuals to walk students through the activities. We also produced a video demonstrating the first guided activity for the exploration lab and compiled all of the CAD files students might need for the design challenge.

We did not develop a demonstration activity as this fell out of scope for this project. We were also unable to do proper user testing of the design challenge. All activities of a multi-week design lab would have required many hours of participation from each tester. However, we did much of the activity ourselves and are confident it will serve professors and student well.

11.2 Recommendations

The entire result of our project is essentially a set of recommendations. The prototypes we created are what we believe to be a good set of components, or at least a good start, but if professors see a need to add additional components in the future they can do so. The lesson plans provided for professors are recommendations for how to implement the lab, but these can of course be adjusted as well.

- We highly recommend that any professor using the activities we produced go through the entirety of the activity themselves, including all related documentation, before giving it to students.
- We recommend a demonstration of a real gear train used in the industry with its inner workings exposed such as a manual car transmission. This is part of the optimal solution to our problem statement, but given time and resource constraints it fell out of scope for this project.
- Components and manufacturing related recommendations can be found in section 8.4.
- We recommend acquiring enough exploration kits to keep group sizes below 6 students each. 3 is optimal.
- Only one fan and set of turbine blades are required, but we recommend at least 2 turbine housings so that one team can be 'on deck' while another is testing on test day. However, one housing for each group is optimal.

11.3 Next Steps

The prototypes provided to our Sponsor at the end of this project (one for each activity) as well as accompanying documentation are fully complete and functional; ready for classroom use. However, More than one kit is required for a class. Therefore, the next steps would be to secure funding from the Industrial Advisory Board, Mechanical Engineering Department, or other source to acquire components for additional kits. Make sure to consult the manufacturing recommendations section, Section 8.4, before purchasing and assembling additional kits.

Then, the kits will need to be assembled including all parts requiring manufacturing. We had some excess parts that could be used in future kits such as the custom motor boards and some screws.

Finally, any professor utilizing either of our activities in their class should go through the entirely of the activity, including documentation, on their own before giving it to students.

That's it! We hope the results of this project satisfy the needs of our sponsor Professor Cooper and benefit the education of many students to come.

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Appendix A Stakeholder Interview Request and Questions

Stakeholder interview email: (Cal Poly faculty version)

Dear ___________,

Hello, my name is James Popolow. I am on a Mechanical Engineering senior project team developing interactive lab experiments meant to enhance the experience of ME 329, Mechanical Systems Design.

A wide range of techniques such as analysis problems, finite element modeling, system/part modelling and simulation, and design projects are already used in lab to help students learn mechanical systems design.

We are working to develop activities that supplement these techniques by providing practical experience with the physical hardware used in mechanical systems. These activities would allow students to directly interact with industrial hardware, adjusting parameters and measuring how they affect the system performance.

Mechanical "Breadboards" previously sold by PIC Design and W.M.Berg, an example of one possible solution.

Given your experience in teaching this subject, we would really appreciate a chance to interview you. If you are willing, please let us know two or three options for a half-hour interview in the next week.

Or, if you would rather, please consider replying with answers to as many of the following questions as you are willing. Any amount of insight is greatly appreciated.

- **Which lab techniques/activities have you found to be effective in teaching Mechanical Systems Design concepts? Why?**
- **Which ones didn't? Why?**
- **Are there any you would like to try but haven't? Why not?**
- **What is your initial reaction to the type of activity we have described? If you like the idea, why? If not, what are you skeptical about?**
- **What about the solution would need to be true for you to consider them an upgrade to your teaching toolbox?**
- **Which concepts in the 329 curriculum or outside do you find student to be most interested in?**
- **Which concepts do you think would most benefit from this kind of hands-on activity?**
- **Have you heard of products similar to the kind we are developing? If so, who from and what did they say about them?**
- **Is there anyone you know who you think would be willing and valuable for us to interview and gather more information?**

Thank you for your time, we look forward to hearing back from you!

James Popolow

Appendix B Student Interest Survey Q3 Responses

Answers to: In a few words, what is it about the types of activities you selected that makes them useful?

- The hands on experience really sticks in your head.
- Most applicable in industry, will help with future internships
- Physically interacting and building upon skills
- The visual aspect and seeing how components interact with each other.
- It helps visualize the concepts a bit better.
- I want to do more hands-on projects to fully understand the concepts.
- I like turtles
- Getting to do something with enough creativity and uniqueness that it can be shown at job applications.
- Preparation for future careers. Hands on experience.
- more hands on, less programing/computer stuff
- They are hands on, they are fun and they will be useful when we get into the industries.
- They are hands on building options that lend themselves to creativity and imagination, while getting away from the boring typical class room assignments
- More involved projects or involving real parts help understand the concepts.
- I believe the interactive and hands on nature of these experiments is what really makes ME 329 impactful. I wish I was able to make things for this lab in person
- Hands-on, interactive
- Very hands on and able to absorb the concepts better
- Being able to iterate and see the results in a physical way.
- Gain experience in dealing with real world stuff
- Allows for more comfort in using the equations, and more hands-on experience with actual examples.
- It is chalenging and sparks creativity, which there is no enough of in Engineering
- One can visualized the problem instead of just doing the problem conceptually.
- It is nice to actually see what the things we are learning look like and interact with each other in real life
- it gives more hand on experience and gives the chance to visually see how things work.
- I believe there is a connection between what we analyze in class with the tools and modeling them in class and seeing hand on the outcome and the test that can analyzed in the real world
- i think CAD is really useful because thats what the real world uses, and the rest i like becuase it is hands on and help learning when you can actually hold something.
- its easier to visualize concepts
- You have the hands on part for the people who learn things visually, and then the simulation part to help cement in the concepts, as it helps to see where the stresses are and what the stress distribution looks like
- I think the purpose of a lab should be to lend real world experience to the theory you read about in lecture. The options I picked above are ones I believe best demonstrate this. The interacting with models and measuring effects helps to visualize the real world effects of changes of things you read about in class as well.
- They show how equipment works, rather than describing it
- Realistic design challenges are the most beneficial thing to do. Simulations allow for parameter changes to see how systems are affected by design choices.
- being able to design and model real life mechanical systems
- You're actually building things with parts that are available, not having to make everything (which isn't usually realistic. I've had to make things based on what is available, i.e. small budget stuff)
- They are hands on and actively collaborative activities that build skills needed for internships and jobs.
- These activities help better understanding of the real world items/design process
- Having hands-on experience or visuals when learning new concepts is a big help in understanding and visualization.
- Attaching an example to an abstract concept, developing tools for problem analysis
- Having hands on experience to fully understand and visualize the systems we learn about
- Computer simulations are boring and are not fun and interactive. Taking things apart doesn't really convey how something works, just what parts are involved. Lego gears are a great resource. Look up the steel Lego axle video, that conveys the principle of mechanical advantage very well.
- They allow me to visualize concepts in action
- I think doing it online was difficult and having part kits would've been beneficial
- understanding the parts that are described in lecture and how the forces result

- More hands on...good for visual learners as well...more than numbers on an excel sheet
- I believe there is much value in performing physical demonstrations alongside theoretical studies. These will help clarify questions that may arise and help with future projects that students find themselves performing whether in clubs, during an internship, or in industry.
- I think rebuilding something like a transmission from a disassembled one could prove amazing for this class. I did take this class fully online so I'm not sure what the actual labs consist of, so you might want to take my advice with a grain of salt.
- They are interactive, hands-on activities that will prepare you for design in the industry.
- I thought my experience with the design project in 329 was a good chance to apply the concepts ourselves
- More hands on/simply more interesting. We've dealt with MATLAB/basic CAD stuff for years and this is supposed to be THE important design class before senior project.
- I learn the best via hands-on learning.
- Hands-on real parts
- Hands on experience, familiarity with real, complex systems
- It's a lot easier to learn concepts like gears and screws when you can see the concepts in action.
- Seeing how the clutches and gear shifting works
- Seeing things that are designed and calculated in class
- Being able to physically interact with systems similar to the ones we analyze in class
- Seeing how real machines work
- I can physically hold/see it
- Seeing the real parts is always fun especially to be able to look at them in 3 dimensions
- Hands-on, physical experiences that encourage creativity and build engineering intuition for how things work
- In a design class, it's an iteration process, so start with ideas, then CAD, FEA analysis, Manufacture, and demo with testing
- seeing the outcomes of design decisions
- a big chunk of 329 is gear systems, and one of the most frequently used gear systems for us is a transmission. when people drive after learning more about it, they will remember what they learned.
- It is very difficult for me to visualize systems based on simplified drawings so the assignments would have been much more manageable if I had seen a physical example
- Understanding the math and applying it really solidifies the concept for me. Doing more FEA and calculations to compare values is one way I learn effectively. I also like design analysis so taking apart existing mechanical items gives me more of an idea of how to successfully use the working principles of mechanical design.
- Hands on, real life, practical
- being able to see what is taught in lecture in action and being able to connect theoretical models to experimental
- Ok, sorry, but I kinda selected them all. I think the best of all are things like disassembling mechanical systems, so you can see how people who actually put more than 3 weeks worth of thought into their designs did things.
- Real world applications, hands on
- Hands on experience with existing systems that relate the math of the simulation to the physical world
- They’re easy to see how they work, and they are the taught concepts in a real world application.
- They are hands on and actually give students visual practice with the components they are learning about in lecture
- More interesting and more interactive
- Hands on experience
- Some are really created while others are practical hands-on experience with mechanical systems. I also selected some activities that help visual learners as that is how a lot of people learn best.
- They are all hands on! Mechanical engineering is one of the engineerings where you can actually see and touch the things you learn about, so take advantage of that!
- Interactive, well-explained/documented process
- Each of the activities involve some online theoretical work along with small scale models to work with. I am personally not a huge fan of holding parts without seeing the parts in use.
- They’re all very applicable to a design type of job and provide useful project experience for students to add to their resume
- I loved the ability to do a real design and be challenged working in a team, like in the trike car project having to design the entire full subsystem.
- Hands on learning, being able to manipulate to see effects

Appendix C Table of Customer Needs and Wants

Type	Needs	Wants
Size	Fits on a cart/through a door	
Number	At least one	Enough for 4-6 groups
Weight	~500lbs	
Motion	Overall stationary, internal moving parts	
Forces/torques	Measurable kinematics present	
Material	Physical product	Industry Quality
Energy	Power provided (Manual or Electric)	Self-contained
Energy output/efficiency/loss		Measurable
Input/output signals	Present	
Operational Safety	Safe with supervision	Safe without supervision
Direct Protection	All potentially dangerous parts enclosed	
Human Factors	Interactive, reasonably easy to use	Intuitive, easy to set up and tear down and store
Production		Producible on-site
Quality		Industrial
Assembly	Within 8 hours	Student shop techs
Transport	Fit and move on a cart. Fit through a door	Only 1 person required
Operation	Student operable, exploratory	Robust
Maintenance	Easily replaceable parts	
Cost	Worth the price	Fairly affordable
Schedule	Implementable by next Fall	
Relevance	Applicable to real world	

The contents of this table are sourced primarily from Professor Cooper [1], and secondarily from other ME 329 professors and students.

Appendix D QFD House of Quality Table

Correlations	
Positive	+
Negative	−
No Correlation	

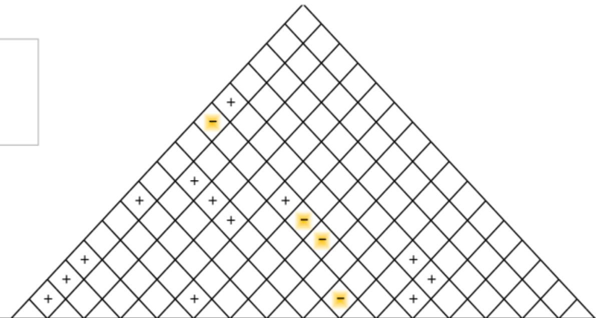
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Mechanical System Activities

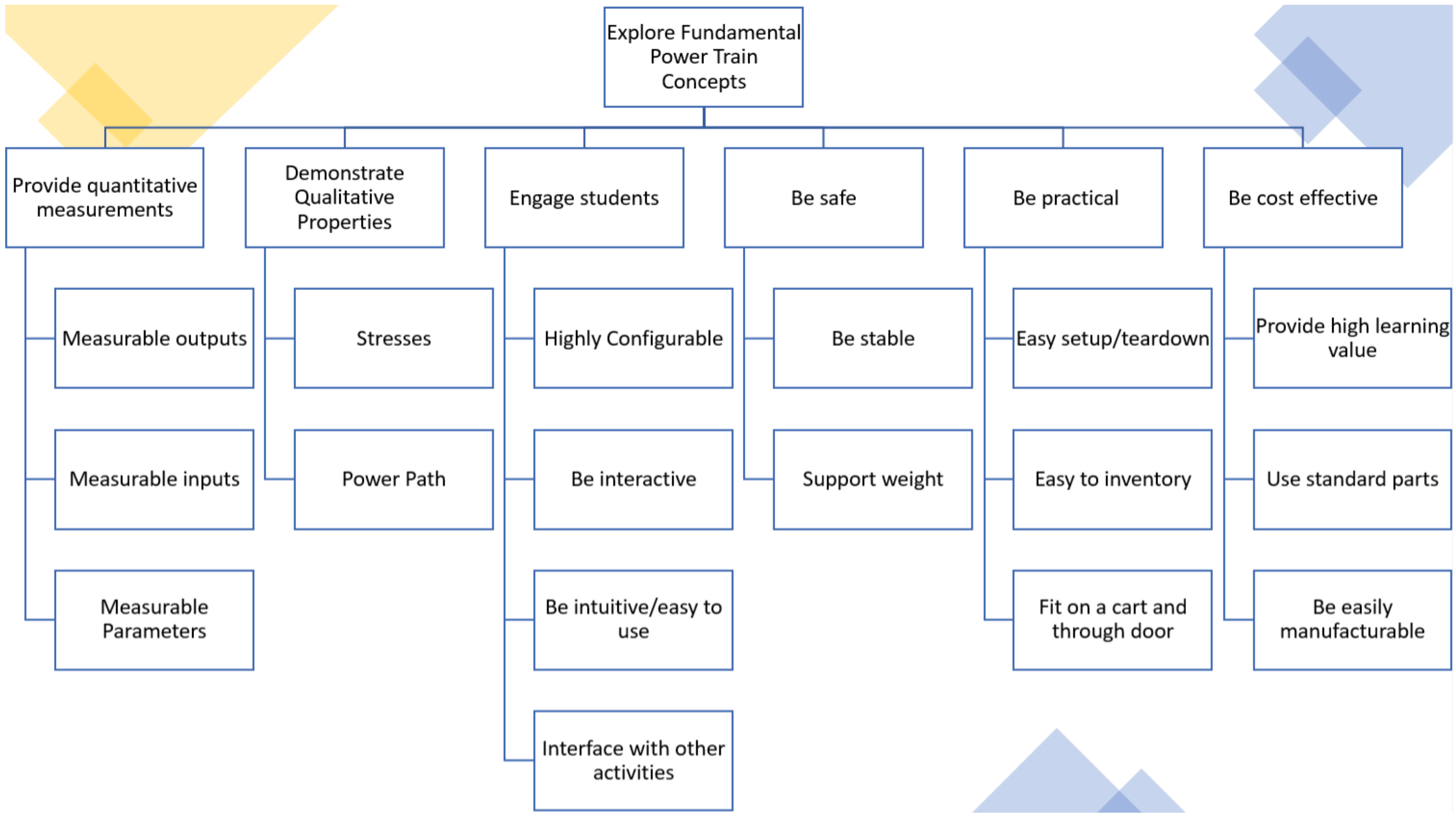
Revision Date: 10/07/20



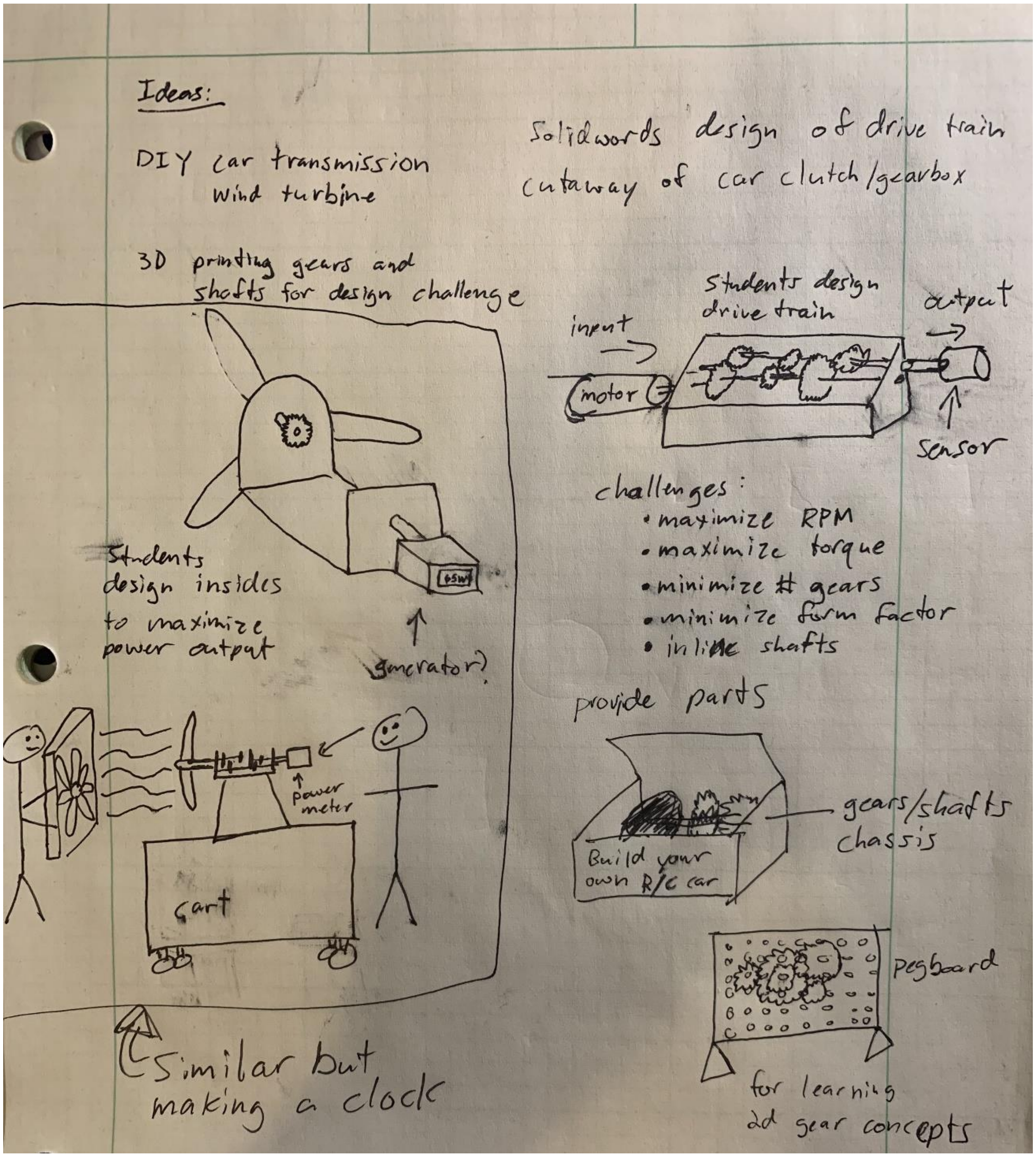
							Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
	WHO: Customers						Direction of Improvement	▼	▼	▼	▼	▲	▲	▲	▼	▼	▼	▼	▼	▲	◇			NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	Proffesor Cooper	Students	Manufacturing	Other ME 329 Professors	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) \ HOW: Engineering Specifications (Tests)	Weight	Length	Width	Height	Output Signals	Input Parameters	Number of Products	Pinch Points	Assembly Time	Machining Time	Price	Set up time	% of Standard Parts	Use survey			Current Teachin Techniques	Competitor #1: *Tecquipment*	Competitor #2: *PIC Design*	Past Senior Project	Competitor #3: *Stokys*	Row #
1		8%	10	2	3	10	9	Fits on a cart	●	●	●	●			▽										0	5	5	5	5	1
2		6%	10	1	1	10	9	Fits through door		●	●	▽								▽					5	5	5	5	5	2
3		8%	6	8	3	8	9	Industry-level Materials							●				●		●				1	5	4	4	1	3
4		8%	10	9	1	9	9	Measurable Outputs					●	●					▽						0	5	2	0	0	4
5		8%	7	8	2	7	9	Multiple Units of Product	●	○	○	○			●				●						0	5	5	0	5	5
6		4%	4	2	2	5	9	Self Contained Power					○	●	○					○					0	1	1	3	5	6
7		10%	10	7	4	10	9	Safe for students	○							●						●			5	5	2	5	5	7
8		10%	8	2	7	9	9	Easy to Maintain	○	○	○	○					○	●			●				5	4	4	4	5	8
9		8%	8	9	1	9	9	Intuitive Use												○		●			-	2	3	2	4	9
10		9%	7	1	9	3	9	Easy to Manufacture	○								●	●			●				5	1	3	1	4	10
11		5%	8	1	1	8	9	Low Cost							●				●		○				5	1?	1?	4	3	11
12		9%	9	10	1	9	9	Interactive					●	●								○			0	3	5	5	5	12
13		9%	10	10	1	8	9	Applicable to Real World					○	○					○		●	●			0	2	3	2	1	13
14		0%																												14
15		0%																												15
16		0%																												16

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	500 lb	45 in	25 in	47 in	2	2	1	0	3 hr	5 hr	$1,000	10 min	80%	80%		
	Max Relationship	9	9	9	9	9	9	9	9	9	9	9	3	9	9		
	Technical Importance Rating	221.2	171	171	124.8	190.3	215.7	205.8	89.96	109.4	166.9	219.5	42.22	332.2	263.3	0	0
	Relative Weight	9%	7%	7%	5%	8%	9%	8%	4%	4%	7%	9%	2%	13%	10%	0%	0%
Curr. Products	Current Teachin Techniques	5	5	5	5	5	5	5	5	0	0	4	5	5	5		
	Competitor #1: Tecquipment	5	5	5	5	5	5	5	5	2	0	1	5	2			
	Competitor #2: PIC Design	5	5	5	5	2	5	5	0	2	2	1	2	2	2		
	Competitor #3: Stokys	5	5	5	5	0	5	5	0	4	3	2	1	4			
	Past Senior Project	5	5	5	5	0	3	5	5	4	1	4	4	3			
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

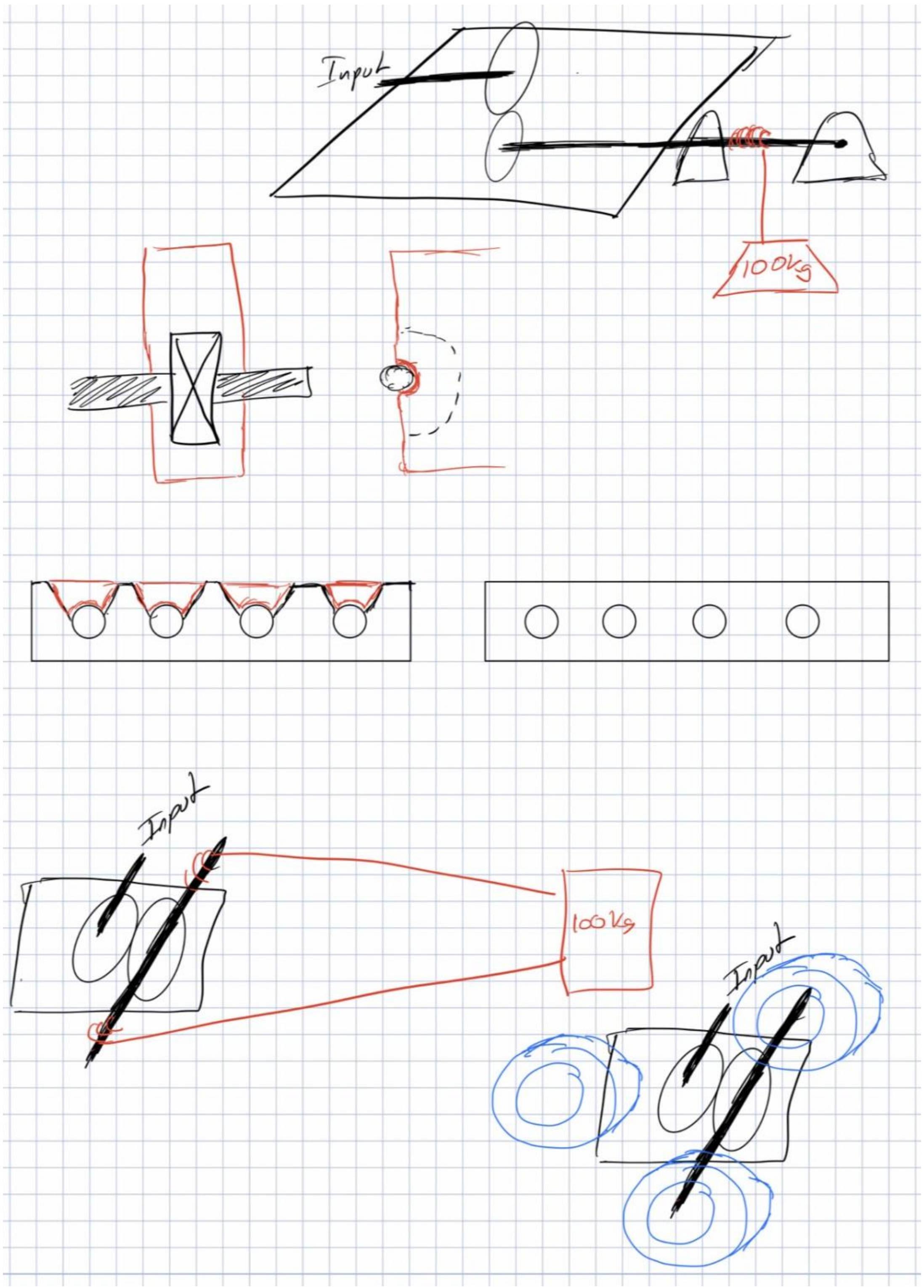
Appendix E Exploration Activity Functional Decomposition



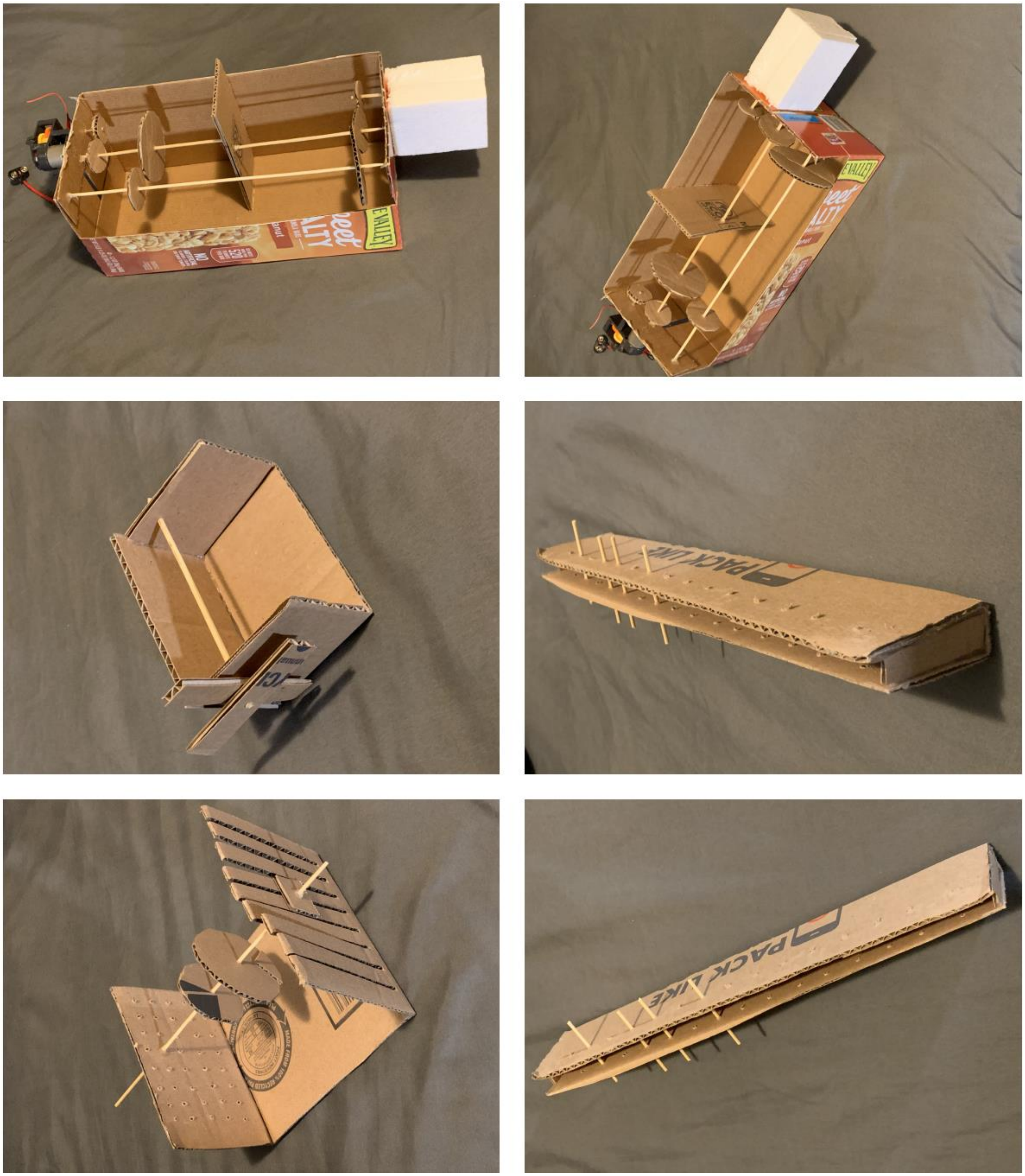
Appendix F Exploration Activity Ideation



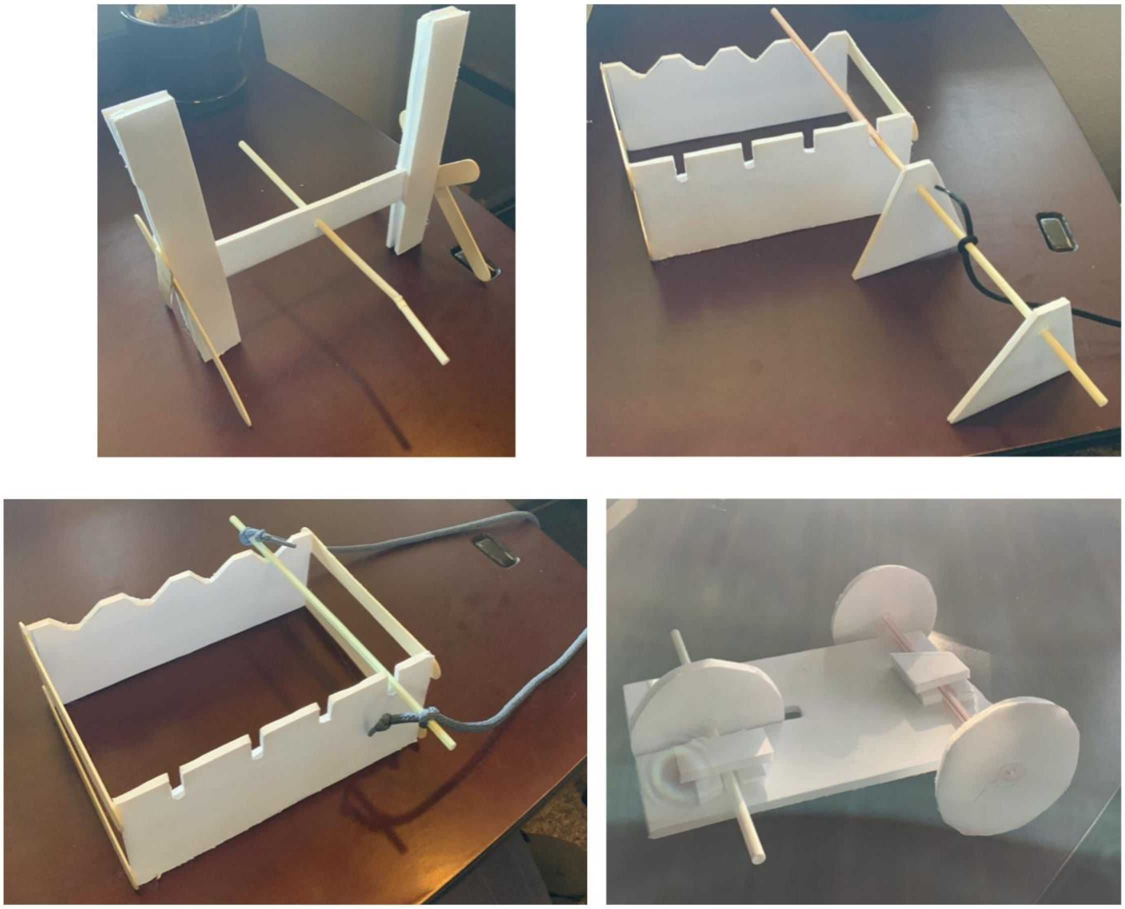
Ideation sketches for multi-step labs and configurable activities.



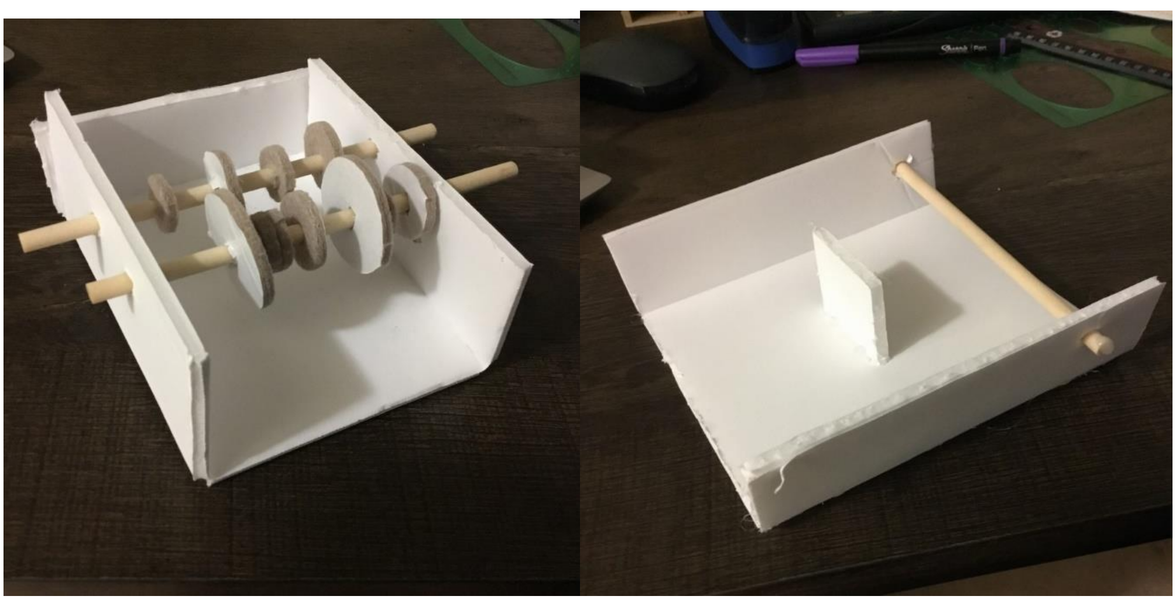
Ideation sketches for configurable gear activities.



Ideation models for making configurable activities



Ideation models for different activities.



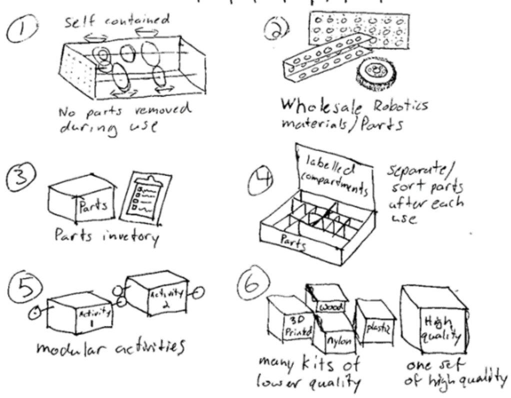
Ideation models for different configurable models and base to incorporate a real car transmission

Appendix G Exploration Activity Pugh Matrices

Pugh Matrix

Practicality

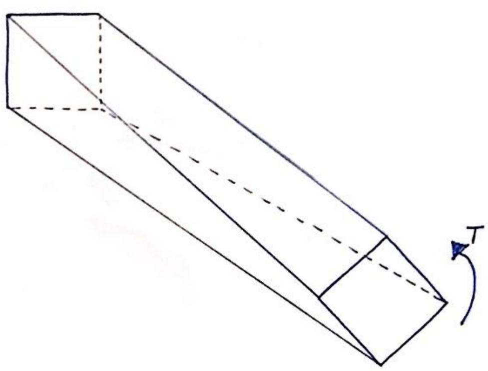
	1-5 *	3-7 *	-1-1	0-2	-2-6 *	2-6 *
	(1)	(2)	(3)	(4)	(5)	(6)
Easy Setup/teardown	+	?	–	–	0	?
Easy inventory	+	?	–	–	?	?
Fit on cart/through door	?	+	+	+	+	0
High learning value	0	+	?	?	+	+
Uses standard parts	?	+	0	0	?	+
Easy to acquire/manufacture	0	+	+	+	?	+
economic	+	+	0.	+	?	+



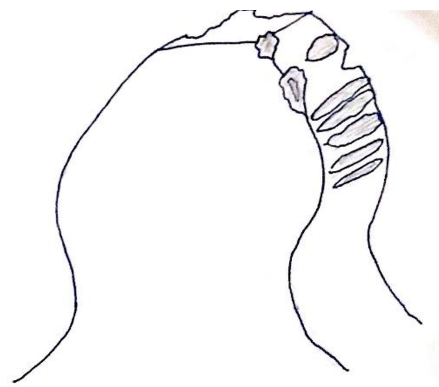
1. If the entire activity could allow students to change parameters without adding or removing parts, it would be very easy to set up, tear down, and keep track of all the parts. This would make it very easy on the professors. However, this would mean it would all have to stay in one piece, potentially taking up space. Also, it may be harder to swap out parts if needed with this approach.
2. Using readily available robotics parts would be a great way to make sure the solution is highly configurable without requiring a lot of custom machining. There are also some very high-quality parts available for robotics, which would give the students great experience. One drawback is that the parts may allow too much configuration and be too confusing or two time consuming for students to properly reconfigure during lab.
5. Modular activities could be broken down and stored more easily than one big integrated apparatus. Also, modules could be added and removed as needed, making the activity as a whole flexible for both professor's and department purchasing. The success of this concept relies heavily on the other design choices made.
6. The idea here is to compose many kits of many low-er quality parts for many groups to use, and one set of high quality components for each team to take turns using to implement their 'final design' after exploring with the other parts. This would be a good compromise between making many parts available to students and keeping costs down while still allowing for some interaction with high quality.parts The downside is it is a lot of parts to keep track of and replace. This one is also somewhat reliant on other design decisions

Provide qualitive properties

Concept / Criteria	1. THRUST FORCE	2. PULLING & LIFTING WEIGHTS	3. PHOTOELASTIC	4. TORQUE/SPEED SCALING	5. SHEARING	6. PITTING FATIGUE	
INDUSTRY LEVEL MATERIALS	S	S	—	S	+	+	
INTUITIVE USE	+	+	+	+	+	+	
INTERACTIVE	+	+	+	+	+	+	
APPLICABLE TO REAL WORLD	+	+	+	+	+	+	

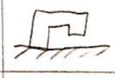
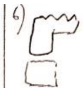


The idea here is that the shaft would twist from a large torque ratio from the gear train. The student will visually inspect the shaft and notice an abundance of torque is being applied that could lead to failure. The picture is rectangular to exagerate the response.



Here we would model a real gear that can mesh with all the other gears of similar Pitch or not. This gear would be plastic and printed in a 3-D printer. It will show the student what will happen if the wrong gear is meshed with the oposing gear as well as a gear reaching infinite life when it has meshed with a proper gear.

Provide a high level of safety

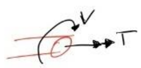
Concept / Criteria	1) Support weight 	2) stable 	3) cover 	4) cut away 	5) Emergency shut off 	6)  Safty switch	
Safe for Students	+	+	+	+	+	+	
Easy to maintain	+	+	+	S	+	+	

Provide quantitative measurements function.

Plug Matrix Analysis

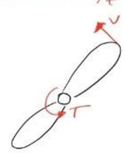
Function: Provide quantitative measurements

① Regular shaft



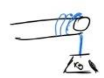
A simple output or input shaft could be used to measure velocity and torque. We could use a tachometer for the velocity. We still need to ideate on what to technique we will apply to measure torque.

② # of rev/t



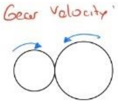
A propeller could be placed on the outer shaft to check for velocity at the different points. The number of revolutions over time and the torque.

③ Tension



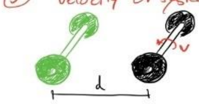
The outer shaft could be connected to a cable. We could calculate the tension on it.

④ Gear Velocity



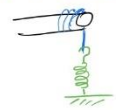
We be able to measure gear velocity and RPM with a given input PRM. This could be calculated with simple gear formulas.

⑤ Velocity of system



The shaft on the right could be attached to two wheel. This shaft will be driven by gears. The velocity of the system could be calculated with distance over rotation.

⑥ spring constant



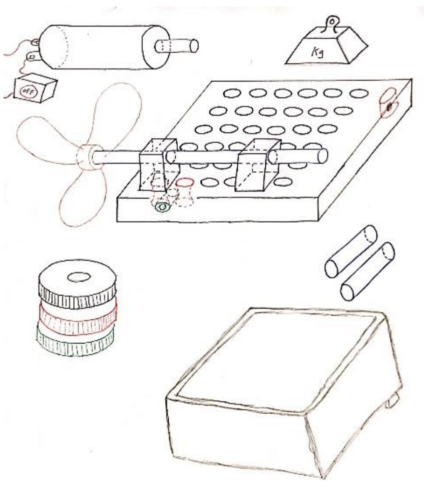
Similarly to 3, a spring could be attached at the end of the cord. The spring constant could be calculated from this.

⑦

Criteria \ Concept	① DATUM	②	③	④	⑤	⑥	⑦
Weight	D	S	—	S	S	S	
Low Cost	A	—	S	—	—	—	
Interactive	T	+	+	+	+	+	
Safe	U	S	S	S	S	S	
Easy to maintain	M	S	S	—	S	S	
Intuitive use		+	+	S	+	+	
easy to manufacture		S	S	S	—	S	
Applicable to real world		+	+	+	+	+	
Total		2	2	0	1	2	
Rank		*	*			*	

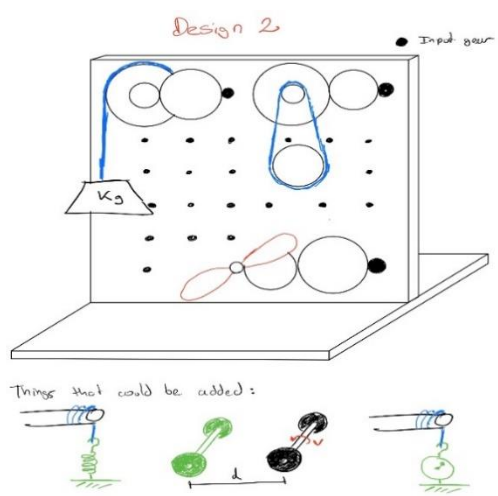
Appendix H Concept Ideas for Exploration Activity

Design 1:



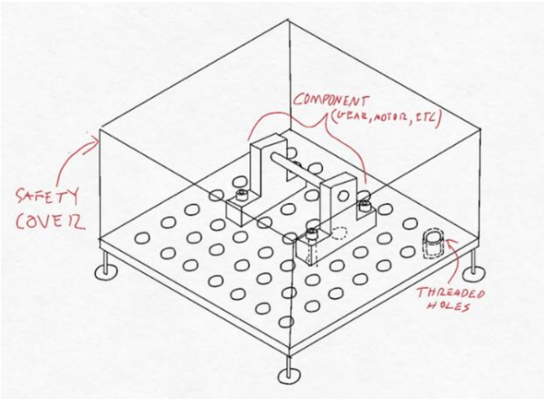
Design concept one incorporates every qualitive and quantitative design feature listed in the morph matrix which is similar to the other design concepts that follows. The main difference that sets this design apart from the rest is the high level of quality in parts. For example, The gears here are all using the highest quality parts from a robotics surplus vender, the type of mechanism used to secure the shaft pillars are expensive and highly precise components that quickly locks the pillars to place on the horizontal pegboard base. This design also incorporates every safety feature that suggested in the matrix, including safety cover, emergency shutoff button, cover Safety switch, and stability. Having all these features increases the manufacturing time considerably as well as increases the total cost of the project but does ensure the students safety. The highest quality components purchased from the vender reduces manufacturing to zero in terms of gear making but does increase the total cost of the budget. Lastly the locking mechanism for the pillars are simple to use and requires a moderate amount of machining to implement the components, on the downside these components are very expensive and will drastically raise the cost of the project. That being said, this design will bring forth the highest quality design model for students to explore concept related to the course.

Design 2:



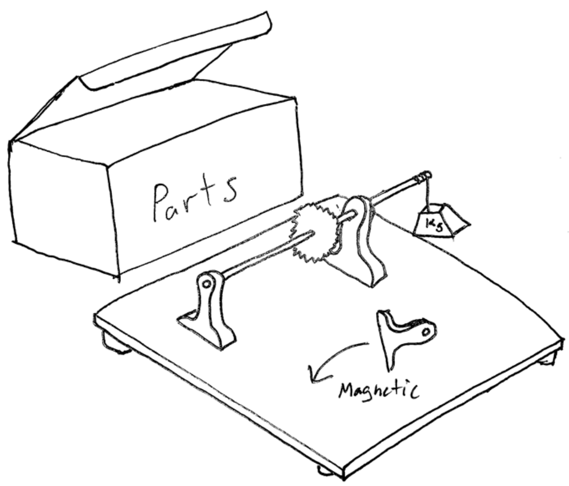
Concept design 2 consists of a vertical pegboard that could be used as a gear exploratory lab. It has multiple holes where shafts and gears could be installed. One of the main functions is getting multiple quantitative measurements from this design. The set up could be done by the instructor before class to teach a specific topic, or the students could explore different configurations during the lab. This design would use only middle quality gears and shafts to keep the price down. Design 2 scored the lowest, but its score is relatively close to the other designs. Manufacturing and maintenance time brought the score down.

Design 3:



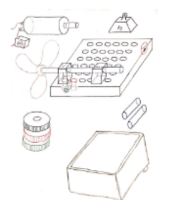
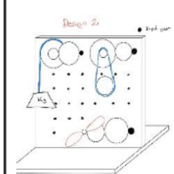
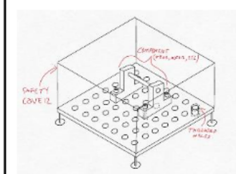
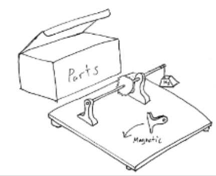
Design 3 is very similar to design 1. Instead of using a quick locking system with pegs like design 1, design 3 uses threaded holes and screws to secure components to the base. The baseplate has a grid of threaded holes that allow users to fasten components without need access to the underside of the plate. Standardized mounts would allow a variety of component configurations. Additionally, a clear cover would encompass the baseplate and components in order to provide an extra layer of safety beyond warning labels. The “feet” on the baseplate are adjustable to account for uneven surfaces.

Design 4:



Design 4 is similar to Design 1, except that it uses magnets to attach components to the base rather than a pegboard. The magnets make it very easy and intuitive for students to use. It is also much easier to manufacture because the base can just be a solid plate and the rest of the components just need to have magnets attached to them. The magnetic attachments also have the advantage of being even more highly configurable. The components would not need to conform to any grid pattern, as they could be placed anywhere on the board. There are a couple of concerns about this design. The magnets will need to be strong enough to prevent the components from slipping around on the base. Perhaps we will need to include other ways to ensure they stay in place. Also, the magnets will become weaker as they are used and abused, so we will have to make it easy to swap them out for new ones.

Appendix I Exploration Activity Weighted Decision Matrix

		Options			
		Design 1	Design 2	Design 3	Design 4
					
Criteria	Weighting	Score	Score	Score	Score
Fits on a Cart	0.08	5	5	5	5
Fits Through Door	0.06	5	5	5	5
Industry Level Materials	0.08	4	4	4	4
Measureble Outputs	0.08	5	5	5	5
Multiple Units of Product	0.08	5	5	5	5
Self Contain Power	0.04	5	5	5	5
Safe for Students	0.1	5	4	5	4
Easy to Maintain	0.1	2	1	1	4
Intuative Use	0.08	4	4	4	5
Easy to Manufacture	0.09	4	2	2	4
Low Cost	0.05	1	5	4	3
Interactive	0.09	5	5	5	5
Applicable to real world	0.09	2	2	2	2
SUM		4.08	3.9	3.95	4.36

Appendix J Hazard Checklist for Exploration Activity

Y	N	**Exploratory Activity**
✓		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	✓	2. Can any part of the design undergo high accelerations/decelerations?
	✓	3. Will the system have any large moving masses or large forces?
	✓	4. Will the system produce a projectile?
	✓	5. Would it be possible for the system to fall under gravity creating injury?
	✓	6. Will a user be exposed to overhanging weights as part of the design?
✓		7. Will the system have any sharp edges?
	✓	8. Will any part of the electrical systems not be grounded?
	✓	9. Will there be any large batteries or electrical voltage in the system above 40 V?
✓		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	✓	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	✓	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	✓	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✓	14. Can the system generate high levels of noise?
	✓	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
✓		16. Is it possible for the system to be used in an unsafe manner?
	✓	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any “Y” responses, on the reverse side add:

(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Pinch points created by rotating gears	Forces at the gears will not be high enough to cause damage. Warning labels will suffice. No loose clothing or long hair or jewelry Note: if analysis shows higher forces clear housing maybe utilized.	02/16/21	
System will have many components made of metal with potential sharp edges	Deburring or sanding on those sharp edges will be required.	02/16/21	
Batteries utilized	Energy stored will not be high enough to be of concern.	02/16/21	
Overpowering electronics	Warning label on design and instructions on how to properly operate the product.	02/16/21	
Creating a projectile launcher	Instruction on how to properly operate the product.	02/16/21	
High magnetic forces	Increase the gap distance between the magnet and the base plate. Most parts will be non-magnetic. Students will not have to handle magnets.	02/16/21	

Appendix K Preliminary Force Calculations

MAXIMUM TRANSMITTED LOAD

MOTOR SPECS: MAX SPEED = 303 RPM

MAX TORQUE = 16.8 oz in

$$HP = T\left(\frac{RPM}{5252}\right)$$

$$T = 16.8\ oz\ in\left(\frac{1\ lb}{16\ oz}\right)\left(\frac{1\ ft}{12\ in}\right) = 0.0875\ lb\ ft$$

$$\Rightarrow HP = 0.0875\ lb\ ft\left(\frac{303\ RPM}{5252}\right) = \underline{0.005\ HP}$$

ASSUMING THE SMALLEST GEAR HAS A DIAMETER OF 0.5 in AND A SPEED OF 10 RPM AND USING THE FOLLOWING EQUATIONS:

PITCH-LINE VELOCITY = CIRCUMFERENCE * SPEED

$$PLV = \pi(0.5\ in)\left(\frac{1\ ft}{12\ in}\right)(10\ RPM) = 1.31\ ft/min$$

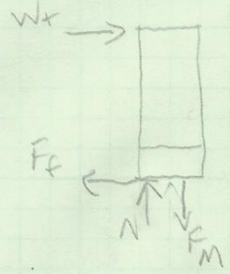
TRANSMITTED LOAD = POWER * PLV

$$W_t = (0.005\ HP)(1.31\ ft/min) = \underline{126.1\ lbf}$$

WE FIND THAT THE MAXIMUM TRANSMITTED LOAD IS 126.1 lbf.

REQUIRED MAGNET STRENGTH TO PREVENT SLIPPAGE

FBD



ASSUMPTIONS

1) W_t IS PURELY HORIZONTAL

2) NORMAL FORCE IS EQUAL TO THE MAGNET'S HOLDING FORCE

3) $\mu_s \approx 0.8$ (STEEL-STEEL OR RUBBER-STEEL)

$$W_t = F_f = \mu_s N = \mu_s F_m$$

$$126.1\,lb = 0.8(F_m)$$

$$F_m = \frac{126.1\,lb}{0.8}$$

$$F_m = 157.6\,lb$$

IF WE USE TWO TOWERS, THEN THE F_m REQUIRED OF EACH IS 79 lb.

Appendix L Exploration Activity Lab Manual

GEARS AND GEAR TRAINS

EXPLORATION ACTIVITY

LAB MANUAL

Cal Poly, Mechanical Engineering

5-31-2021

CONTENTS

SAFETY

HAZARDS

The following safety hazards are present for this activity:

- Strong magnets
- Rotating components
- Pinch points
- Low voltages and currents
- Lasers

PROCEDURES AND POLICIES

All individuals interacting with the equipment for this activity should follow the following safely procedures:

- **Do not** remove the magnets or plastic magnet mounts from the **U-channel pillars**.
- Wear safety glasses.
- Wear close-toed shoes.
- Secure long hair.
- Remove or secure loose clothing, chains, and jewelry (including any **ferrous rings)**.
- Keep fingers away from rotating components during operation.
- Do not attempt to back-drive any motor that does not allow you to do so easily using only your hand directly on the motor shaft.
    - Use the **124 RPM motor for input** and **970 RMP motor as a generator**.
- **Do not** point the laser tachometer at a person, especially their face.

COMPONENTS

INVENTORY

All components for this activity, aside from the steel base plate, should be stored in the provided tacklebox when not in use.

Please return all components to the correct tacklebox in an organized fashion after use.

TOOLS AND COLOR CODING

The only tools required for this activity are three hex keys.

3/32 Hex Key

Use on all brass **pinions**

9/64 Hex Key

Use for bevel and worm gear sets

7/64 Hex Key

Use for all other parts

USAGE

CONFIGURATION

There is no one specific way to arrange the gear train components and not all components must be used. Use your imagination to increase or reduce the output shaft speed and torque. A sample configuration of using all components is shown below.

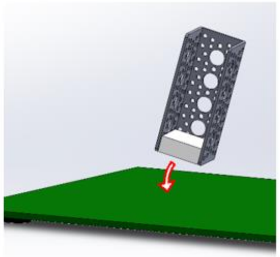
STEEL BASE PLATE

The steel **base plate** is what you will build your configuration on.

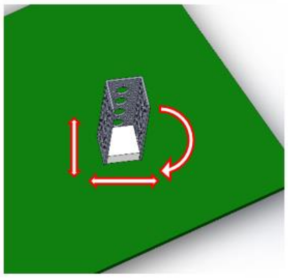
PILLARS

The **pillar** assemblies consist of a U-channel, a magnet, a magnet mount, and screws. **Pillars** will be pre-assembled and will come in two sizes (four and nine holes). **<u>Do not remove the magnet or magnet mount from pillars.</u>**

Simply place **pillars** magnet side down on the **base plate** to provide supports for your gear train.



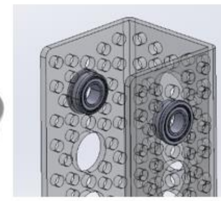
The friction between the **pillars** and **base plate** will allow them to resist some force, but you should be able to slide them and rotate them with your hands without too much trouble.



BEARINGS AND PILLOW BLOCKS

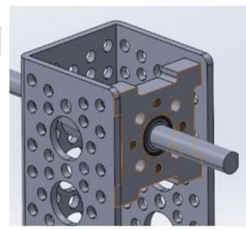
Use **bearings** to support **shafts** in your configurations. They sit in the large holes in the **U-channel**.

It is a clearance fit, so make sure to use your **gears**, **pinions**, and **shaft collars** to constrain the **bearings** to make sure they do not fall out.

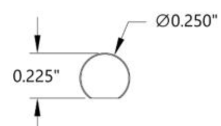
You also have a small number of **pillow blocks** available to you. These are simply bearings housed in a mount that you can attach to anything with the patterned holes, such as a **U-channel**.

The individual **bearing** should work for most applications but **pillow block** can sometimes be handy!

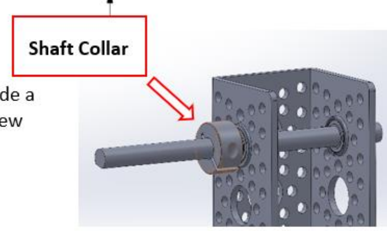



SHAFTS AND SHAFT COLLARS

The provided **shafts** are ¼" and have a D-shaped cross-section. This allows for higher torque transfer using set screws or hubs with a similar profile.



To prevent axial movement from the **D-shaft**, slide a **shaft collar** onto the **D-shaft** and tighten the screw with the larger Hex Key.



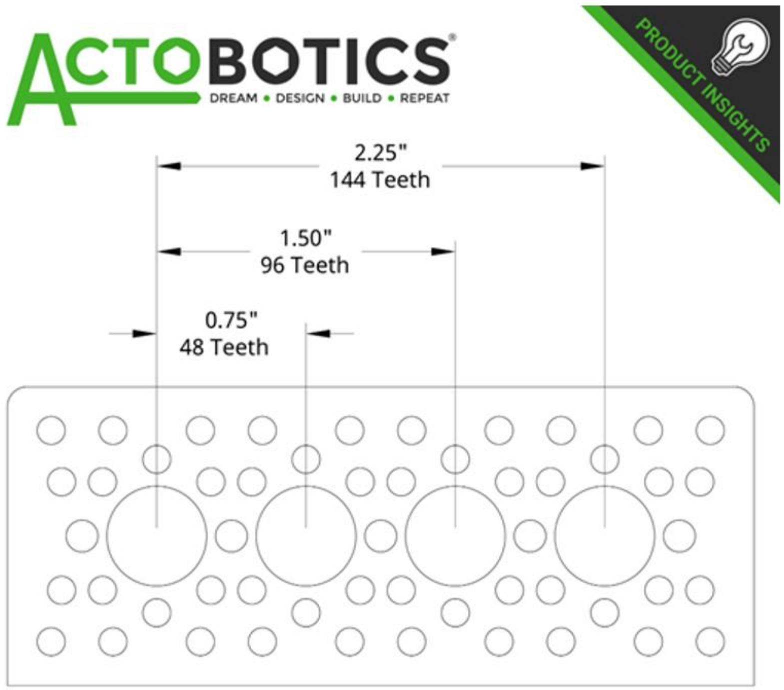
GEARS

Two types of gears are offered in this kit, **pinion** gears and **hub** gears. These gears come in many sizes and teeth numbers. The larger gears requiring a hub will come pre-assembled, ready to be mounted onto the shaft. **Do not remove hub mounts from gears.**

The pinion gears come with a set screw that will be used to secure the gear onto the shaft. **Please only tighten set screws on flat portion of D-Shaft**

GEAR MESHING

All provided gears have a pitch of 32 and will mesh together. However, if two meshing gears need to be configured on a single U-channel, the sum of their teeth must be a multiple of 48.



32 Pitch Gears Product Insight #1

For any two 32 pitch gears to mesh properly on Actobotics Channel (given the 3/4" spacing of the 1/2" holes) the sum of teeth must be a multiple of 48. Just add the teeth of two gears and **divide by 48**. If you get a whole number, they will mesh on Actobotics channel.

Example A:
32T + 64T = 96 Teeth
96 / 48 = 2
They will mesh on channel.

Example B:
32T + 48T = 80 Teeth
80 / 48 = 1.67
They will NOT mesh on channel. [1]

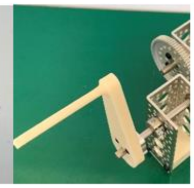
[1] Actobotics - ServoCity.com

INPUT

Once you have configured your gear trains you will want to test them. For this you have two options, manual or powered input.

MANUAL

The **crank arm** assembly can be used as a mechanical input. Slide the assembly onto the **D-shaft** and tighten the set screw.

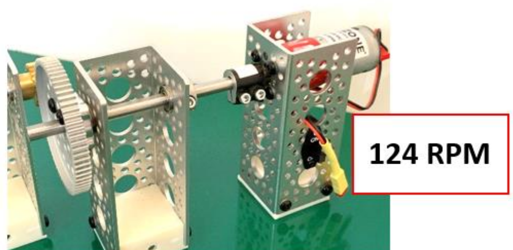


POWERED

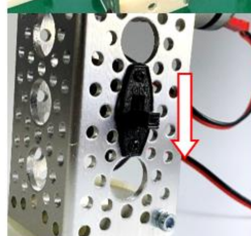
A motor can be used to apply a rotational moment into your gear train assembly. Before connecting the motor assembly to the gear train, make sure your gear train is secured and meshes properly.

Connect the shaft of the **124 RPM input motor** to the input **shaft** of the geartrain using a shaft coupler.

Do not use the 970 RPM motor for input.



Before applying power to the motor, make sure that the motor switch is in the off position.



Connect the motor to the power supply with the wires provided.

Set the voltage on the power supply no higher than 12 Volts and, finally, turn the motor switch to the on position. **Do not let motors stall.**

Voltage ≤ 12V

MEASUREMENT

POWER OUTPUT

You can also use the **generator assembly** to measure the power output of your gear train.

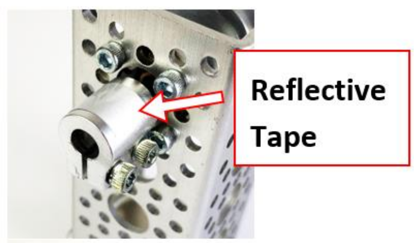
Connect the **970 RPM motor** to the output **shaft** of your gear train using a **shaft coupler**.

Do not use the 56 RPM motor. Attempting to back-drive this motor will damage the internal gears.

Turn your multimeter on. Make sure it is set to measure either DC voltage (20) or current. Then, connect the leads coming from the multimeter to the pins sticking out from the motor board on the back of the motor.

SHAFT SPEED

Use the provided tachometer to check the rotational speed of components. There is reflective tape on all **shaft collars** and on the **shaft coupler** of the **output generator.**



Aim the tachometer laser to the reflective tape to get rotational speed values. **Make sure the entire laser dot is on the reflective tape for accurate readings.**

LAB

PRE-LAB

SKETCHING

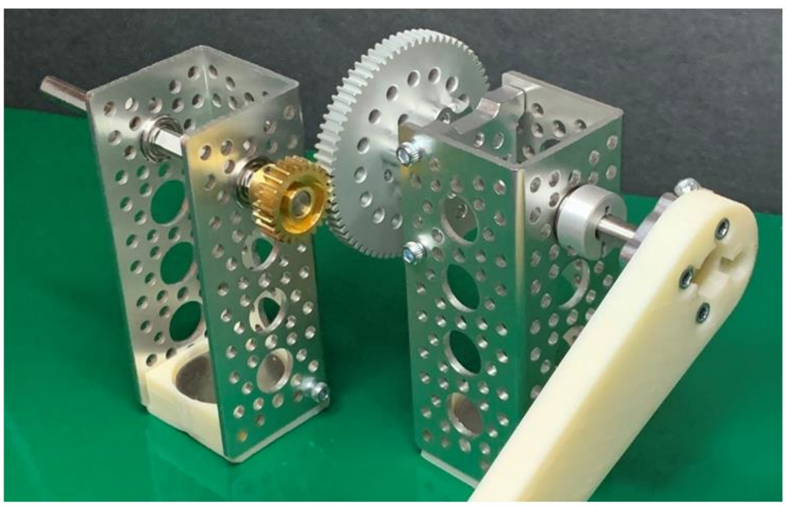
Sketch a configuration of this activity that would function as a speed increaser. Clearly label every instance of the following components:

- Pillars
- Shafts
- Bearings and Pillow Blocks
- Collars

FREE BODY DIAGRAM

- Make a free body diagram of the configuration you sketched above. Calculate and identify the point of max stress and the point of failure.

GUIDED ACTIVITY – SIMPLE CONFIGURATION



You will be making a very simple, 2-gear drive train using a manual crank for input.

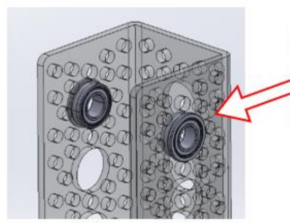
1) Place metal **base plate** on table surface with rubber feet down

2) Open the lab kit and select one pre-assembled **4-hole pillar**.

Place it on the metal **base plate**.

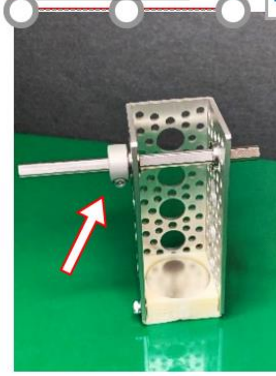
3) Select 4” **shaft** and two **bearings**.

4) Slide **bearings** to the upper two large holes on the **pillar** and slip the **shaft** through both of them.

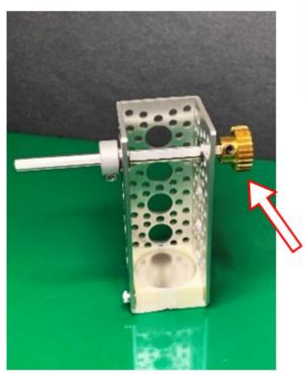


Top holes

5) Secure one end in place with a **shaft collar**



6) Select a **pinion** gear and attach it to the **shaft**. Make sure to tighten set screw with small hex key tool **on the flat surface of the D-shaft** to prevent damage.



7) Follow step 2-4 to prepare another **pillar** with a **gear** that will mesh with the first one.

   Note: You will need to tighten the **hub mount** quite a bit until there is no axial movement along the **shaft**

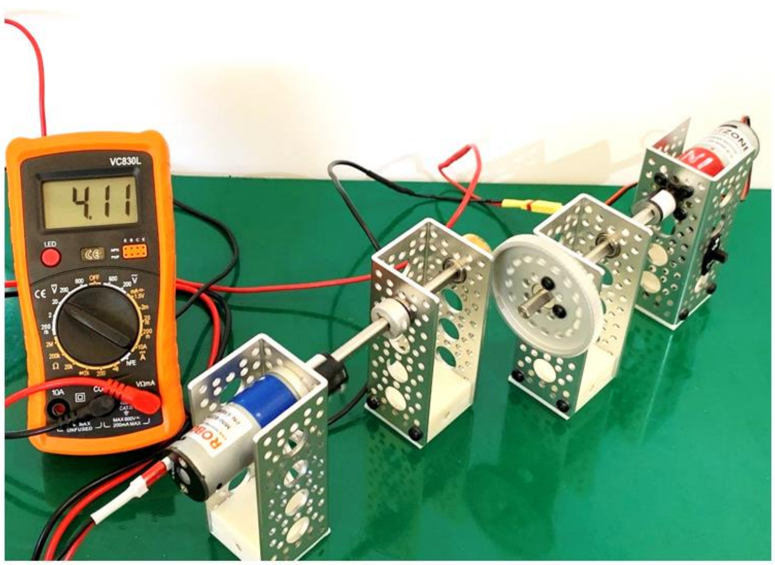
8) Attach the **crank arm** assembly to one end of one **shaft**.

   Try it out! Note the gear ratio and the effort required to turn the gear.

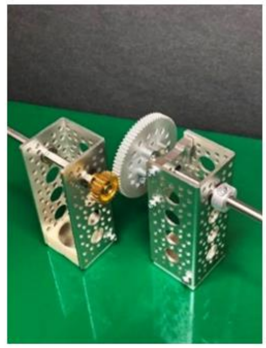
9) Now, put the **crank arm** on the other **shaft**. Note the differences between this setup and the first

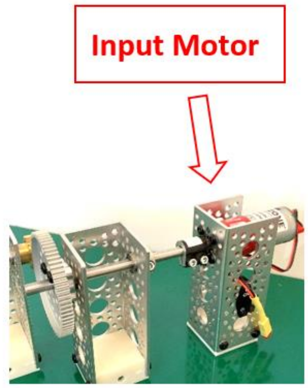
These were the steps to a simple configuration, there are infinite ways to arrange them. This setup is just to give you a basic understanding of how to secure the components you will use for all other configurations you can make.

GUIDED ACTIVITY – POWERED INPUT AND TAKING MEASUREMENTS

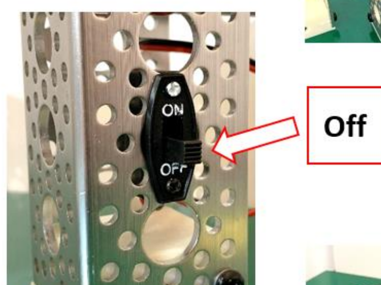


1) Set up a configuration similar to the one in the first guided activity, but without the **crank arm**. Make sure both your input and output **shafts** are four large holes up from the **base plate**.

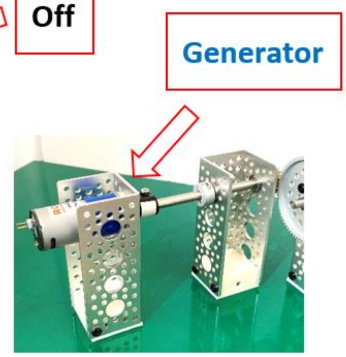




2) Select the **input motor assembly** and align it with your input **shaft**. Connect it to your input **shaft** using the **shaft coupler**.



3) Make sure the switch is set to **off**.

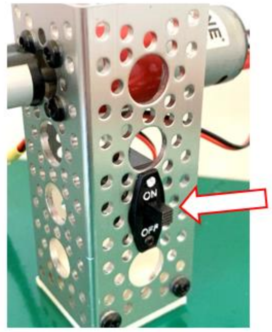


4) Do the same as step 2 to secure the **generator assembly** to your output **shaft**.

5) Connect the **multimeter** leads to the **output generator** motor and the power supply leads to the **input motor**. Turn the **multimeter** on to DC 20 V mode.

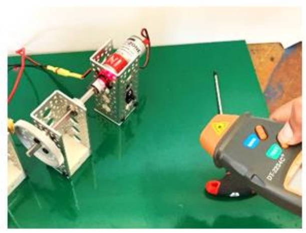
6) Make sure the power supply is set to 6 Volts
7) Plug the banana connector ends of input leads into the power supply.

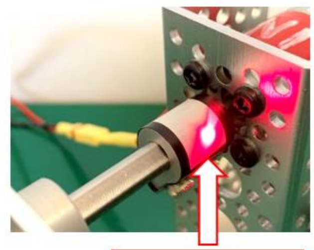
8) Turn the **input motor** power switch on and read the output voltage from the **multimeter**. Record it in a table similar to the one at the end of this section.



9) Switch the **input motor** off, then install the **amperage measurement adapter** on the back of the **generator** between the motor and the **multimeter** leads. Switch the **multimeter** to measure current and record these measurements as well

10) Use the laser **tachometer** to measure the input and output **shaft** speeds by pointing the laser **tachometer** at the **shaft couplers** connected to the **motors**. **Make sure the entire laser dot is on the reflective tape, and be careful not to shine the laser into anyone's eyes.**

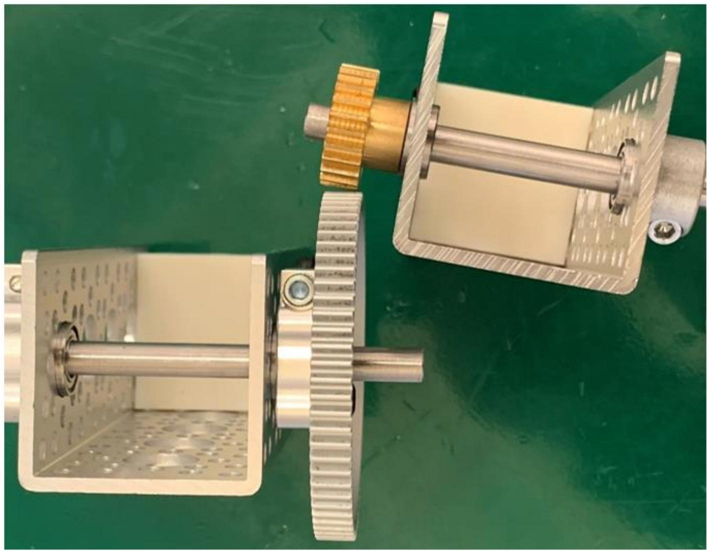




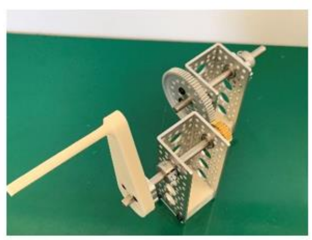
11) Repeat steps 8 – 10 at increasing the voltage by 2 each time up to 12 Volts. Record measurements.

Gear Ratio	Input			Output		
	(V)	(A)	(RPM)	(V)	(A)	(RPM)
	6					
	8					
	10					
	12					

GUIDED ACTIVITY – FORCES BETWEEN GEARS

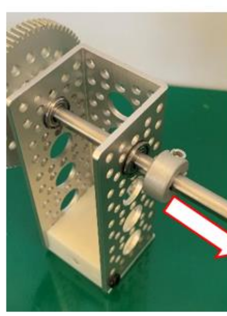


1) Set up a configuration like the one in the first guided activity.

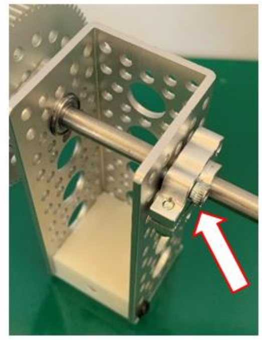


2) Obtain a **hub mount**, and thread a **screw** through one of the four holes so that the **screw** sticks out on the flat side of the **mount** as shown here:

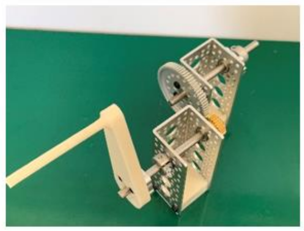
3) Remove the **shaft collar** from one of the **shafts** in your configuration.



4) Slide the **hub mount** onto the **shaft**, inserting the end of the **screw** into a hole on the **pillar**. This should prevent the shaft from rotating. Tighten the **hub mount** onto the shaft

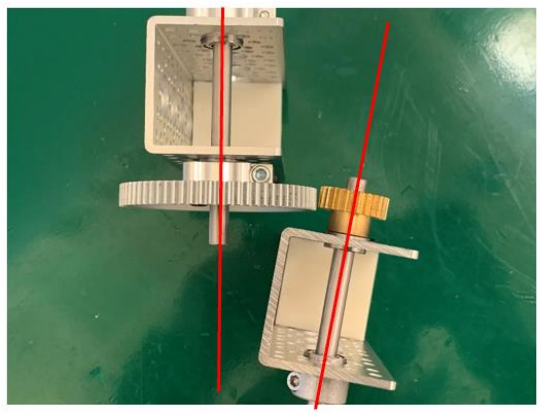


5) Position the two **pillars** so that their **gears** mesh and attempt to turn the freely rotating **shaft** with the manual **crank arm**.



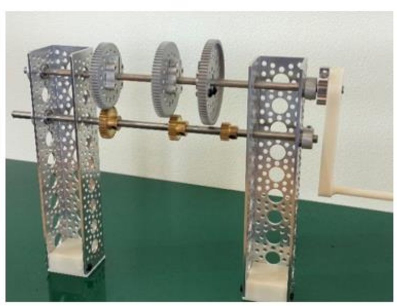
1) Notice that the **gears** push apart and one or both of the **pillars** probably rotated a little bit.

What does this tell you about the forces between the gears? Are there forces acting tangentially between the gears? Are there forces acting radially between the gears? Discuss among your group until you reach a consensus.



ADVANCED CONFIGURATION – 2-3 SPEED TRANSMITION

If you are up for a challenge, try to build a model of a 2 or 3-speed transmission like the one pictured below!



For an added challenge, try to make this as compact as possible, and add an output motor to measure the power.

MAINTENANCE

BASE PLATE

The base plate is a366/1008 cold rolled carbon steel. To prevent rust from the plate there is a coat of Rust-oleum protective paint on every surface and a layer of vinyl on the top surface. If the paint or vinyl layer is damaged, take off the damaged vinyl, repaint the base plate and place new vinyl. Do not add double layers to the base plate. Doing this will increase the distance between the magnet and base plate resulting in a lower magnetic force than desired.

All gear train components including the housing are sourced from one vendor, ServoCity.com. Replace any component with a new one if defective. For all part numbers and information, refer to bill of material.

SHAFTS

Material: Stainless Steel

If components are getting stuck sliding along the shaft, check the shaft for burs and divots. These can occur when students tighten a set screw down on the rounded portion of the shaft rather than the flat area of the profile. In this case, some light sanding should fix the problem. Replace the shaft if it becomes too damaged.

MOTORS

Two different speed motor/generator are used in this experiment. If part is defective, replace it with a new one from Servocity.com. A new motor board will need to be acquired, prepared, and attached to the motor. See manufacturing guide for further guidance.

MOTOR BOARDS

If electrical board is defective or if the male connectors are broken, replace them. For all part numbers and information, refer to bill of material. See manufacturing guide for further guidance.

MANUAL INPUT

The crank arm assembly will consist of 3D printed components. If 3D components are defective or broken, replace them with a new one.

MULTIMETER

Storage: Dry location

Battery: 9V

TACHOMETER

Storage: Dry location

Battery: 9V

Appendix M Exploration Activity Lesson Plan

Exploration Activity Lesson Plan

Learning Objectives

This activity has several core learning objectives that students should achieve, such as:

- Practical behaviors of gears and gear trains
- Practical experience with spur gears
- Design and behavior of speed increasing and torque increasing systems
- Properties of forces between meshing gears
- Measurement of drive train system properties

In addition, there are several learning objectives that students can achieve with careful observation or by experimenting with the ‘extended learning’ components.

- Observe causes and effects of shaft bending
- Observe causes and effects binding of shafts and bearings
- Observe causes and effects of drive train friction
- Practical experience with worm gear systems
- Practical experience with helical gear systems
- Practical experience with bevel gear systems
- Practical experience with chain drive systems
- Practical experience with belt drive systems

The Activity

This activity is meant to give students who may not have much hands on experience with drive train components an opportunity to get up to speed, as well as for more experienced students to share their knowledge. There are several guided activities in the lab manual, and you may come up with other goals for students, but it is important to allow them to explore and discover on their own as well.

Before Lab

We recommend providing the lab manual to students in digital form ahead of time and having them read it up to the beginning of the first activity. This includes the ‘Pre-lab’ section, which students should complete and bring to lab with them. This will give students some idea of what parts are available to them, how to use them, and get them started thinking about what they might want to try.

During Lab

Split students into groups (The smaller the better; 3 seems to be ideal, no larger than 6) and give a kit (consisting of a base plate and tacklebox) to each group.

We recommend starting the lab by having the students complete the guided activities in the lab manual, starting with the first one. After that, they can explore and do whatever they want with the components in the activity.

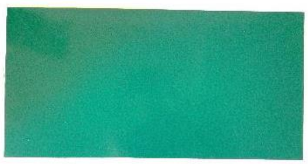
Note: Make sure to reiterate to only tighten set screws on the flat part of the D-shaft. Otherwise, resulting burs will interfere with bearings and shaft collars.

Time

We recommend allowing 1.5 – 3 hours for this lab activity.

Appendix N Inventory Checklist

Inventory Checklist

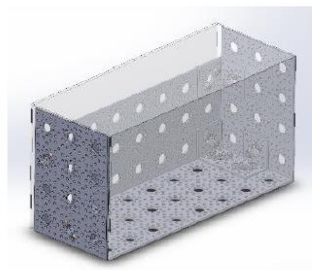
Components		
 (1) Steel Base Plate	 Screw (30) 6-32 x 7/16	 (30) Wing Nut
 (1) Crank Arm Assembly	 Aluminum Hub Gear (2) 64-Tooth (1) 72-Tooth (1) 80-Tooth	 (4) Shaft Coupler
 U-Channel Pillar (4) 4-Hole (2) 9-Hole	 Brass Pinion (1) 32-Tooth (2) 24-Tooth (1) 16-Tooth	 (15) Shaft Collar
 (4) Angle Bracket	 (12) Ball Bearings	 D-Shaft (2) 3” (5) 4” (2) 7” (2) 10”

(1) 970 RPM Generator Assembly

(2) Pillow Block

(1) Fan

(1) 124 RPM Input Motor Assembly



(1) Housing and acrylic cover

(1) Turbine Blades Assembly

(1) Chain drive set

(1) Bevel Gear Set

(1) Worm gear set

(2) 3/32 Hex Key

(2) 7/64 Hex Key

(1) 9/64 Hex Key

(1) Multimeter

(1) Laser Tachometer

(1) Anemometer

The average ABS filament properties listed in the table below comes from engineersedge.com and is for two components listed in the check list:

- Magnet Block
- Crank Arm

Property	ABS
Density [Mg/m^3]	1.00-1.22
Youngs Modulus [GPa]	1.12-2.87
Yield Stress [MPA]	18.5-51
Tensile Strength [MPa]	25-50
Ultimate Tensile Strength [MPa]	33-110
Shear Modulus [GPa]	3180
https://www.engineersedge.com/3D_Printing/abs_plastic_filament_engineering_information_14211.htm	

ServoCity states that the material they use is aluminum. The exact alloy was not specified so properties for aluminum 1100, a common alloy, are shown below.

Property	Aluminum 1100
Youngs Modulus [GPa]	68.9
Shear Modulus [GPa]	25.9
Yield Strength [MPa]	24.1
Tensile Strength [MPa]	75.8
https://www.engineeringtoolbox.com/properties-aluminum-pipe-d_1340.html	

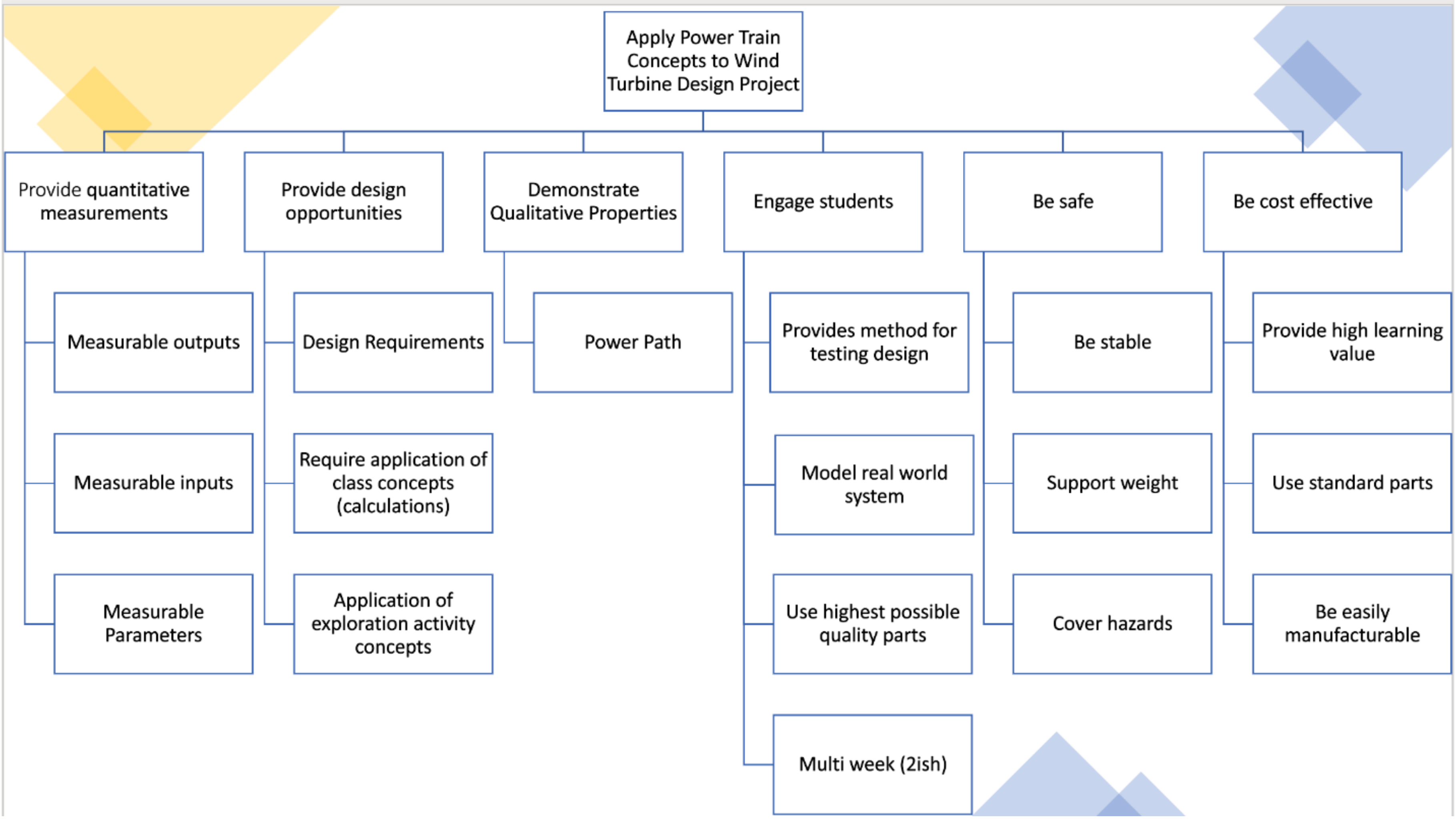
The following components are made of this material:

- 4-Hole U-Channel
- 9-Hole U-Channel
- Angle Bracket
- 64-Tooth Gear
- 72-Tooth Gear
- 80-Tooth Gear
- Hub Mount
- Shaft Coupler
- Shaft Collar
- Pillow Block
- Motor Mount

Appendix O Exploration Activity FMEA

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Base/ Provides sturdy component attachment surface	Is too small	User can't assemble a useful power train	6	Plate selected is too small	Overestimate required plate size	3	Team and customer feedback	5	90	Make the plate bigger					
	Isn't ferrous	Components can't be attached	8	Plate is not iron/steel	Use steel for plate	1	Observation	1	8	Get a steel plate					
	bends easily	Components become unaligned	7	Plate is too thin	Overestimate plate thickness	3	Observation	2	42	Get a thicker plate					
Base/ Stability	Tips over	a) Measurements are difficult b) components break c) Learning is not achieved	7	Base not wide enough, pillars too tall/heavy	use an almost square plate	1	Team and customer feedback	1	7	Make the plate wider or stick it down to surface					
	Slides around on desk	user is frustrated	6	Coefficient of friction too small	Add rubber feet to plate	4	Team and customer feedback	2	48	Add a mechanism to stick it to surface					
Pillars/ Attaches to base via magnet	Detaches from base undesireably	Components become unaligned, gears unmesh, learning is not achieved	7	a) magnet too weak b) magnet damaged c) magnet falls off	a) force analysis b) prototyping c) Wide base for pillars	7	Team and customer feedback	3	147	Add array of holes to plate to fasten pillars to using bolts					
Pillars/ support shafts & bearings	Can't support power train	a) user can't learn concepts b) components break	8	a) Pillars tip over / topheavy b) bearings not secure to pillars	a) force analysis b) prototyping	3	Team and customer feedback	2	48	Use stronger parts					
Pillars/ Allingment to other Pillars	Rotates or translates resulting in loss of gear meshing	a) User is frustrated b) Learning is not achieved	7	a) magnet too weak b) coefficient of friction between plate and pillar too low c) alignment between pillars not secured	Using 'beams' to hold desired alingments steady.	7	Team and customer feedback	3	147	Add array of holes to plate and pins to pillars to prevent rotation/translation					
Power Train/ Transfer power	Fails to transfer power	a) Measurements are difficult b) Learning is not achieved	7	a) components break b) components bind c) set screws slip	a) force analysis b) prototyping c) tighten set screws	5	Team and customer feedback	3	105						
Measuring Devices/ Take measurements from power train	Doesn't read measurements	Learning is less achieved	7	a) batteries run out b) user error c) Faulty/broken instruments	a) test devices b) supply backup batteries c) provide instructions for use	4	Team and customer feedback	2	56	Replace instrument					
Inventory management/ keeps track of components	Components are lost or disorganized	User cannot use activity effectively	5	a) system is ineffective b) system is too cumbersome	practice use	6	Team and customer feedback	3	90						

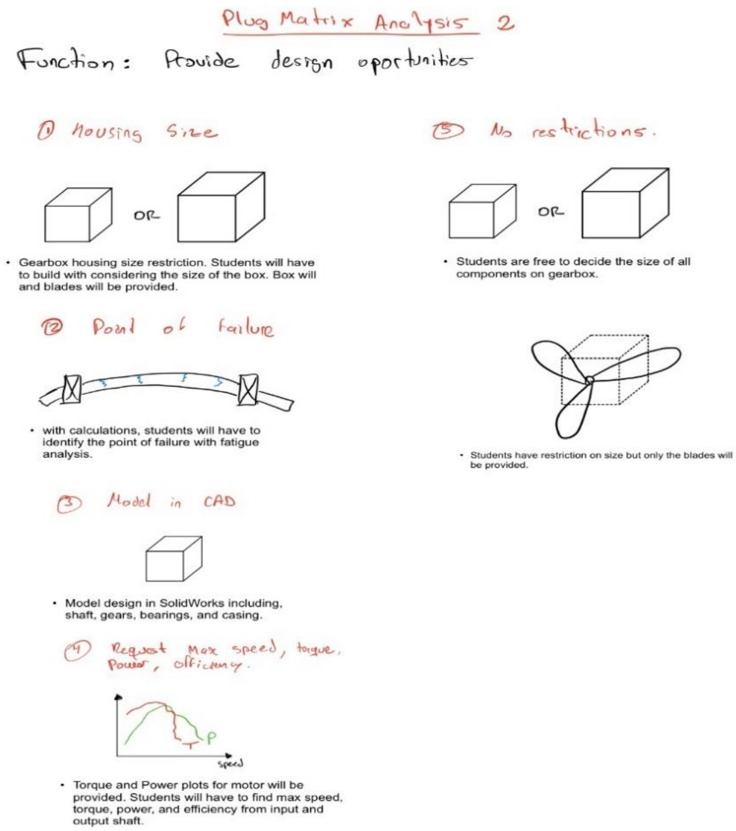
Appendix P Design Activity Functional Decomposition



Appendix Q Design Activity Ideation

- Provide quantitative measurements
  - Supply tachometer for input/output speed
  - Supply 'generator' and read voltage current w/ multimeter
  - Measure torque
  - Attach weight
  - Spring mechanical scale
  - Wind speed gauge/calculations
  - Plug and play equations?
  - Stress measurement
  - Photo-elastic film
  - Stress meters
  - Gear ratios
- Provide design opportunities
  - Design requirements
  - Restrict 'housing' size
  - Require inline input/output shafts
  - Withstand certain forces/torques
  - Identify point of failure
  - Request maximum speed/torque/power/efficiency
  - Have students model designs in CAD
- Demonstrate qualitative properties
  - Power path
  - System statics
  - System smoothness
  - Observe efficiency concepts
- Engage students
  - Students implement and test design
    - Supply some parts, students collect/3D print parts build it
    - Provide structure and high quality parts, allow students to configure parts
  - Models a real world system
  - Wind turbine
  - Having students compete with their designs
  - Fastest output
  - Most Power
  - Highest efficiency
  - Comparing theoretical design numbers with testing outcomes
  - Use multiple weeks for project
  - Have students work in a team to accomplish a design goal
  - Have students present their work
  - Video
  - Presentation
  - Report
- Be safe
  - Have a cover for gearbox
  - Having emergency switch
  - Quick-stop button
  - Speed limiter on input shaft
  - Have limits in requirements
  - Be stable
  - Wide base with
  - Attach it to surface
  - Bolts
  - Clamps
  - Make low center of gravity
  - Warning labels
  - "cage" for blades
  - Bright colors
- Cost effective
  - Have students print and provide gears (sandbox)
  - Equipment fee for students
  - Have students buy materials
  - Shop from robotics supply sources rather than brand-name industrial suppliers
  - Attempt to solicit donations from companies (Misumi)
  - Have only one unit
  - Use as many standard parts as possible
  - Re-use parts from exploration activity
  - Collect 3D printed parts for future use

Appendix R Design Activity Pugh Matrices

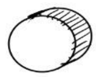


Criteria \ Concept	① DATUM	②	③	④	⑤	⑥	⑦
Weight	D	S	S	S	S		
Low Cost	A	S	S	S	S		
Interactive	T	S	S	S	—		
Safe	U	S	S	S	S		
Easy to maintain	M	S	S	S	S		
Intuitive use		S	S	S	S		
easy to manufacture		S	S	S	S		
Applicable to real world		S	S	S	S		
Total		0	0	0	−1		
Rank	★	★	★	★			

Plug Matrix Analysis 2

Function: Cost effective

① Have student 3-D print

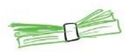


- Have students 3D print their model.

② Equipment fee

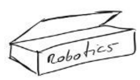
- Equipment fee will pay for special materials for their design. This Could help to pay for materials already bought.

③ Have student buy material



- Students will use their own money to buy their own parts. Website will be provided.

④ Robotic supplier



- Shop from robotics supply sources rather than brand-name industrial suppliers.

⑤ Donations from suppliers

- Contact supplier to attempt to solicit donations or discounts.

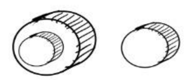
⑥ One unit

- Have students design only one unit.

⑦ Standard Parts

- Have students use as many standard parts as possible.

⑧ Re-use Parts From Part I



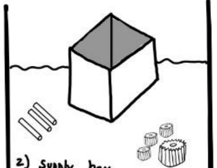
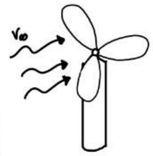
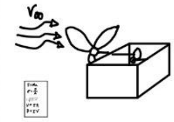
- Students could re-use as many parts as possible form exploratory activity.

⑨ Collect 3-D printed part

- Recollect all design parts for future use in designs.

Criteria \ Concept	① DATUM	②	③	④	⑤	⑥	⑦	⑧	⑨
Weight	D	S	S	S	S	S	S	S	S
Low Cost	A	–	+	–	–	S	–	+	S
Interactive	T	S	–	S	S	S	S	S	–
Safe	U	S	S	S	S	S	S	S	S
Easy to maintain	M	S	S	S	–	+	S	S	S
Intuitive use		S	S	S	S	S	S	S	S
easy to manufacture		S	S	+	+	S	S	S	+
Applicable to real world		S	S	+	+	–	+	+	S
Total		-1	0	1	0	0	0	2	0
Rank	★			★			★	★	

Engage Students Pugh Matrix

concept / criteria	 1) create custom parts	 2) Supply box	 3) Real World Model	 4) Competition	 5) Theo. VS. Experimental	 6) Presentation
intuitive use	+	+	—	S	+	S
Applicable to real world	—	+	+	S	+	+
Develope intuition & deeper understanding of concepts	+	+	S	+	+	+
experimentation	+	+	+	S	S	S
collaboritive problem solving	S	S	+	+	+	+
Experimental and data analysis	S	S	+	+	+	+
Accuracy and precision	+	—	S	+	+	+
Total	3	3	3	4	6	5

1) Students are expected to utilize 3D printing technology to achieve their design
2) Students will need to utilize the components used in the exploratory lab to achieve their design
3) Students will model their design based on a real world scenario of a wind turbine
4) Students will compete in order to demonstrate whose design is superior
5) Students will compare their theoretical and experimental results
6) Students will present their design and discuss about it to the whole class

GEARS AND GEAR TRAINS

WIND TURBINE DESIGN ACTIVITY

LAB MANUAL

Cal Poly, Mechanical Engineering
5-31-2021

CONTENTS

SAFETY

HAZARDS

The following safety hazards are present for this activity:

- Strong magnets
- Rotating components
- Pinch points
- Low voltages and currents

PROCEDURES AND POLICIES

All individuals interacting with the equipment for this activity should follow the following safely procedures:

- **Do not** remove the magnets or plastic magnet mounts from the U-channel pillars.
- Wear safety glasses.
- Wear close-toed shoes.
- Secure long hair.
- Remove or secure loose clothing, chains, and jewelry (including any **ferrous rings)**.
- Keep fingers away from rotating components during operation.
- Do not supply more that the rated amount of current or voltage to motors.
- Do not attempt to back-drive any motor that does not allow you to do so easily using only your hand directly on the motor shaft.
    - **Do not** use the **124 RPM input motor** for this activity.
    - Use the **970 RMP motor** as a generator. It should be already attached to the housing.

COMPONENTS

INVENTORY

All drive train components for this activity come from the gear train exploration activity and should be stored in the provided tacklebox when not in use. The **fan**, **turbine blade assembly**, wind turbine **housing**, and **acrylic cover** should all be stored together.

Please return all components to the correct tacklebox in an organized fashion after use.

TOOLS AND COLOR CODING

The only tools required for this activity are two hex keys.

3/32 Hex Key

Use on all brass **pinions**

9/64 Hex Key

Use for bevel and worm gear sets

7/64 Hex Key

Use for all other parts

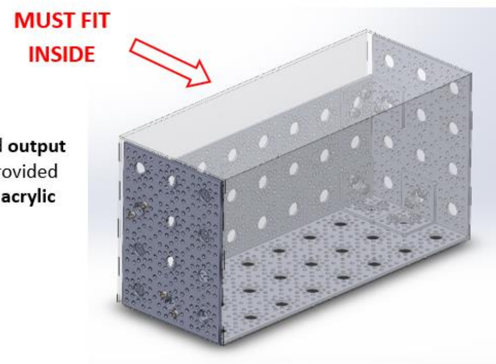
DESIGN

The purpose of this activity is to design and test a power train for this model wind turbine to meet a desired goal. This goal will usually be provided by your professor and examples include maximizing power output, maximizing output speed, or maximizing output torque.

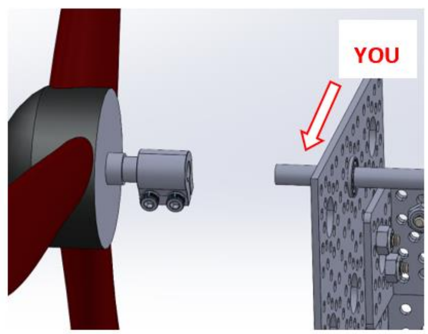
CONSTRAINTS

In addition to any project requirements provided by your professor, your design must satisfy the following constraints:

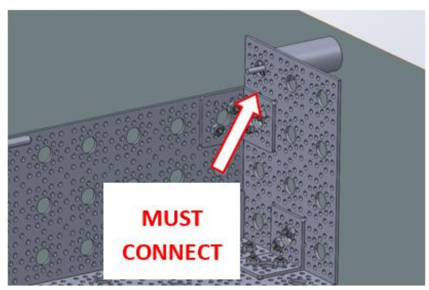
All components (aside from the input **shaft** and **output generator**) must fit within the volume of the provided **housing**, otherwise they will interfere with the **acrylic safety cover** during testing.



You must provide an input **shaft** protruding a short distance (~1") from the front of the **housing**. The **Turbine blades** will attach to this **shaft**.



Your design must interface with the **generator** attached to the back of the **housing**.



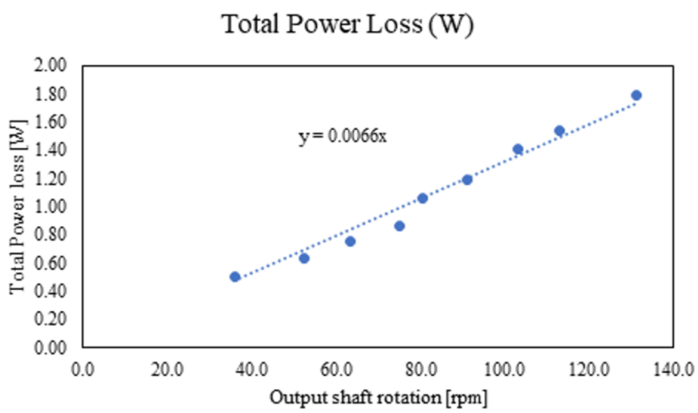
ESTIMATING POWER INPUT

The input power available to a wind turbine is a function of the fluid speed and density and turbine blade dimensions. Visit https://www.raeng.org.uk/publications/other/23-wind-turbine, a document presented by The Royal Academy of Engineering, find out how to calculate this power.

Make sure you understand what the Power Coefficient, C_p is and whether or not it is a constant.

ESTIMATING POWER LOSSES

There will be power losses throughout the drive train, from the moment the wind hits the blades to point at which your multimeter reads the voltage and current. You may be asked to measure or calculate the efficiency of your gear train. If so, you will need to know how much power loss occurs in the generator. The following graphs provides this data, though you are encouraged to double-check the results yourself.



Consult your lecture notes for strategies on calculating the efficiency of the other components in your drive train.

TEST

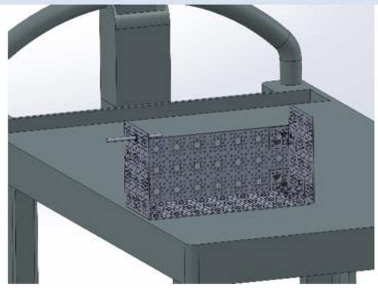
CONFIGURATION

Once you have designed your power train and it is time to test it, use the materials from the exploration activity and any others you have acquired to implement your design in the provided **housing**.

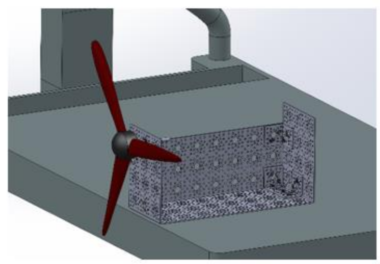
SETUP

1) With a geartrain configuration already in mind, implement all the components inside the housing.

   you With your drive train implemented in the **housing**, set it up with the input **shaft** hanging over the edge of the cart or a table.

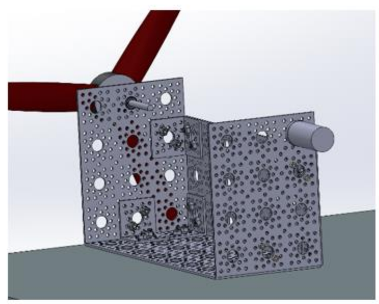


2) Select the **turbine blade** and attach it to the input **shaft** of your geartrain by using a **shaft coupler**.

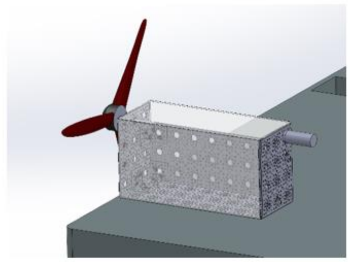


3) Attach the other end of your geartrain to the output generator with a shaft coupler.

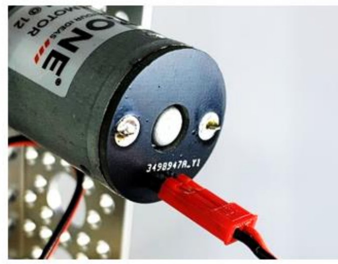
   At this point, your geartrain should be fully connected and meshed properly. To check proper operation, use crank arm as the input and rotate it.



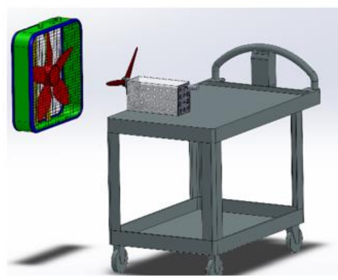
4) Place the **acrylic cover** over the **housing**.



5) Attach the electrical leads from the multimeter to the pins located on the back of the **generator.**



6) Position the **fan** in front of **turbine blades**, about 3 feet away.



OPERATION

Once the apparatus has been set up for testing, it is time to begin.

1. Make sure the **acrylic cover** is over the **housing.**
2. Make sure no one is near the **turbine blades.**
3. Turn on the multimeter.
4. Turn on the **fan**, holding it about 3 feet from the turbine blades
5. Let the **turbine blades** reach full speed and measure the voltage produced by your power train.
6. Taking care not to shine the laser in anyone’s eyes, measure the output shaft speed using the tachometer. Point it at the reflective tape on a shaft **collar** or **coupler**.

CLEANUP

Before leaving lab, you must make sure the following tasks are complete:

1) Multimeter, tachometer, and all drive train components (aside from the **generator motor**) should be removed from the turbine **housing** and returned to the exploration activity tacklebox.
   a. If you purchased or created the component you may choose to keep it. Otherwise, donate it to future students by putting it back with the other parts.
   b. Use the Inventory Checklist to make sure no components have been lost.
2) Make sure the following items are on the activity cart:
   a. Anemometer
   b. **Housing** with baffles and **generator motor**
   c. **Turbine blades** with **shaft coupler**
   d. Fan

MAINTENANCE

This section details maintenance information for materials specific to the Wind Turbine Design Activity. For any components not mentioned here, see the Exploration Activity Lab Manual

INPUT ASSEMBLY

Inspect propeller for cranks or chips. If defective, replace part with a new one. For all part numbers and information, refer to bill of material.

FAN

Should be stored in a dry place.

Clean dust and debris of fan blades before and after use.

MEASUREMENT EQUIPMENT

ANEMOMETER

Battery: DC 9V

Appendix T Design Activity Lesson Plan

Design Activity Lesson Plan

Learning Objectives

Core Learning Objectives (* = direct from class syllabus):

- Generate ideas and concepts for mechanical designs*
- Select appropriate machine elements, components, and materials for mechanical systems*
- Analyze and size selected machine components for appropriate strength, stiffness, or fatigue life*
- Apply computer-aided engineering techniques to component and system design*
- Kinematic analysis and design of gear trains*

In addition, students will achieve the following objectives if most or all of the recommended requirements described below are requested.

Extension Learning Objectives:

- Predict and measure power losses in drive trains
- Measure efficiency of a mechanical drive train system
- Integration of fluid dynamics with mechanical systems
- Selection of optimal electro-mechanical components

The Challenge

Challenge teams of 3-5 students to design the drive train for the model wind turbine apparatus with the goal of producing the highest power output.

- Alternative challenges could include maximizing torque (i.e. wind powered lift) or maximizing output speed. However, we feel that both of these are less applicable to the real world and more likely to have a single, easily identifiable optimal solution.
- The challenge for producing the highest power output will likely lie in finding the right balance between speed and torque, not just increasing one as high as possible. This will require students to calculate many things such as required torque and expected power losses in the system.

Requirements and Constraints

- Power train must fit within housing.
  - This one is highly recommended and naturally enforced by the testing apparatus.
  - The housing size will be configurable allowing professors to adjust constrains quarter to quarter.
- In-line input and output shafts
- A CAD model of their final design
  - Nearly all drive train components are sourced from Servo City which provides spec sheets and CAD files for most of their parts. Students should find and use these.
- Force analyses
  - FEA of their design.
  - Calculation of all forces within their power train.
  - Identification of point of failure in their design.

  - Calculation of expected shaft bending.
  - Fatigue analysis
- Calculation of expected input power
  - Students can measure the speed of the 'wind' created by the fan using a provided anemometer and will be provided with relevant parameters such as frontal area of turbine blades.
  - Since Fluid Dynamics is not a prerequisite for this course, appropriate equations will be provided to students.
- Calculation of expected power losses, output power, and efficiency
- Design review presentation including all of the preceding items in this list.
  - This serves not only as good practice for teams and a chance for them to get feedback, but also to verify that they have done the calculations necessary to ensure their design is safe and not likely to fail in a dangerous or catastrophic way.
- Calculation of actual efficiency using expected output power and output power measured during testing.
- Post-testing report/presentation explaining suspected reasons for variation between expected and actual results.

Length of Challenge

Professors could require anything from an informal 1-lab design, build, and test process with only a few of these requirements to a quarter-long formal design process that even includes design reviews. The number of weeks allocated for this lab should of course be adjusted accordingly.

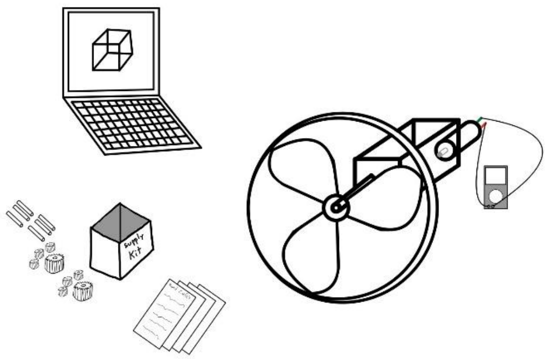
Equipment

The wind turbine housing, blades, generator, and fan are provided for this activity. Drive train components will come primarily from the core components of the gear exploration activity. However, there are additional options that may add to the learning experience:

- Professors can choose to allow extended learning parts such as chain drives if they wish. Doing so will reduce the competitive integrity of a contest between teams but it may also produce a wider variety of results.
- We also recommend allowing students to design and 3D print components if they would like to use something that is not supplied in their kit.
- Students could also be allowed to purchase components from Servo City for their final design. This would provide experience with researching and sourcing existing parts for a design from a supplier.
  - We recommend setting a budget if this option is used. Maybe $10 per team member or $50 per team. This would be enough for anywhere from 3-6 components probably.
  - If students are willing to donate their purchased components after the project, a pool of useful components will build up over time for future groups.
  - Lead times for part delivery can be 1-2 weeks, so professors will need to build this into their lab schedule.

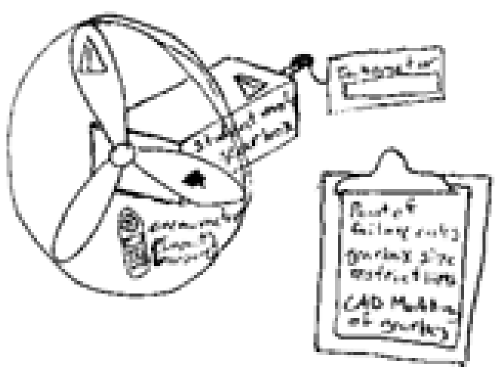
Appendix U Concept Ideas for Design Activity

Design 1:



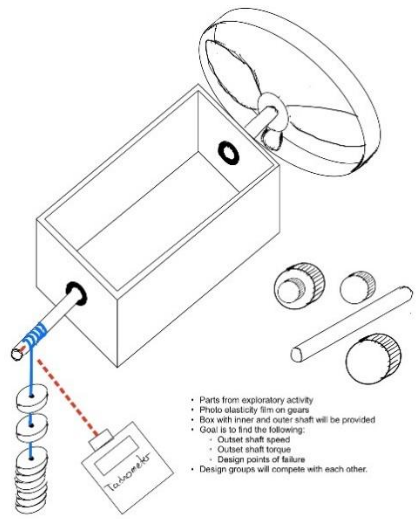
Design 1 allows the students to have the freedom to create a gearbox design with few restrictions as opposed to most of the other designs. For this design, the components had to be sourced from a robotics website. This allows students to use industry level materials, but it also increases the total production cost. Safety measures are applied by adding a blade and housing cover. A tachometer and a voltmeter would be used to get quantitative measurements from the output shaft. A way to engage students in this design is by having them create a video describing their findings in the design.

Design 2:



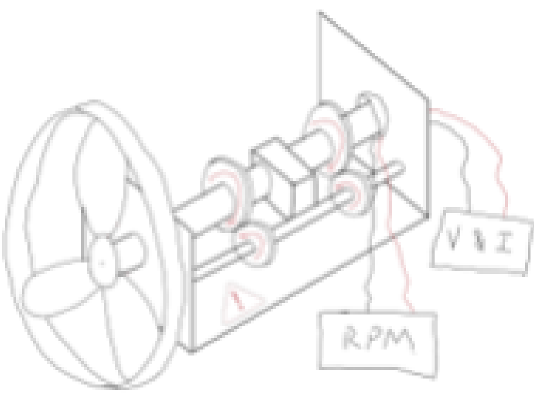
Similar to design 1, this design also allows students to design a gearbox with minimum restrictions for the housing. For this design though, students would be able gain 3D printing skills because they will be printing all the geartrain components. This engages students with their design and allows more design opportunities. 3D printing also keeps the total cost down as compared with some design where their parts needs to be bought. A warning label and safety shield would be added to the blades since this is the area with high risks. Another way to engage students is by having them compare their final designs and creating a friendly competition as the conclusion of the lab.

Design 3:



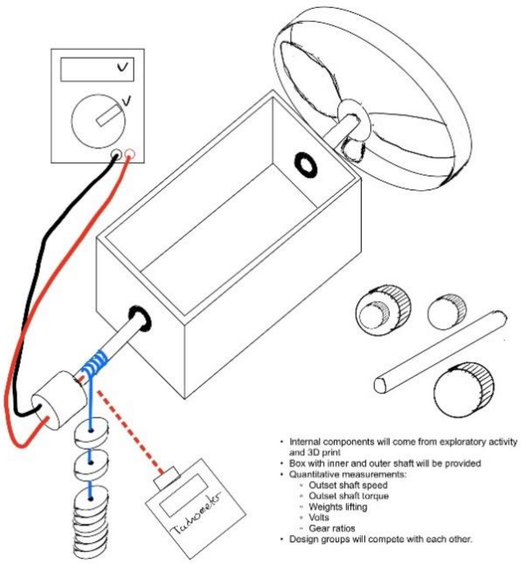
Design 3 allowed students to design and build a gearbox. As seen in the figure, the housing and input and output shaft will be provided. This will provide some parameter restrictions that students must consider when designing the geartrain. The internal components in the gearbox will reuse parts from exploratory activity. Even though this decreases the production time and the total cost for this design, this does not provide students with enough design opportunities to build a unique design as 3D printing their own parts. Qualitative properties can be gathered from FBDs and by covering gears with photo elastic film to see the gear's stress concentrations. A tachometer can be used to measure output shaft rotation velocity and weights could be used to measure torque at the shaft.

Design 4:



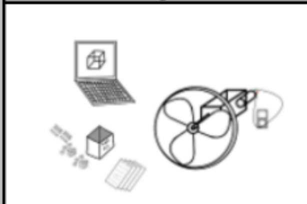
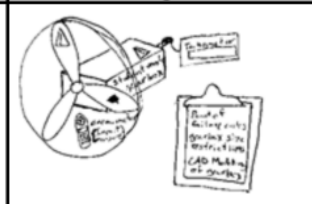
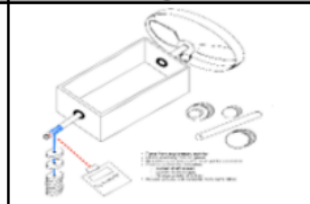
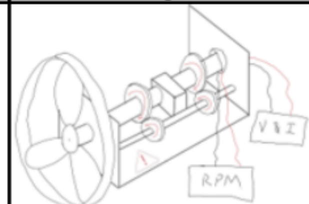
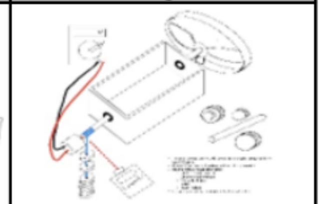
Design 4 provides a hosing size that students will need to consider when designing the geartrain. This housing can be configurable by the instructor or students. Similarly to design 2, this design will use a tachometer and a anemometer to get qualitative measurements. The internal components will be made by students using a 3D printer. Warning labels and a blade guard will surround the blades for safety. To engage students, they will be assigned to present their design in a five-minute class presentation and will have to compare their outputs with other groups.

Design 5:



Design 5 has a configurable housing that is either set by the instructor or the students. If the housing is provided by instructor, it will serve as a size constraint. The other option is for students to put the housing together around their design. This design will use all the different ways to measure quantitative measurements stated in the other designs increasing the amount of options for our sponsor to pick from. Internal components in this design will include both used parts from exploration activity and part that will be 3D printed by students. This expands the design opportunity for students and keeps the total price down for the design. It also reduces maintenance and production time because parts would be provided by a robotics supplier instead of having to build it from raw materials. For safety, this design will include all the ones mentioned in the other designs, which includes a blade guard, gear housing shield, and warning labels. Design 5 also includes some key features that were excluded from the pugh matrix for having low scores, but it is still important consider in the final product. These functions can be seen in the idea 5 column in Table 5.

Appendix V Design Activity Weighted Decision Matrix

		Options				
		Design 1	Design 2	Design 3	Design 4	Design 5
						
Criteria	Weighting	Score	Score	Score	Score	Score
Fits on a Cart	0.08	5	5	5	5	5
Fits Through Door	0.06	5	5	5	5	5
Industry Level Materials	0.08	4	2	4	2	4
Measureble Outputs	0.08	5	5	5	5	5
Self Contain Power	0.04	0	0	0	0	0
Safe for Students	0.1	5	3	4	3	5
Easy to Maintain	0.1	4	5	4	5	5
Intuative Use	0.08	4	4	5	5	5
Easy to Manufacture	0.09	3	2	4	3	4
Low Cost	0.05	3	3	2	2	2
Interactive	0.09	4	5	4	5	5
Applicable to real world	0.09	5	4	5	4	5
SUM		3.87	3.52	3.89	3.64	4.18

Appendix W Hazard Checklist for Design Activity

Y	N	**Design Activity**
✓		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	✓	2. Can any part of the design undergo high accelerations/decelerations?
	✓	3. Will the system have any large moving masses or large forces?
	✓	4. Will the system produce a projectile?
	✓	5. Would it be possible for the system to fall under gravity creating injury?
	✓	6. Will a user be exposed to overhanging weights as part of the design?
✓		7. Will the system have any sharp edges?
	✓	8. Will any part of the electrical systems not be grounded?
✓		9. Will there be any large batteries or electrical voltage in the system above 40 V?
	✓	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	✓	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	✓	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	✓	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✓	14. Can the system generate high levels of noise?
	✓	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
✓		16. Is it possible for the system to be used in an unsafe manner?
	✓	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any “Y” responses, on the reverse side add:

(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Pinch points created by rotating gears	Low forces so warning labels will suffice No loose clothing or long hair or jewelry Note: if analysis shows higher forces clear housing/cover maybe utilized	02/16/21	
System will have many components made of metal with potentially sharp edges	Deburring or sanding on those sharp edges will be required	02/16/21	
Fan Electricity	Fan will be power and grounded with wall outlet.	02/16/21	
Overpowering electronics	Warning label on design and instructions on how to properly operate the product.	02/16/21	
Creating a projectile launcher	Instruction on how to properly operate the product.	02/16/21	

Appendix X Design Activity FMEA

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Severity	Action Results: Occurrence	Action Results: Criticality
Housing/ size restriction	small	a) gears hit boundaries of housing b) not enough space to add enough gears	6	1) gear diameters to large 2) thickness of gear restricts amount of gears utilized	1) large work area	2	Team and customer feedback	2	24						
Housing/ Component attachment surface	miss alignment	binding	3	1) shafts don't align with pilars	1) use one pillar 2) motion control coupling	7	Team and customer feedback	2	42						
Housing/ Stability	vibrations	a) unforeseen wear b) breaks of apparatus	6	1) missaligned gear meshes 2) base not secured properly	1) minimun four bolts 2) clamps	3	Team and customer feedback	1	18						
Power Train/ Transfer power	gear meshing poor contact	a) loss of power transfer b) uneven wear on gears c) slipping	8	1) gears to far apart from each other 2) gears to close in contact	1) relocate pillar	7	Team and customer feedback	3	168						
	no power transfer	no readings from meters	3	1) low input torque 2) blades not spinning	1) hand calculations 2) greese	2	Team and customer feedback	1	6						
Measuring Devices/ Take measurements from power train	measurements not read	no data	3	1) meter not utilized	1) data needed to be turned in	1	Team and customer feedback	1	3						
	un-accurate	error in any analysis	4	1) meter on wrong setting 2) bias error	1) hand calculationstting 2) greese	2	Team and customer feedback	2	16						
	wont turn on	no data	3	1) dead batteries 2) broken	1) spare batteries 2) additional meters	1	Team and customer feedback	1	3						
Inventory management/ keeps track of components	lost components	unable to perform lab	8	1) misshandling	1) 3D print spares 2) order new components to replace lost ones	3	Team and customer feedback	3	72						
Blades/ Attach and Detach to Housing	Not secured	projectiles launched in the room	10	1) not screwed on correctly 2) wear	1) double check blade is secure 2) order log of previously purchased components 3) blade guard	4	Team and customer feedback	3	120						
	doesn't detach	un-able to properly store away	3	1) siezed bolt or screw 2) stripped bolt or screw	1) drill out bolts or screws 2) lock tight to prevent overtighttening	3	Team and customer feedback	3	27						
Fan/ input power to blades	fan blades don't turn	a) unable to operate or utilize project properly b) unable to take readings	8	1) broken fan	1) order new fan	1	Team and customer feedback	1	8						

Appendix Y List of Materials

Vendor	Name	Full Product Name	Vendor Part #	Product Hyperlink	Price	Qty/Pack	Price Per Unit	Units Req.	Packs Req.	Total Cost	Packs Acquired	Packs to Acquire	Notes
Amazon	Anemometer	PROTMEX 6252A Wind Speed Meter, \	B019RU17XC	https://ww	$ 29.99	1	$ 29.99	1	1	$ 29.99	1	0	
Amazon	Multimeter	Digital Multimeter Pocket Clamp Mul	VC830L	https://ww	$ 10.97	1	$ 10.97	1	1	$ 10.97	1	0	
Amazon	Tachometer	Digital Tachometer Handheld Photo L	1-1024-17	https://ww	$ 15.99	1	$ 15.99	1	1	$ 15.99	1	0	
Grainger	Tacklebox	Adjustable Compartment Box, Transl	1NTH6	https://ww	$ 8.50	1	$ 8.50	0	0	$ -	1	0	replaced by other tacklebox
Harbor Freight	Fan	20 In. High Velocity Floor Fan		https://ww	$ 49.99	1	$ 49.99	1	1	$ 49.99	1	0	
Home Depot	Acrylic	12 in. x 24 in. x 1/16 in. Thick Acrylic C	308669979	https://ww	$ 14.99	1	$ 14.99	1	1	$ 14.99	1	0	
Home Depot	Rubber Feet	1-1/2 in. Self-Adhesive Anti-Skid Surf	176838	https://ww	$ 2.88	8	$ 0.36	4	1	$ 2.88	4	0	
Home Depot	Set Screws	#6-32 x 3/16 in. Internal Hex Socket-H	3273	https://ww	$ 7.21	20	$ 0.36	0	0	$ -	0	0	Just in case we want extras
Home Depot	Wing Nuts	#6-32 Zinc Plated Wing Nut (6-Pack)	802331	https://ww	$ 1.18	6	$ 0.20	25	5	$ 5.90	5	0	
In House	Magnet Mount	-	-	-	$ -	1	$ -	8	8	$ -	8	0	
In House	Crank Arm	-	-	-	$ -	1	$ -	1	1	$ -	1	0	
In House	MM Plate	Magnet Mount Plate	-	-	$ -	1	$ -	0	0	$ -	0	0	Re-designed mount, not needed
In House	Shrink Wrap Sleeves	Heat Shrink Tubing (560pc Assortmen	3201-0005-0001	https://ww	$ 8.99	560	$ 0.02	4	1	8.99	4	0	
JLCPCB	Custom Motor Board	Custom Motor Board	-	https://cart	$ 6.40	25	$ 0.26	1	1	6.4	1	0	
K&J Magnets	Magnet	DX46 Disc Magnet	DX46	https://ww	$ 12.67	1	$ 12.67	8	8	$ 101.36	8	0	
Master Airscre\	Blades	3-Blade - 16x8 Propeller	-	https://ww	$ 18.98	1	$ 18.98	1	1	$ 18.98	1	0	It's sharp!
Home Depot	Large Hex Key	9/64 in. Ball-End Journeyman T-Handl	JTH6E09BE	https://ww	$ 6.50	1	$ 6.50	1	1	$ 6.50		1	
Home Depot	Main Hex Key	7/64 in. Ball-End Journeyman T-Handl	JTH6E07BE	https://ww	$ 4.97	1	$ 4.97	2	2	$ 9.94		2	
McMaster-Carr	Small Hex Key	Ball-End Two-Tip T-Handle Key	6286A13	https://ww	$ 7.40	1	$ 7.40	1	1	7.4	2	0	
McMaster-Carr	Painted Screws	Painted Steel Pan Head Torx Screw w	97690A158	https://ww	$ 8.50	50	$ 0.17	36	1	8.5	1	0	
McMaster-Carr	Painted short screws	Painted Steel Pan Head Torx Screw w	97690A155	https://ww	$ 8.25	50	$ 0.17	12	1	8.25	1	0	
McMaster-Carr	Extra Small Kex Key	Ball-End T-Handle Hex Key	37095A31	https://ww	$ 3.30	1	$ 3.30	0	0	0	2	0	Purchased by mistake
Michaels	Accordian Tacklebox	3 Tray Storage Box by Artist's Loft	10998650	https://ww	$ 34.99	1	$ 34.99	1	1	34.99	1	0	
Mustang 60	Vinyl Sticker		-	-	$ 1.00	1	$ 1.00	1	1	$ 1.00	1	0	
Online Metals	Steel Plate	0.125" Mild Steel Sheet A366/1008 Co	13973	https://ww	$ 27.04	1	$ 27.04	1	1	$ 27.04	1	0	
Servo City	10 in Shaft	0.250" (1/4") x 10.00" Stainless Steel [	634092	https://ww	$ 4.39	1	$ 4.39	2	2	$ 8.78	2	0	
Servo City	124 RPM Motor	124 RPM Econ Gear Motor	638352	https://ww	$ 14.99	1	$ 14.99	1	1	14.99	1	0	
Servo City	16T Pinion	16T, 0.250" (1/4) Bore 32P Shaft Moun	615242	https://ww	$ 7.99	1	$ 7.99	1	1	$ 7.99	1	0	
Servo City	16T Sprocket	16 T 0.770" Hub Mount Sprocket	615102	https://ww	$ 3.99	1	$ 3.99	$ 1.00	1	3.99	1	0	
Servo City	2" 5/16 Round shaft	0.3125" (5/16") x 2.00" Stainless Steel	634182	https://ww	$ 1.29	1	$ 1.29	1	1	$ 1.29	1	0	Increase size for final list of materia
Servo City	24T Pinion	24T, 0.250" (1/4) Bore 32P Shaft Moun	615250	https://ww	$ 7.99	1	$ 7.99	2	2	$ 15.98	2	0	
Servo City	3 in Shaft	0.250" (1/4") x 3.00" Stainless Steel D-	634078	https://ww	$ 2.19	1	$ 2.19	$ 2.00	2	4.38	2	0	
Servo City	32T Pinion	32T, 0.250" (1/4) Bore 32P Shaft Moun	615254	https://ww	$ 7.99	1	$ 7.99	1	1	$ 7.99	1	0	
Servo City	32T Sprocket	32 T 0.770" Aluminum Hub Mount Spr	615114	https://ww	$ 5.29	1	$ 5.29	$ 1.00	1	5.29	1	0	
Servo City	3x4 Hole Pattern Plate	3 x 4 Hole Pattern Plate (4.50" x 6.00")	585002	https://ww	$ 8.99	1	$ 8.99	4	4	$ 35.96	4	0	
Servo City	3x8 Hole Pattern Plate	3 x 8 Hole Pattern Plate (4.50" x 12.00'	585004	https://ww	$ 13.99	1	$ 13.99	2	2	$ 27.98	2	0	
Servo City	4 Hole U-Channel	U-Channel (4 Hole, 3.75" Length)	585443	https://ww	$ 4.49	1	$ 4.49	6	6	$ 26.94	6	0	
Servo City	4 in Shaft	0.250" (1/4") x 4.00" Stainless Steel D-	634080	https://ww	$ 2.39	1	$ 2.39	6	6	$ 14.34	6	0	
Servo City	5/16 to 1/4 Shaft coupler	0.250" to 0.3125" Clamping Shaft Cou;	625046	https://ww	$ 4.99	1	$ 4.99	1	1	$ 4.99	1	0	
Servo City	64T Gear	32 Pitch, 64 Tooth (.50" Bore) Alumin\	615194	https://ww	$ 12.99	1	$ 12.99	1	1	$ 12.99	1	0	
Servo City	7 in Shaft	0.250" (1/4") x 7.00" Stainless Steel D-	634086	https://ww	$ 3.39	2	$ 1.70	$ 2.00	1	3.39	1	0	
Servo City	72T Gear	32 Pitch, 72 Tooth (.50" Bore) Alumin\	615198	https://ww	$ 12.99	1	$ 12.99	2	2	$ 25.98	2	0	
Servo City	80T Gear	32 Pitch, 80 Tooth (.50" Bore) Alumin\	615206	https://ww	$ 12.99	1	$ 12.99	1	1	$ 12.99	1	0	
Servo City	9 Hole Channel	U-Channel (9 Hole, 7.50" Length)	585448	https://ww	$ 6.99	1	$ 6.99	2	2	$ 13.98	2	0	
Servo City	90 Degree Pattern	90° 0.770" Pattern Mount	545400	https://ww	$ 4.99	1	$ 4.99	0	0	$ -		0	No longer planning to use
Servo City	Angle Brackets	90° Single Angle Pattern Bracket	585424	https://ww	$ 1.89	1	$ 1.89	14	14	$ 26.46	14	0	
Servo City	Bearings	1/4" ID x 1/2" OD Flanged Ball Bearing	535198	https://ww	$ 2.89	2	$ 1.45	12	6	$ 17.34	6	0	
Servo City	Bevel Gear Set	2:1 Bevel Gear Set (1/4" Bore Pinion, :	637222	https://ww	$ 24.99	1	$ 24.99	$ 1.00	1	24.99		1	
Servo City	Chain	0.250"P Plastic Chain (48 Links, 1ft)	615150	https://ww	$ 6.99	1	$ 6.99	$ 2.00	2	13.98		2	
Servo City	Generator	970 RPM Econ Gear Motor	638358	https://ww	$ 14.99	1	$ 14.99	2	2	$ 29.98	2	0	
Servo City	Header Pins	Single Header Row Pin	HPS-100-36	https://ww	$ 2.49	36	$ 0.07	2	1	$ 2.49	1	0	
Servo City	Hinge	Actobotics Hinge	585644	https://ww	$ 4.99	1	$ 4.99	0	0	$ -		0	No longer planning to use
Servo City	Hub Mount	0.250" Bore Clamping D-Hub (Tapped)	545619	https://ww	$ 7.99	1	$ 7.99	5	5	$ 39.95	5	0	
Servo City	Lock Nuts	6-32 Nylock Nuts Pack (25 pack)	632142	https://ww	$ 1.89	25	$ 0.08	40	2	$ 3.78	2	0	
Servo City	Male Banana Pair	Alligator Clip to Banana Plug Extensio	X24231	https://ww	$ 0.99	1	$ 0.99	1	1	0.99	1	0	
Servo City	Motor	56 RPM Econ Gear Motor	638348	https://ww	$ 14.99	1	$ 14.99	0	0	$ -	1	0	Replaced by 124 RPM
Servo City	Motor Board	Gear Motor Input Board B	605114	https://ww	$ 0.99	1	$ 0.99	2	2	$ 1.98	25	0	Update to reflect custom boards
Servo City	Motor Mount	Aluminum Motor Mount F	555104	https://ww	$ 4.99	1	$ 4.99	3	3	$ 14.97	3	0	
Servo City	Pillow Blocks	Actobotics 1/4" Ball Bearing Quad Pill	535130	https://ww	$ 7.49	2	$ 3.75	2	1	$ 7.49	1	0	
Servo City	RCY Lead	Male JST RCY Lead	JST20M	https://ww	$ 2.49	1	$ 2.49	2	2	4.98	2	0	
Servo City	Screws	6-32 x 0.375" (3/8) Zinc-Plated Socket	632110	https://ww	$ 2.09	25	$ 0.08	64	3	$ 6.27	6	0	
Servo City	Shaft collar	0.250" (1/4) Aluminum Clamp Collar	625296	https://ww	$ 1.99	1	$ 1.99	16	16	$ 31.84	16	0	
Servo City	Shaft Coupler	0.250" D-Bore to 4mm Clamping Coup	625049	https://ww	$ 4.99	1	$ 4.99	2	2	$ 9.98	2	0	
Servo City	Short Screws	6-32 x 0.1875" (3/16) Zinc-Plated Sock	632104	https://ww	$ 1.75	25	$ 0.07	0	0	$ -	1	0	Replaced by painted screws
Servo City	Switch	JST Switch	607019	https://ww	$ 1.99	1	$ 1.99	1	1	$ 1.99	1	0	
Servo City	Worm Gear Set	27:1 Worm Gear Set (1/4" Bore Worm	637225	https://ww	$ 21.99	1	$ 21.99	$ 1.00	1	21.99		1	
Servo City	XT150 Male Banana Blk	Male XT150 Banana Plug (Black)	607026	https://ww	$ 1.49	1	$ 1.49	0	0	0		0	Not needed
Servo City	XT150 Male Banana Blue	Male XT150 Banana Plug (Blue)	607028	https://ww	$ 1.49	1	$ 1.49	0	0	0		0	Not needed
	Blade Guard				$ -	1	$ -	0	0	$ -		0	Not needed
	Loc Tite		-	-	$ -	1	$ -	0	0	$ -	1	0	
In House	Electric Current Adapter		-	-	$ -	1	$ -	$ 1.00	1	$ -		1	
Total								324	144	$ 881.73	175		

Appendix ZDesign Verification Plan and Report (DVPR)

DVP&R - Design Verification Plan (& Report)

Project:	F14 Mechanical Systems Activity			Sponsor:	Lauren Cooper						Edit Date:	2/3/2021
TEST PLAN											TEST RESULTS	
Test #	Specification	Type	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
A	Magnet Power	Preliminary	Verify that the magnets are strong enough to suport pillars and forces between gears	Observation	Able to set up and power a drive train using magnetic pillars	Steel plate, desk to test on	Two pillars with magents, a few drive train components	Brennen	1/26/2021	1/26/2021	N/A	Test Successful. Magnets performed well and verified magnetic pillar design concept
B	Drive Train Component Integrity	Preliminary	Set up a simple drive train configuration and run it at high speed to test the component integrity	Observation	Drive train is able to run at high speeds with no concerning tendencies	Desk to test on, hand drill	SP	Brennen	1/26/2021	1/26/2021	N/A	Test Successful. Components help up nicely and drive train ran smoothly.
C	Fan as Input Method	Preliminary	Set up simple drive train with turbine blades attached and power it with a fan to make sure enough input power is present	Observation	Drive train is powered with a decent amount of force	A fan, desk to test on	SP for drive train configuration, Turbine blades	Brennen	2/16/2021	2/16/2021	N/A	Test Successful. We used 3D printed tubine blades and fan blades and an underpowered motor and still got decent power.
D	Wind Backwash	Preliminary	Set up housing and configure rotor in the middle of pattern plate with the ten inch shaft. Move the shaft inward in small increments and take RPM mesurements untill rotor is close to pattern plate.	RPM mesurements	RPM not affected	Table, fan, tachometer, anemometer	Housing, rotor, bearings, shaft,	Jose	5/13/2021	5/13/2021	RPM of input shaft only 2.3% lower than average RPMs across all distances	Backwash didn't have enough of an affect to cause us to change our design in any way.
E	Generator Power Losses	Verification	Measure the amount of power lost in motor when used as a generator	Voltage and Current	N\A	Multimeter	generator, resistor assembly	Diego	5/22/2021	5/22/2021	Data collected successfully	This data will be supplied to students allowing them to isolate power losses in their gear trains.
1	Weight	Verification	The combined weight of final products will be tested on a scale	Weight	< 500 lbs	Scale	All at SP/VP level	Jose	3/20/2021	5/22/2021	46lb	Well under spec
2	Size	Verification	The final height, length, and width of each product will be measured with a tape measurement.	Size	45"x25"x47"	Measuring Tape	All at VP level	Jose	3/20/2021	5/19/2021	18"x24"12	Well under spec
3	Production Cost	Verification	Add up total cost of obtaining each activity. This will include the total price for parts and manufacturing of the final product.	Cost	< $1000 for both wind turbine kit and one exploration activity	Excel/Calculator	None (Just BOM)	Diego	4/16/2021	4/22/2021	272.72 dollars remaining	We still have 1/4 of the total buget. This will be updated later on.
4	Assembly Time	Verification	We will time how long it takes to produce a full kit from all the individual materials. This will include 3D printing and Inventory management	Time Duration	< 8 hours	Stopwatch	All at VP level	Brennen	4/7/2021	5/19/2021	6 hours	Conservative estimate. Could be reduced if manufacturer is efficient.
	Set up time	Verification	We will time how long it takes to set up the lab activity starting the time when the kit is rolled into the class room and ending once the kit is set up for the students to use.	Time Duration	< 10 min	Stopwatch	All at VP level	Diego	4/7/2021	5/19/2021	2 min	well organized kits and easy wiring plug in helped on keeping this time down.
5	% of Standard Parts	Verification	Count the number of non-standard parts and divide by the total number of parts	Count of Parts	>= 80%	Calculator	None (Just BOM)	Diego	4/16/2031	4/22/2021	5/47=.10 about 90% of parts are standard	Test Successful.
6	Ease of Use	Verification	Cal Poly students will test the ease of use of the final product. They will assign it with a pass or fail.	Perception	80% Pass	None	None	Jim	4/16/2021	5/13/2021	93% Positive feedback on ease of use	Pass
7	Measurables	Verification	Input/Output measurement from the gearbox will be measured with multiple devices.	Number of measuremnts	4±2	N/A	None	Jim	4/7/2021	5/13/2021	Voltage output, rotational velocity, current, and wind speed	Test successful. Could not get current for slow rated rpm.
8	Noise	Verification	The noise will be measured with a cell phone application	Noise	<85dBA	Noise Measurment App	All as VP level	Brennen	4/7/2021	3/20/2021	~65dB	Original max noise level: 60dB. 60-70 dB did not feel uncomfortable for the testers and did not significantly impact ability to hold a conversation. Therefore, we feel comfortable with increasing our noise limit to 85 dB based on OSHA recommendations for noise limits in 8-hour workday environments.

Test #	Specification	Criteria	Numerical Results	Pass/Fail
1	Weight	< 500 lbs	46 lbs	Pass
2	Size	< 25" x 45" x 47"	12"x24"24"	Pass
3	Production Cost	< $1000	$881.73	Pass
4	Assembly Time	< 8hr	~6 hours	Pass
5	Set up Time	< 10 min	~ 2 min	Pass
6	% of Standard Parts	> 80%	~90%	Pass
7	Ease of Use	> 80% Positive Feedback	93% Positive	Pass
8	Measurable Inputs and Outputs	>= 2	4	Pass
9	Noise	Original: < 60 dB, Final: < 85dB	~65dB	Re-assessed -> Pass

Test #	Characteristic	Purpose	Results
A	Magnet Power	Magnets are strong enough to suport pillars and forces between gears	Pass
B	Drive Train Component Integrity	Components are able to perform well in high stress/speed configurations	Pass
C	Fan as Input Method	Fan is powerful enough to power turbine gear train implementations	Pass
D	Wind Backwash	Determine minimum distance between housing and blades to avoid signicant loss in efficiency	RPM of input shaft at minimum distance only 2.3% lower than average RPMs across all distances
E	Generator Power Losses	Identify amount of power lost within generator.	Data Collected

Appendix AA Test Procedures

F14 – Weight Test Procedure

Test Name:
F14 – Measuring minimum weight requirement.
Purpose:
This test is meant to measure the overall weight of the apparatus which includes wind turbine lab and exploratory lab kits. This information will be useful in determining if the weight will be within the specifications of a utility cart.
Scope:
This experiment tests the weight of the whole apparatus that includes fans, measuring instruments, and kits to ensure the kart can carry the weight of the lab design.
Equipment:

- Model wind turbine apparatus
- Fan
- Anemometer
- Voltmeter
- Exploratory kits
- Weight scale

Hazards:

- Each component of the kit does not weigh enough to strain oneself
- Depending on fan, weight of fan may strain the tester
- Dropping components on toes

PPE Requirements:

- Closed-toe shoes

Facility:
This test will occur at Brennen Irey's house.
Procedure:

1. Before beginning, ensure all participants are wearing proper safety equipment (closed toe shoes).
2. Calibrate weight scale to read 0 with no weight on it
3. Select one of every different component (since similar parts will weigh about the same)
4. Place one of the selected components and record the weight.
5. Multiply the component weight with the number of similar components and record the value.
6. Repeat step 4 and five until all components are accounted for.
7. For larger components (fan) lift with knees and place on scale and record the weight
8. Add up the total value.
9. Ensure the with is below specification.

Results:
The weight of the components will be as accurate of the scale, but if the scale reads a value other than zero after being empty we will re-zero the scale.

Component	Weight
Fan	14 lbs
All Other Components	32 lbs
Total	**46 lbs**

Test Date(s):
Friday, April 30
Test Results:
Pass
Performed By:

Brennen Irey

F14 – Size Test Procedure

Test Name:
F14 – Measuring size of the apparatus
Purpose:
This test is to ensure the whole apparatus fits within the boundaries of the kart.
Scope:
The components will be places within a tackle box (this models a complete set for one group) the tackle box will be measured along with every other part of the whole apparatus to ensure it fits within the confines of the kart.
Equipment:

- Model wind turbine apparatus
- Fan
- Anemometer
- Voltmeter
- Measuring tape
- Exploratory kits

Hazards:

- Cut hazard from edge of blades
- Dropping components

PPE Requirements:

- Closed-toe shoes

Facility:
This test will occur at Brennen Irey's house.
Procedure:

1. Identify the largest component in each dimension.
2. Measure this component and compare to 25"x45"x47", the maximum size that can fit through a standard door while sitting on a standard utility cart.
3. Place all activity components on a utility cart.
4. Ensure all part fit on the cart securely and are not likely to fall off.

Results:
We do not yet have a cart to place the apparatus in so we need to theoretically be able to fit everything with our measurements. We expect the measuring tape to make accurate readings for our test.

Largest Component	Width	Length	Hight
Fan	9"	24"	24"
Base Plate	12"	24"	0.5"
Max	12"	24"	24"
Criteria	25"	45"	47"

Test Date(s):
Friday, April 30
Test Results:
Pass
Performed By:
Brennen Irey

F14 – Production Time Test Procedure

Test Name:
F14 – Assembly time
Purpose:
This test measures the assembly time required during the manufacturing process.
Scope:
The test will only measure the time it takes to manufacture and assemble the permanent assemblies (Hub-mount gears, magnet bases, etc.)
Equipment:

- Hub-mount gears
- Hub-mounts
- Magnet
- Magnet block
- U-channels
- 3D-printer
- Screws
- Motors
- Timer

Hazards:

- Magnets slamming together

PPE Requirements:

- Safety glasses

Facility:
This test will occur at Brennen Irey's house.
Procedure:

5. Before beginning ensure all participants are wearing proper safety equipment
6. 3D print all necessary components, record actual print time
7. Start timer and assemble all components
8. Stop timer and add print time for total assembly time

Results:
Accounting for overlapping in assembly processes while parts print and paint dries, we estimate a shop tech could put everything together in less than 6 hours, potentially even less if they are efficient.

Test Date(s):
Friday, March 20
Test Results:
Pass
Performed By:
Brennen Irey

Ease of Use Test Procedure

Test Name:

Ease of Use Test

Purpose:

The purpose of this test is to determine whether the apparatus's that we develop are easy enough for students and professors to use

Scope:

Activity setup, placement of pillars (for the exploration activity), assembly of drive train, powering of drive train, and measurement of outputs.

Equipment:

Verification prototypes for both activities

Hazards: (list hazards associated with the test)

- Moving/rotating parts
- Electrical components
- Pinch Points

PPE Requirements:

Safety goggles, loose clothing/hair secured, closed-toed shoes

Facility:

Anywhere accessible by the test subjects. Perhaps a classroom or lab.

Procedure:

1) Allow users to interact with the apparatuses and complete at leas part of each lab.

2) Have the users fill out a survey asking questions about the ease of use of various features.

Results:

Target number of surveyed users: 15

Pass criteria: Average 6/10 across all questions and all users.

1. I am a

More Details Insights

Former ME 329 Student	5
Current ME 329 Student	1
Future ME 329 Student	2
Former/Current ME 329 Profe...	2
Other	6

2. When answering a question that requires rating something on a scale, 1-5 for example, I am a person who

More Details Insights

Has no problem selecting 1 or...	10
Is more likely to select 5 if I m...	1
Is not likely to select 1 or 5 unl...	4
Is very unlikely to choose 1 or ...	1

3. I interacted with, and can give feedback about, the exploration activity with the magnetic pillars

More Details

Yes	16
No	0

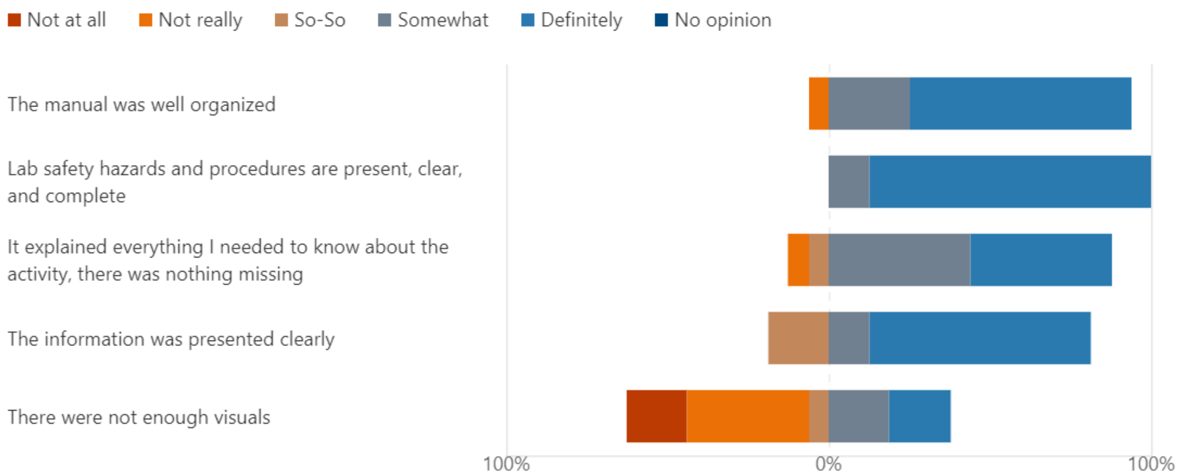
4. What was your initial impression of the lab activity overall?

16 Responses

1	James Popolow	great fun. Wanted more time.
2	James Popolow	very excited and immediately saw so opportunities to talk about the agma gear stress equations in a conceptual wayl
3	James Popolow	I didn't know what to do until I had already set up the basic setup with two gears and the generator
4	James Popolow	Fun, I like the opportunity for innovation
5	James Popolow	I liked it, it is a fun activity to help gain an understanding of gears
6	James Popolow	It was a fun little activity and I got to learn about gear ratios by actually visibly working. It was also a good activity to learn about the power output you can get from the gears.
7	James Popolow	Overall it was a good manual with relatively easy steps to follow. My only addition would be to show what tools for what step.
8	James Popolow	It was very easy and simple to follow and construct. The gear teeth were difficult to identify. Maybe add a step in the instructions saying to count the teeth for each gear or label each gear if you dont want the students to figure it out.
9	James Popolow	Easy to follow and get numeric results
10	James Popolow	Excited to get hands on with it, I've worked with VEX and First robotics in the past
11	James Popolow	Super intuitive and interesting
12	Jack Cerron	The background to the lab could be condensed a bit more but the information to actually build the lab was thorough and clear.
13	Jack Cerron	I was excited to experiment with gears and gear trains because I have never actually handled these components.
14	James Popolow	I thought it was very well put together and very easy to follow. I think it can provide good insight on both DC motors, and gear ratios as well as gear spacing.
15	James Popolow	It was fairly simple but I had fu figuring out each of the components
16	James Popolow	I was initially worried seeing the final product and what I would be building but the begining activity had several useful pictures to follow along with!

5. Please indicate your agreement with the following statements regarding the lab MANUAL

More Details



6. Please explain any non-neutral answers to the question above here, if you'd like.

More Details

9

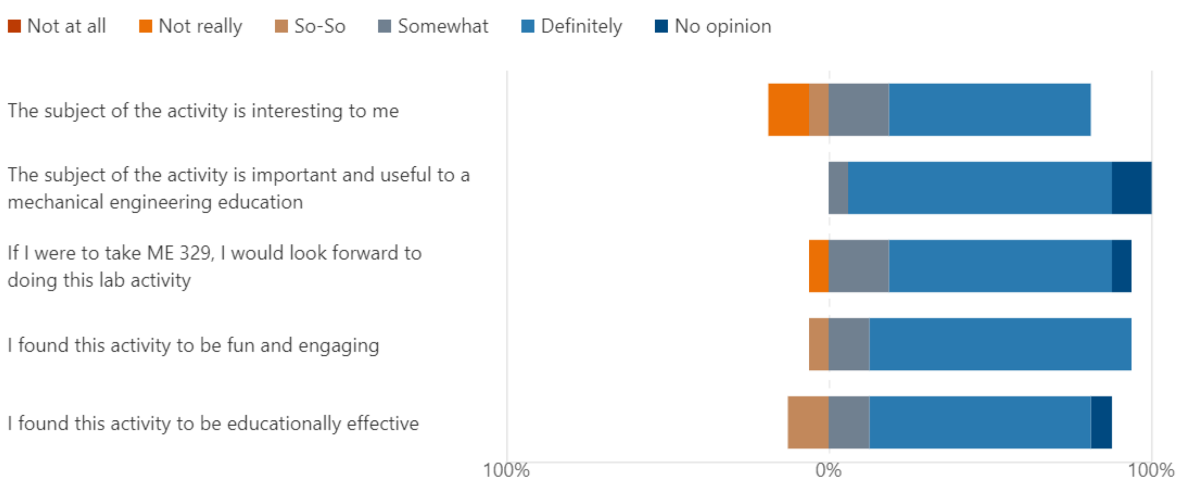
Responses

Latest Responses

"I understand the Lab manual is a draft"

7. Please indicate your agreement with the following statements regarding the lab CONCEPT

More Details



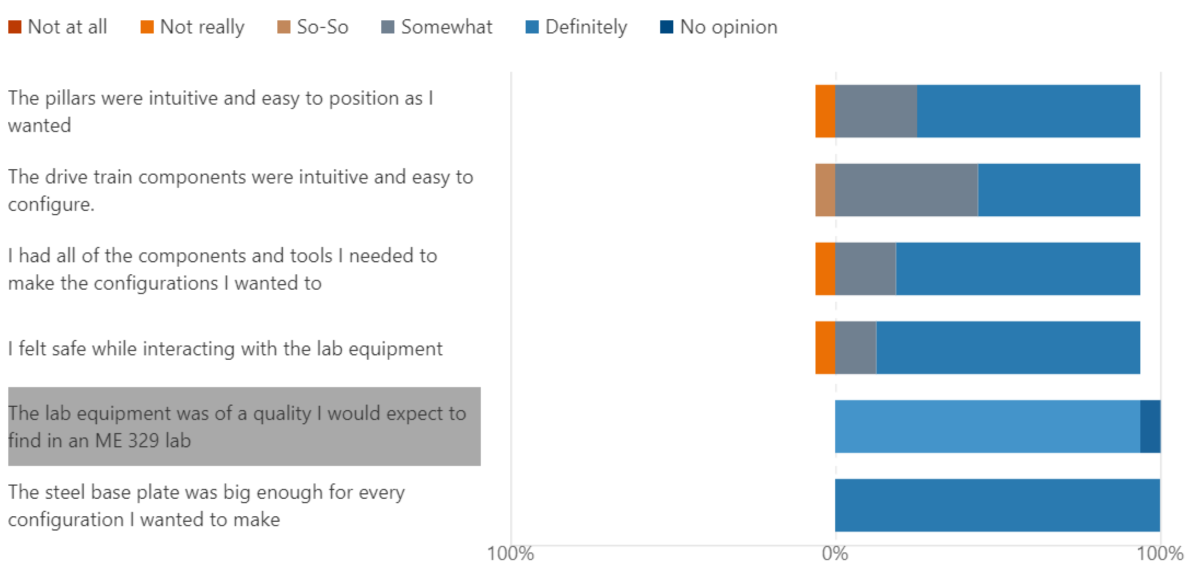
8. Please explain any non-neutral answers to the question above here, if you'd like.

3 Responses

ID↑	Name	Responses
1	James Popolow	I only did the most basic activity with the generator. With only two gears, I don't need to go through 20 minutes of understanding the activity and setup to know how gear ratios work. For more difficult concepts like gear train transmissions this would be much more worth while
2	James Popolow	While I had fun constructing the assembly, it would honestly feel like just another lab to me due to the subject matter. It's nothing that your team could fix though so I wouldn't worry about it too much.
3	James Popolow	I think this lab would be fun, however, it was just a little bit basic. I think adding more things to do, or testing out different ratios would be more intreseting.

9. Please indicate your agreement with the following statements regarding the lab EQUIPMENT

More Details



10. Please explain any non-neutral answers to the question above here, if you'd like.

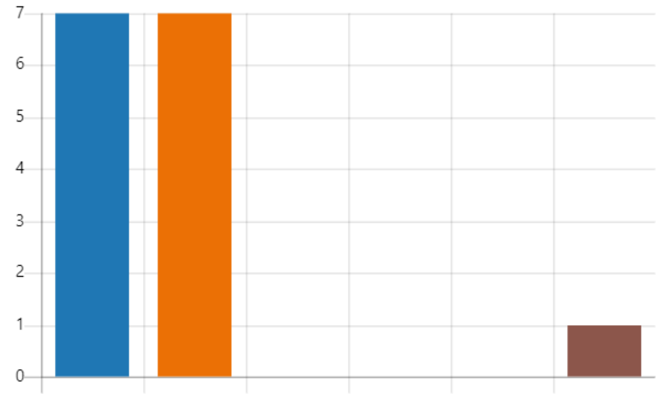
5 Responses

ID↑	Name	Responses
1	James Popolow	More types of components.
2	James Popolow	Safety: The magnets did make me a little uneasy as they are very strong. It isn't a big deal, but I was always a little cautious when initially placing the towers Configuration: It was not the most fun to use an alan wrench to tighten every single part...
3	James Popolow	magnets to the base plate were a little too strong. Also, it was hard to keep the bearings from moving around.
4	James Popolow	Great construction of the parts. Seems super high quality and reliable. The only issue I had is with the magnets being a bit too strong to manage sometimes. The strength may also cause damage to the base plate/magnets over time due to the high force collisions of slamming it onto the plate.
5	James Popolow	Damn the magnets surprised me with how hard they snapped on the plate.

11. What size group would be ideal for this activity?

More Details Insights

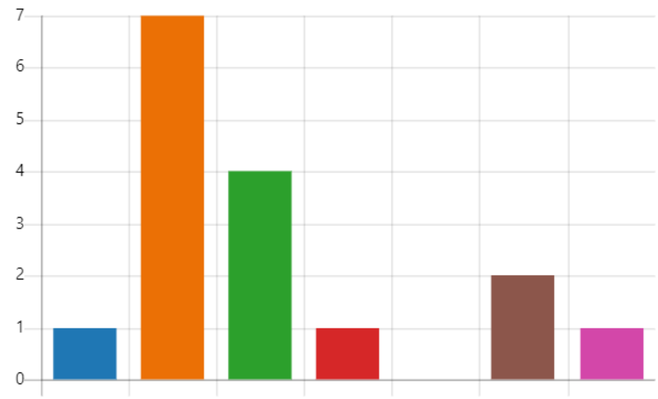
2 students	7
3 students	7
4 students	0
5 students	0
6 students	0
Other	1



12. How long would be a good amout of time to give students with this activity?

More Details

15 minutes	1
30 minutes	7
1 hour	4
1.5 hours	1
2 hours	0
3 hours	2
Other	1



13. Do you have any suggestions to improve this activity? Is there anything you would add, remove, or change?

11 Responses

ID↑	Name	Responses
1	James Popolow	give specific goals to achieve before opening up to exploration.
2	James Popolow	Talked to James
3	James Popolow	Adding videos of the different setups would be nice.
4	James Popolow	I would include the tools needed, with photos.
5	James Popolow	Potentially add labels to the gears
6	James Popolow	I think even more axels/ one more guided activity would be nice
7	Jack Cerron	Maybe give all the students a starting gear train so they know what they're doing. They can compare data to make sure they're mating the gears correctly. They can then build off of that.
8	Jack Cerron	I would add prompts for the students to follow such as "design a speed reduction gear train" or "design a gear train with three gears that increases output speed" and I would also add a table to the second activity to collect data on input and output speeds for different voltages.
9	James Popolow	I would just add more content if possible that would look into the different gear ratios.
10	James Popolow	suggest adding another collar on the end of the gear
11	James Popolow	I would love to see more photos - the ending was difficult to follow along with because there were only instructions.

14. I interacted with, and can give feedback about, the wind turbine design activity

More Details Insights

Yes	2
No	14

Test Date(s):

5/3/21 – 5/13/21

Test Results:

Exploration Activity – Pass

Design Challenge – Inconclusive due to low numbers of testers

Performed By:

James Popolow

Measurable Outputs Test Procedure

Purpose:

Tests to make sure we have included the number of measurable inputs and outputs in our design

Scope:

Quantitative measurements that can be taken from our activities

Equipment:

- Verification prototypes for both activities
- Tachometer

Hazards:

- Rotating components

PPE Requirements:

- None

Facility:

Anywhere. Most likely Brennen's house

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

1) General Inspection
    a. Count the number of measurable inputs/outputs
2) Tachometer
    a. Set up motor input pillar
    b. Apply reflective tape to shaft coupler attached to motor
    c. Energize the motor and measure rotation to ensure tachometer is working

Results:

Pass criteria: >= 2 measurable inputs/outputs, tachometer works as expected

Test Date(s):

Tachometer Test – 4/13/21

Test Results:

4 total inputs/outputs – PASS, Tachometer Test - PASS

Performed By:

Tachometer Test – Brennen Irey

Insights:

Reflective metal can mess with the tachometer a little bit.

F14 – Test Procedure

Test Name:
F14 – Noise Limit
Purpose:
This test is to ensure the noise generated by the equipment does not exceed 60 dB
Scope:
The test will encompass all components during normal operation. Noise created from accidents and/or improper use.
Equipment:

- Equipment for both exploratory and design projects
- iPhone Decibel meter app ("Decibel X")
- Power supply

Hazards:

- Cut hazard from edge of blades
- Dropping components
- Pinch hazard from gears
- Entanglement from rotating parts

PPE Requirements:

- Closed-toe shoes
- Safety glasses

Facility:
This test will occur at Brennen Irey's house.
Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

9. Before beginning ensure all participants are wearing proper safety equipment
10. Setup an example exploratory lab (Motor-driven gear train)
11. Connect the motor to power supply
12. Set power supply to 12 volts, 3 amps
13. Record decibel reading continuously around the system in a 1 ft radius, record highest reading
14. Turn off power supply and disassemble exploratory setup
15. Setup an example design lab (Fan-driven dear train)
16. Turn fan on
17. Record decibel reading 1 ft away in every direction from the fan, average results.
18. Turn fan off and disassemble design setup

Results:
We will use the results to determine if our current design meets our initial noise requirements. We will also analyze the results to determine if the noise level should be changed from 60 dB.

Test Date(s):
Friday, March 20, Tuesday April 13
Test Results:
Input motor was measured at around 60-70 dB

Performed By:
Brennen Irey

Insights:

60-70 dB did not feel uncomfortable for the testers and did not significantly impact ability to hold a conversation. Therefore, we feel comfortable with increasing our noise limit to 85 dB based on OSHA recommendations for noise limits in 8-hour workday environments.

Motor Power Losses Test

Purpose:

Experimentally determine the power losses occurring in the motors during operations.

Scope:

We are only concerned with the power losses in the motors themselves. Therefore, the motors will be connected directly together without any gearing ratio between them.

Equipment:

- Motor Input Assembly
- Generator Assembly
- 4 Hole Pillar
- 4" shaft
- Base Plate
- Multimeter and leads
- Tachometer

Hazards: (list hazards associated with the test)

- Rotating components

PPE Requirements:

- Safety glasses

Facility:

Components stored location (Brennen's house)

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

1) Connect generator to 4-hole pillar using motor mount.
2) Connect input motor to generator via 4" shaft using shaft couplers
3) Connect input motor to variable power supply
4) Set power supply to 0.5A and vary the voltage from 4 to 12V at 1V increments. Measure the shaft speed using the tachometer and output voltage and amperage from the generator using a multimeter
5) For each measurement, calculate the power produced by the generator and subtract it from the power input from the power supply. This is the power lost in the two motors.

Results: Pass Criteria, Fail Criteria, Number of samples to test

No pass or fail criteria. However, results will include a graph of power losses vs input power

Test Date(s):

5/26/21

Test Results:

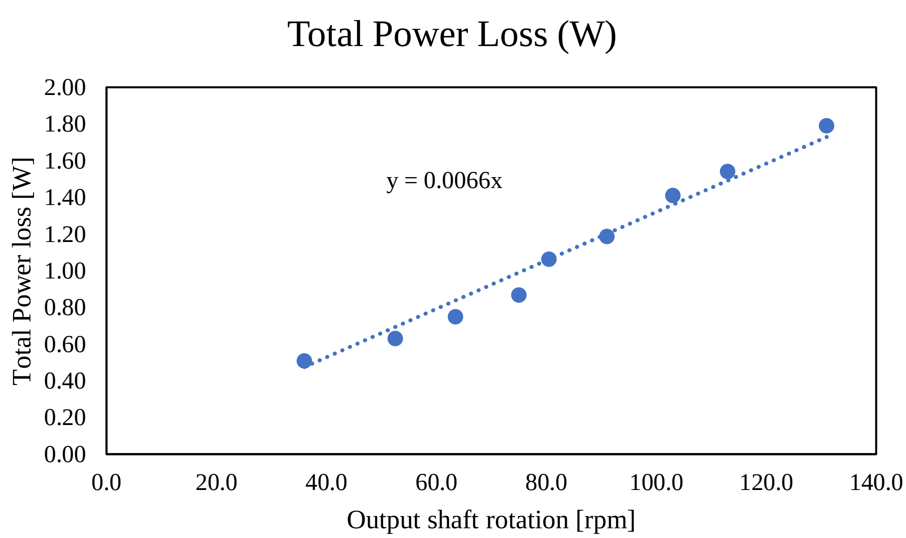
Data Collected

Performed By:

Jack Cerron

Data Sheet:

Input Current (A)	Input Voltage (V)	Input Power (W)	Shaft Speed (rpm)	Shaft Speed Act(rpm)	Output Current (mA)	Output Voltage (V)	Output Power (W)	Total Power Loss (W)
0.13	4.00	0.52	72	36.0	28.2	0.450	0.013	0.51
0.13	5.00	0.65	105	52.5	36.6	0.575	0.021	0.63
0.13	6.00	0.78	127	63.5	44.2	0.700	0.031	0.75
0.13	7.00	0.91	150	75.0	52.3	0.828	0.043	0.87
0.14	8.00	1.12	161	80.5	60.2	0.954	0.057	1.06
0.14	9.00	1.26	182	91.0	68.0	1.088	0.074	1.19
0.15	10.00	1.50	206	103.0	75.4	1.200	0.090	1.41
0.15	11.00	1.65	226	113.0	83.0	1.320	0.110	1.54
0.16	12.00	1.92	262	131.0	90.8	1.444	0.131	1.79



F14 – Backwash Effect Test Procedure

Purpose:

This test is meant to measure the effects of backwash on the efficiency of our model wind turbine. Using this data we can decide how far from the housing our turbine blades need to be mounted.

Scope: (Defines what feature or function the test is for)

This experiment tests the mounting system for the turbine blades on the turbine housing. Indirectly a test to make sure our system can produce measurable output power and that our measurement devices work.

Equipment:

- Model wind turbine apparatus
- Fan
- Tachometer
- Voltmeter
- Engineering scale

Hazards:

- Entanglement in rotating components
- Cut hazard from edge of blades

PPE Requirements:

- Safety glasses
- Hair tied back
- Closed-toe shoes

Facility:

This test will occur at Brennen Irey's house.

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

1. Before beginning ensure all participants are wearing proper safety equipment (safety glasses, closed toe shoes, ect...).
2. Calibrate anemometer to read 0 with no airflow
3. Calibrate tachometer to read 0 with no wind
4. Set up apparatus for experiment with blades 1 inch away from housing and fan 25 inches from blades
5. Turn on fan, measure windspeed at 25 inches from fan
6. Allow turbine blades to reach full rotation speed
7. Measure RPM with tachometer
8. Turn off fan, let apparatus reach cold state
9. Repeat steps 4-7 twice more to ensure consistency of readings
10. Move housing 1 inch farther away from fan, holding blades in place
11. Repeat steps 4-7 and 9 five more times.

Results:

We expect the anemometer readings to stay consistent throughout the test, but we expect the output voltage readings to increase gradually as the blades get further from the housing, perhaps plateauing at a certain point.

D [in]	RPM	U_{00} [m/s]
9.125	540	2.5
8.125	620	2.64
7.5	395	2.43
6.5	610	2.8
4.5	540	2.8
3.5	535	2.3
2.5	525	2.7

Test Date(s):

Thursday, May 13

Test Results:

- Measurements
    - Anemometer read wind speed to ensure constant parameter throughout tests***.***
    - multimeter read the voltage produced from turbine with blades positioned a certain distance from the pattern plate.
    - The distance between the blades and pattern plate.
- Analysis
    - We will be able to produce a graph of output voltage vs distance between blades and housing

The pattern plate did not have any significant impact on the rotation of the blade. Results from the table shows that the rotor was not spinning consistent with distance, this maybe be due to friction caused by bearings in to close of contact with shaft collar.

Performed By:

Jose Chavez

Motor Power I/O Test Procedure

Purpose:

Verify that the input motor performs as expected and that the output generator produces a measurable amount of output when given a reasonable input.

Scope:

Motor input assembly and generator assembly input/output will be checked by using a multimeter. The input for both will come from either a power source or wind.

Equipment:

- 2 4-Hole U-Channels assemblies
- 57 RPM Motor (12V, 3.85A)
- 970 RPM motor (12V, 3.8A)
- 4” shaft
- Shaft couplers
- Metal base
- Multimeter and leads
- Power supply

Hazards: (list hazards associated with the test)

- Rotating components
- Do not add more amperage to the motors than its rating to prevent motor damage.

PPE Requirements:

- Safety glasses

Facility:

Components stored location (Brennen’s house)

Procedure: (List number steps of how to run the test, can include sketches and/or pictures):

6) Connect generator to 4-hole U-channel using motor mount.
7) Connect input motor to generator via 4” shaft using shaft couplers
8) Connect input motor to variable power supply
9) Set power supply to 6, 9, and 12V and measure the outputs from the generator using a multimeter

Results: Pass Criteria, Fail Criteria, Number of samples to test

Pass: Input motor runs smoothly at expected speed(s) and is able to turn the generator shaft. Generator produces consistent and measurable output at various speeds.

Fail: Any other outcome

Number of samples: 3 input voltages from 6 – 12V

Test Date(s):

4/7/2021

Test Results:

Pass

Performed By:

Brennen Irey

Appendix BB Indented Bill of Materials

Mechanical Systems Lab Activities
Indented Bill of Material (iBOM)

Assembly Level	Assembly Part #	0	1	2	3	4	Part	Qty Per Subassembly	Cost Per Unit	Total Unit Qty	Total Unit Cost	Vendor	Vendor Part #	Notes
0	**1.0.0.0.0**	**Final Assy**						**1**	**$ 851.56**	**1**	**$ 851.56**			
1	**1.1.0.0.0**		**Exploration Activity**					**1**	**$ 613.01**	**1**	**$ 613.01**			
2	**1.1.1.0.0**			**4 Hole Pillar**				**6**	**$ 17.67**	**6**	**$ 106.02**			
2	1.1.1.0.0-1						Magnet	1	$ 12.67	6	$ 76.02	K&J Magnets	DX46	
2	1.1.1.0.0-2						Magnet Mount	1	$ -	6	$ -	In House	-	
2	1.1.1.0.0-3						4 Hole U-Channel	1	$ 4.49	6	$ 26.94	Servo City	585443	
2	1.1.1.0.0-4						Painted Screws	3	$ 0.17	18	$ 3.06	McMaster-Carr	97690A158	
2	**1.1.2.0.0**			**9 Hole Pillar**				**2**	**$ 20.17**	**2**	**$ 40.34**			
2	1.1.1.0.0-1						Magnet	1	$ 12.67	2	$ 25.34	K&J Magnets	DX46	
2	1.1.1.0.0-2						Magnet Mount	1	$ -	2	$ -	In House	-	
2	1.1.2.0.0-3						9 Hole Channel	1	$ 6.99	2	$ 13.98	Servo City	585448	
2	1.1.1.0.0-4						Painted Screws	3	$ 0.17	6	$ 1.02	McMaster-Carr	97690A158	
2	**1.1.3.0.0**			**Base Plate**				**1**	**$ 29.48**	**1**	**$ 29.48**			
2	1.1.3.0.0-1						Steel Plate	1	$ 27.04	1	$ 27.04	Online Metals	13973	
2	1.1.3.0.0-2						Rubber Feet	4	$ 0.36	4	$ 1.44	Home Depot	176838	
2	1.1.3.0.0-3						Vinyl Sticker	1	$ 1.00	1	$ 1.00	Mustang 60	-	
2	**1.1.4.0.0**			**Drive Train Components**				**1**	**$ 227.95**	**1**	**$ 227.95**			
3	**1.1.4.1.0**				**80T Gear Assy**			**1**	**$ 21.31**	**1**	**$ 21.31**			
3	1.1.4.1.0-1						80T Gear	1	$ 12.99	1	$ 12.99	Servo City	615206	
3	1.1.4.1.0-2						Hub Mount	1	$ 7.99	1	$ 7.99	Servo City	545619	
3	1.1.4.1.0-3						Screws	4	$ 0.08	4	$ 0.33	Servo City	632110	
3	**1.1.4.2.0**				**72T Gear Assy**			**2**	**$ 21.49**	**2**	**$ 42.98**			
3	1.1.4.2.0-1						72T Gear	1	$ 12.99	2	$ 25.98	Servo City	615198	
3	1.1.4.1.0-2						Hub Mount	1	$ 7.99	2	$ 15.98	Servo City	545619	
3	1.1.1.0.0-4						Painted Screws	3	$ 0.17	6	$ 1.02	McMaster-Carr	97690A158	
3	**1.1.4.3.0**				**64T Gear Assy**			**1**	**$ 21.49**	**1**	**$ 21.49**			
3	1.1.4.3.0-1						64T Gear	1	$ 12.99	1	$ 12.99	Servo City	615194	
3	1.1.4.1.0-2						Hub Mount	1	$ 7.99	1	$ 7.99	Servo City	545619	
3	1.1.1.0.0-4						Painted Screws	3	$ 0.17	3	$ 0.51	McMaster-Carr	97690A158	
3	**1.1.4.4.0**				**Crank Arm**			**1**	**$ 8.50**	**1**	**$ 8.50**			
3	1.1.4.1.0-2						Hub Mount	1	$ 7.99	1	$ 7.99	Servo City	545619	
3	1.1.4.4.0-2						Crank Arm	1	$ -	1	$ -	In House	-	
3	1.1.1.0.0-4						Painted Screws	3	$ 0.17	3	$ 0.51	McMaster-Carr	97690A158	
3	**1.1.4.5.0**				**Assorted Parts**			**1**	**$ 133.67**	**1**	**$ 133.67**			
3	1.1.4.5.0-1						4 in Shaft	6	$ 2.39	6	$ 14.34	Servo City	634080	
3	1.1.4.5.0-2						3 in Shaft	2	$ 2.19	2	$ 4.38	Servo City	634078	
3	1.1.4.5.0-3						7 in Shaft	2	$ 1.70	2	$ 3.39	Servo City	634086	
3	1.1.4.5.0-4						10 in Shaft	2	$ 4.39	2	$ 8.78	Servo City	634092	
3	1.1.4.5.0-5						Shaft collar	16	$ 1.99	16	$ 31.84	Servo City	625296	
3	1.1.4.5.0-6						Pillow Blocks	2	$ 3.75	2	$ 7.49	Servo City	535130	
3	1.1.4.5.0-7						Bearings	12	$ 1.45	12	$ 17.34	Servo City	535198	
3	1.1.4.5.0-8						Angle Brackets	4	$ 1.89	4	$ 7.56	Servo City	585424	
3	1.1.4.1.0-3						Screws	20	$ 0.08	20	$ 1.67	Servo City	632110	
3	1.1.4.5.0-10						Wing Nuts	25	$ 0.20	25	$ 4.92	Home Depot	802331	
3	1.1.4.5.0-11						32T Pinion	1	$ 7.99	1	$ 7.99	Servo City	615254	
3	1.1.4.5.0-12						24T Pinion	2	$ 7.99	2	$ 15.98	Servo City	615250	
3	1.1.4.5.0-13						16T Pinion	1	$ 7.99	1	$ 7.99	Servo City	615242	
2	**1.1.5.0.0**			**Motor Input**				**1**	**$ 32.29**	**1**	**$ 32.29**			**Also uses one 4-hole pillar assembly**
2	1.1.5.0.0-1						Shaft Coupler	1	$ 4.99	1	$ 4.99	Servo City	625049	
2	1.1.5.0.0-2						124 RPM Motor	1	$ 14.99	1	$ 14.99	Servo City	638352	
2	1.1.5.0.0-3						Motor Board	1	$ 0.99	1	$ 0.99	Servo City	605114	
2	1.1.5.0.0-4						Switch	1	$ 1.99	1	$ 1.99	Servo City	607019	
2	1.1.5.0.0-5						Motor Mount	1	$ 4.99	1	$ 4.99	Servo City	555104	
2	1.1.5.0.0-6						Painted short screws	4	$ 0.17	4	$ 0.66	McMaster-Carr	97690A155	
2	1.1.5.0.0-7						Header Pins	2	$ 0.07	2	$ 0.14	Servo City	HPS-100-36	
2	1.1.5.0.0-8						Male Banana Pair	1	$ 0.99	1	$ 0.99	Servo City	X24231	
2	1.1.5.0.0-9						Shrink Wrap Sleeves	4	$ 0.02	4	$ 0.06	In House	3201-0005-0001	
2	1.1.5.0.0-10						RCY Lead	1	$ 2.49	1	$ 2.49	Servo City	JST20M	
2	**1.1.6.0.0**			**Motor Output**				**1**	**$ 20.90**	**1**	**$ 20.90**			**Also uses one 4-hole pillar assembly**
2	1.1.6.0.0-1						Generator	1	$ 14.99	1	$ 14.99	Servo City	638358	
2	1.1.5.0.0-5						Motor Mount	1	$ 4.99	1	$ 4.99	Servo City	555104	
2	1.1.6.0.0-3						Custom Motor Board	1	$ 0.26	1	$ 0.26	JLCPCB	-	
2	1.1.5.0.0-6						Painted short screws	4	$ 0.17	4	$ 0.66	McMaster-Carr	97690A155	
2	1.1.6.0.0-5						Electric Current Adapter	1	$ -	1	$ -	In House	-	
2	**1.1.7.0.0**			**Measurement**				**1**	**$ 26.96**	**1**	**$ 26.96**			
2	1.1.7.0.0-1						Tachometer	1	$ 15.99	1	$ 15.99	Amazon	1-1024-17	
2	1.1.7.0.0-2						Multimeter	1	$ 10.97	1	$ 10.97	Amazon	VC830L	
2	**1.1.8.0.0**			**Inventory**				**1**	**$ 34.99**	**1**	**$ 34.99**			**New Row**
2	1.1.8.0.0-1						Accordian Tacklebox	1	$ 34.99	1	$ 34.99	Michaels	10998650	New Row
2	**1.1.9.0.0**			**Tools**				**1**	**$ 23.84**	**1**	**$ 23.84**			
2	1.1.9.0.0-1						Large Hex Key	1	$ 6.50	1	$ 6.50	Home Depot	JTH6E09BE	
2	1.1.9.0.0-2						Main Hex Key	2	$ 4.97	2	$ 9.94	Home Depot	JTH6E07BE	
2	1.1.9.0.0-3						Small Hex Key	1	$ 7.40	1	$ 7.40	McMaster-Carr	6286A13	
2	**1.1.10.0.0**			**Advanced Components**				**1**	**$ 70.24**	**1**	**$ 70.24**			
2	1.1.10.0.0-1						Bevel Gear Set	1	$ 24.99	1	$ 24.99	Servo City	637222	
2	1.1.10.0.0-2						Worm Gear Set	1	$ 21.99	1	$ 21.99	Servo City	637225	
2	1.1.10.0.0-3						32T Sprocket	1	$ 5.29	1	$ 5.29	Servo City	615114	
2	1.1.10.0.0-4						16T Sprocket	1	$ 3.99	1	$ 3.99	Servo City	615102	
2	1.1.10.0.0-5						Chain	2	$ 6.99	2	$ 13.98	Servo City	615150	
2	**1.1.11.0.0**			**Spare Components**					**$ 14.97**	**0**	**$ -**			
2	1.1.5.0.0-1						Shaft Coupler	2	$ 4.99	0	$ -	Servo City	625049	
2	1.1.11.0.0-2						5/16 to 1/4 Shaft coupler	1	$ 4.99	0	$ -	Servo City	625046	

1	**1.2.0.0.0**	**Wind Turbine**			**1**	**$ 238.55**	**1**	**$ 238.55**				
2	**1.2.1.0.0**		**Housing**		**1**	**$ 104.20**	**1**	**$ 104.20**				
2	1.2.1.0.0-1			3x4 Hole Pattern Plate	4	$ 8.99	4	$ 35.96	Servo City	585002		
2	1.2.1.0.0-2			3x8 Hole Pattern Plate	2	$ 13.99	2	$ 27.98	Servo City	585004	Drawing package has 2	
2	1.1.4.5.0-8			Angle Brackets	10	$ 1.89	10	$ 18.90	Servo City	585424		
2	1.2.1.0.0-4			Hinge	0	$ 4.99	0	$ -	Servo City	585644		
2	1.2.1.0.0-5			90 Degree Pattern	0	$ 4.99	0	$ -	Servo City	545400		
2	1.1.4.1.0-3			Screws	40	$ 0.08	40	$ 3.34	Servo City	632110		24
2	1.2.1.0.0-7			Lock Nuts	40	$ 0.08	40	$ 3.02	Servo City	632142		24
2	1.2.1.0.0-8			Acrylic	1	$ 14.99	1	$ 14.99	Home Depot	308669979		
2	**1.2.2.0.0**		**Input**		**1**	**$ 105.24**	**1**	**$ 105.24**				
2	1.2.2.0.0-1			Fan	1	$ 49.99	1	$ 49.99	Harbor Freight	0		
2	1.2.2.0.0-2			Blades	1	$ 18.98	1	$ 18.98	Master Airscrew	-		
2	1.2.2.0.0-3			2" 5/16 Round shaft	1	$ 1.29	1	$ 1.29	Servo City	634182		
2	1.1.11.0.0-2			5/16 to 1/4 Shaft coupler	1	$ 4.99	1	$ 4.99	Servo City	625046		
2	1.2.2.0.0-5			Anemometer	1	$ 29.99	1	$ 29.99	Amazon	B019RU17XC		
2	**1.2.3.0.0**		**Output**		**1**	**$ 29.11**	**1**	**$ 29.11**				
2	1.1.6.0.0-1			Generator	1	$ 14.99	1	$ 14.99	Servo City	638358		
2	1.1.5.0.0-6			Painted short screws	4	$ 0.17	4	$ 0.66	McMaster-Carr	97690A155		
2	1.1.5.0.0-5			Motor Mount	1	$ 4.99	1	$ 4.99	Servo City	555104		
2	1.1.5.0.0-3			Motor Board	1	$ 0.99	1	$ 0.99	Servo City	605114		
2	1.1.5.0.0-1			Shaft Coupler	1	$ 4.99	1	$ 4.99	Servo City	625049		
2	1.1.5.0.0-10			RCY Lead	1	$ 2.49	1	$ 2.49	Servo City	JST20M		
						Total	**324**	**$ 851.56**				

Appendix CC Team Contract

Team Roles

All members will participate in all portions of the project. The people named in the roles below are simply responsible to making sure the duties of their role are executed, no matter who ends up performing the tasks.

- Managing team progress – Jose
- Managing team budget – Brennen
- Conducting meetings – Jack
- Documenting team information – Jim
- Communicating with stakeholders – Jim
- Recording meeting minutes – Rotating responsibility

Commitments

We will:

- Only take on duties we are qualified to do.
- Have realistic ideas about planning, project scope, schedule, and cost.
- Be proactive in problem solving, and work to avoid potential problems.
- Alert sponsor/customer if any change affects them as soon as possible.
- Keep all team members up to date.
- Keep focus on what is best for the project overall.
- See the project to completion.
- Respond to:
    - Sponsors, advisors, and coach within 1 day
    - One another within 6 hours, be it via text, email, etc.
- Check the OneNote 2 times per week and make team members aware of when new documents are added to the OneDrive.
- Practice commitment to team goals, not individual goals.
- Team members will make sure that the tasks they own are completed and submitted on time
- Meet for 6 hours a week as a team at the time decided upon by the team
- Work individually on the project at least 4 hours a week each.

Team Ground Rules:

A. Participation

We will:

- Keep issues that arise in meetings in confidence within the team unless otherwise indicated.
- Be honest and open during meetings.
- Encourage a diversity of opinions on all topics.
- Give everyone the opportunity for equal participation
- Be open to new approaches and listen to new ideas.
- Avoid placing blame when things go wrong. Instead we will discuss the process and explore how it can be improved.
- Put in the time and effort when manufacturing or assembling project.

B. Communication

We will:

- Seek first to understand, and then to be understood.

- Foster an environment that allows for open expression ideas free from judgement.
- Ensure every team member gets the chance to have his/her ideas heard.
- Practice active and effective listening.
- Keep discussions on track.
- When necessary and applicable, use visual means such as drawings, charts, and tables to facilitate discussion.
- Based on good judgement, include all team members in important communications.

C. Problem Solving

We will:

- Clearly define what problem we are assessing.
- Build on one another's ideas.
- Use research collected to assist in problem solving.
- Encourage all ideas to be presented prior to evaluating each of them individually.
- Discourage becoming fixated on one idea.

D. Decision Making

We will:

- Acquire enough information prior to coming to a decision.
- Find consensus before proceeding to the next step in the project.
- Deliberate on each idea presented through a set of criteria.
- Search for addition information when a decision has reached an impasse.
- Handle each argument respectively.

E. Handling Conflict

We will:

- Use conflict as a source for growth and understanding.
- Listen to others point of view before trying to solve the dispute.
- Discuss the conflict outside of normal meeting times.
- Ask the other person if your understanding of their issue is correct.
- Acknowledge valid points from the other person.
- State our points of view in a calm and non-judgmental manner.
- Search for common ground.

Meeting Guidelines:

- Standing team meetings each week (Fall: 6pm-7pm Wednesdays and 11am-12pm Saturdays).
- Agendas will be finalized by 8pm the day before the meeting.
- Meetings will be led by the team facilitator.
- Meeting minutes will be issued by 8pm on the day of the meeting.
- Agenda & minutes completed by team Record Keeper (rotating team role).

Meeting Procedures:

- Meetings will begin and end on time.
- All meetings will have a purpose.
- Team members will come to meetings prepared with his/her individual assignments for that week completed.
- Agenda items for the next week will be discussed at the end of each meeting.
- Unresolved issues will be documented and addressed at the next meeting.
- All team members who are available must attend meetings.

- Any member must notify the team 24 hours in advance if he/she cannot attend an in person meeting, or 6 hours in advance of a virtual meeting.
- If a team member cannot attend a meeting, he/she must still have completed the assigned tasks/responsibilities by the time of the meeting.

________________________________ _______________

Signature Date

________________________________ _______________

Signature Date

________________________________ _______________

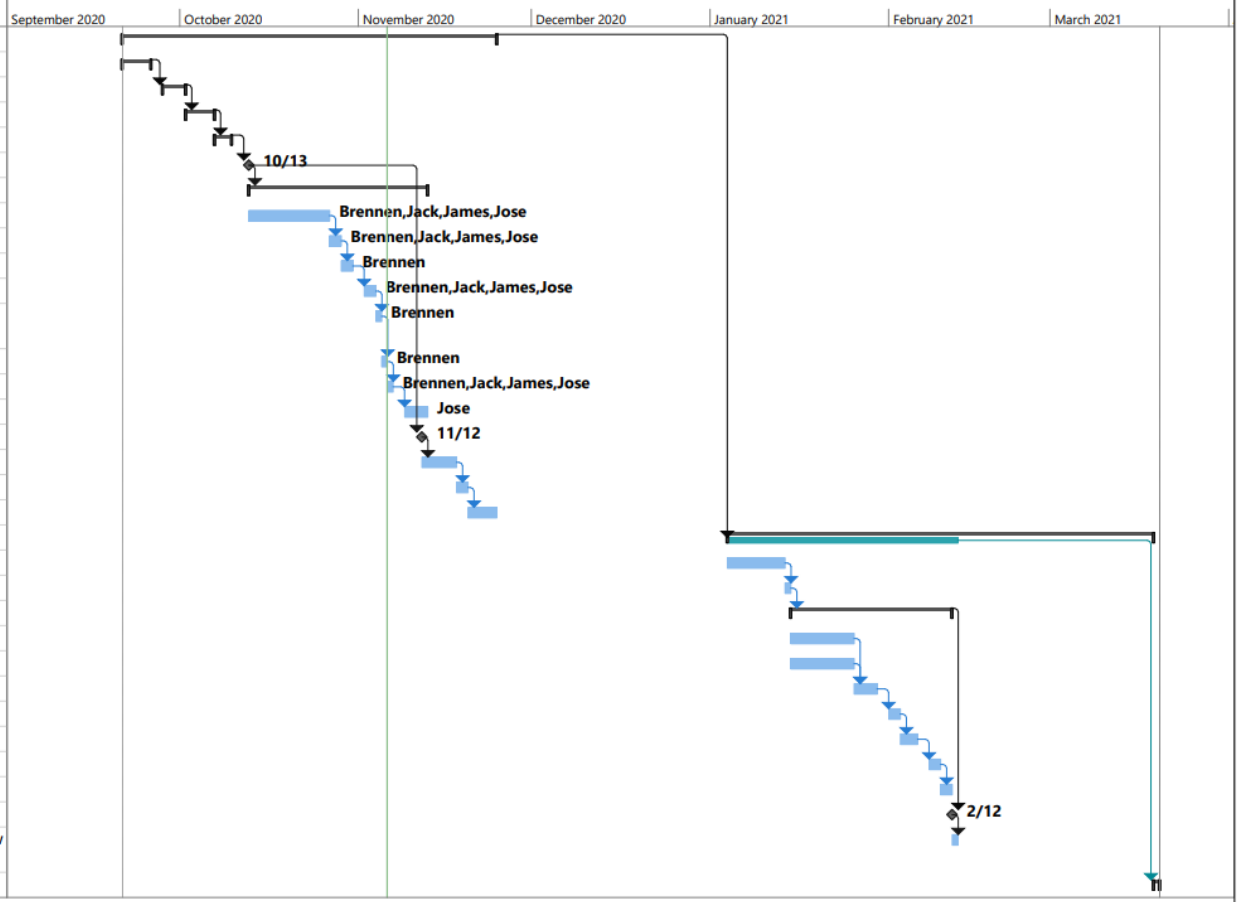
Signature Date

________________________________ _______________

Signature Date

Appendix DD Gantt Chart

ID	Task Mode	Task Name
1		**FALL QUARTER**
2		**Research**
6		**Problem Definition**
9		**QFD House of Quality**
13		**Project Scope**
22		Scope of Work
23		**Concept Design**
24		Ideation
25		Concept Selection
26		Concept CAD
27		Concpet Prototype
28		Write Concept Design Chapter
29		Compile Draft PDR
30		Peer Review
31		Final Draft
32		PDR
33		FMEA
34		DFMA
35		Winter Plan
36		**WINTER QUARTER**
37		Design Analysis
38		Interim Design Review
39		**Final Design**
40		Final CAD
41		Part Selection
42		Structural Prototype
43		Bill of Materials
44		Drawings and Diagrams
45		Prepare Presentation
46		Prepare Report
47		CDR
48		Manufacturing and Test Review
49		**SPRING QUARTER**



Project: F14 Gantt Chart
Date: Fri 11/6/20

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

Page 1

Appendix EE Drawing List and Part Drawings

11000 – Exploration Activity Assembly
- **11100** – 4 Hole Pillar Assembly
  - **11100-1** – Magnet
  - **11100-2** – Magnet mount
  - **11100-3** – 4 Hole U-channel
  - **11100-4** – Painted Screws
- **11200** – 9 Hole Pillar Assembly
  - **11100-1** – Magnet
  - **11100-2** – Magnet Mount
  - **11200-3** – 9 Hole Channel
  - **11100-4** – Painted Screws
- **11300** – Base Plate
  - **11300-1** – Steel Plate
  - **11300-2** – Rubber Feet
  - **11300-3** – Vinyl Sticker
- **11400** – Drive Train Components
  - **11410 –** 80T Gear Assembly
    - **11410-1** – 80T Gear
    - **11410-2** – Hub Mount
    - **11410-3** – Screws
  - **11420** – 72T Gear Assembly
    - **11420-1** – 72T Gear
    - **11410-2** – Hub Mount
    - **11100-4** – Screws
  - **11430 –** 64T Gear Assembly
    - **11430-1 –** 64T Gear
    - **11310-2** – Hub Mount
    - **11100-4** – Painted Screws
  - **11440 –** Crank Arm Assembly
    - **11410-2 –** Hub Mount
    - **11440-2 –** Crank Arm
    - **11100-4 –** Painted Screws
  - **11450 –** Assorted Parts
    - **11450-1 –** 4 in Shaft
    - **11450-2 –** 3 in Shaft

- **11450-3 –** 7 in Shaft
- **11450-4 –** 10 in Shaft
- **11450-5 –** Shaft collar
- **11450-6 –** Pillow Blocks
- **11450-7 –** Bearings
- **11450-8 –** Angle Brackets
- **11410-3 –** Screws
- **11450-10 –** Wing Nuts
- **11450-11 –** 32T Pinion
- **11450-12 –** 24T Pinion
- **11450-13–** 16T Pinion

11500 – Motor Input Assembly

- **11500-1 –** Shaft Coupler
- **11500-2 –** 124 RPM Motor
- **11500-3 –** Motor Board
- **11500-4 –** Switch
- **11500-5 –** Motor Mount
- **11500-6** – Painted Short Screws
- **11500-7 –** Header Pins
- **11500-8 –** Male Banana Pair
- **11500-9 –** Shrink Wrap Sleeves
- **11500-10 –** RCY Lead

11600 – Motor Output

- **11600-1 –** Generator
- **11500-5 –** Motor Mount
- **11600-3 –** Custom Motor Board
- **11500-6 –** Painted Short Screws
- **11600-5 –** Electric Current Adapter

11700 Measurement

- **11700-1 –** Tachometer
- **11700-2 –** Multimeter

11800 Inventory

- **11800-1 –** Accordian Tacklebox

11900 Tools

- **11900-1 –** Large Hex Key
- **11900-2 –** Main Hex Key
- **11900-3 –** Small Hex Key

111000 Advanced Components

- **111000-1 –** Bevel Gear Set
- **111000-2 –** Worm Gear Set
- **111000-3 –** 32T Sprocket
- **111000-4 –** 16T Sprocket
- **111000-5 –** Chain

111100 Spare Components

- **11500-1 –** Shaft Coupler
- **111100-2 –** 5/16 to 1/4 Shaft Coupler

12000 – Wind Turbine Assembly

12100 – Housing

- **12100-1** – 3x4 Hole Pattern Plate
- **12100-2** – 3x8 Hole Pattern Plate
- **11450-8** – Angle Brackets
- **12100-4** – Hinge
- **12100-5** – 90 Degree Pattern
- **11410-3** – Screws
- **12100-7** – Lock Nuts
- **12100-8** – Acrylic

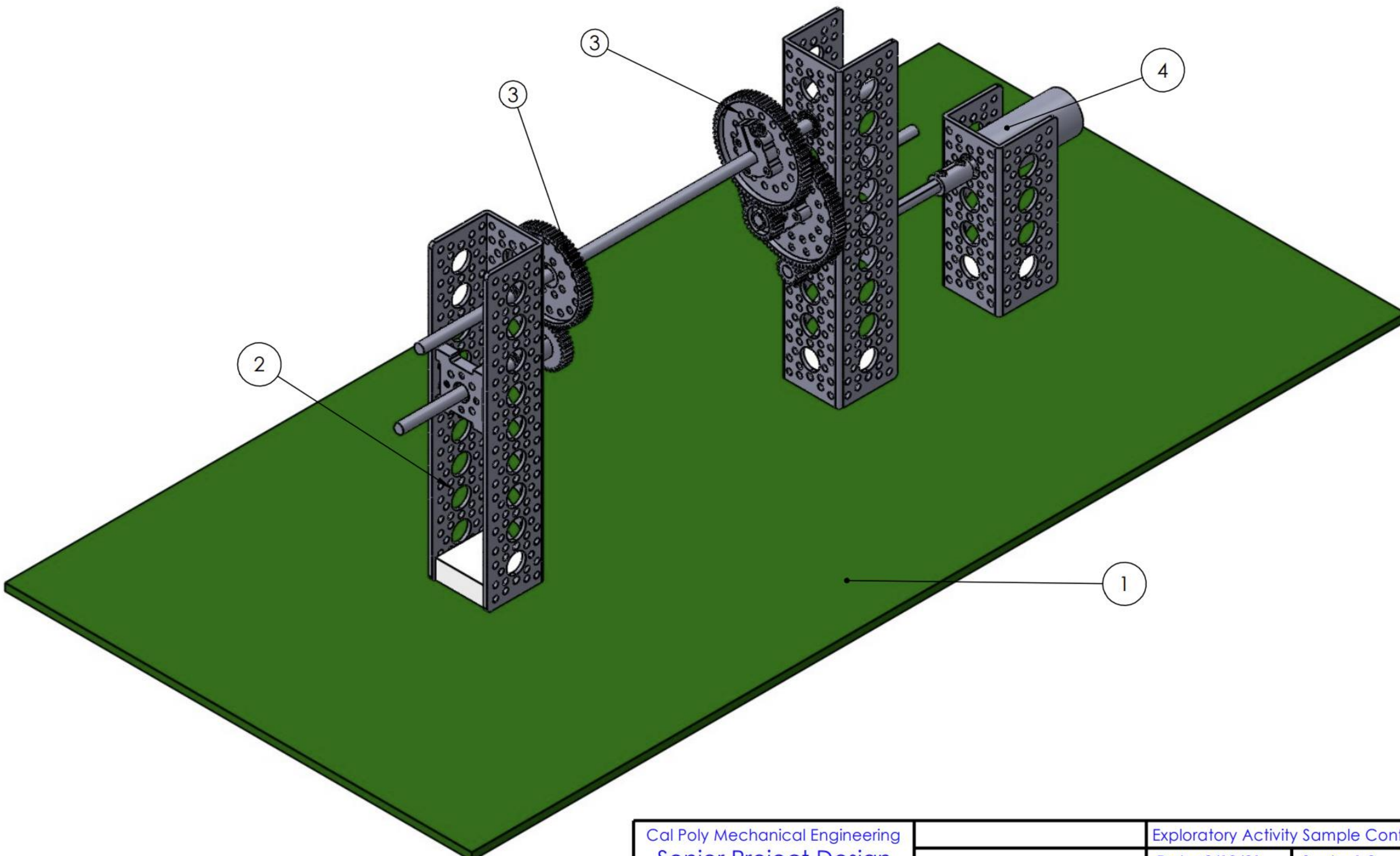
12200 – Input

- **12200-1** – Fan
- **12200-2**– Blades
- **12200-3** – 2" 5/16 Round shaft
- **111100-2** – 5/16 to 1/4 Shaft coupler
- **12200-5** – Anemometer

12300 – Output

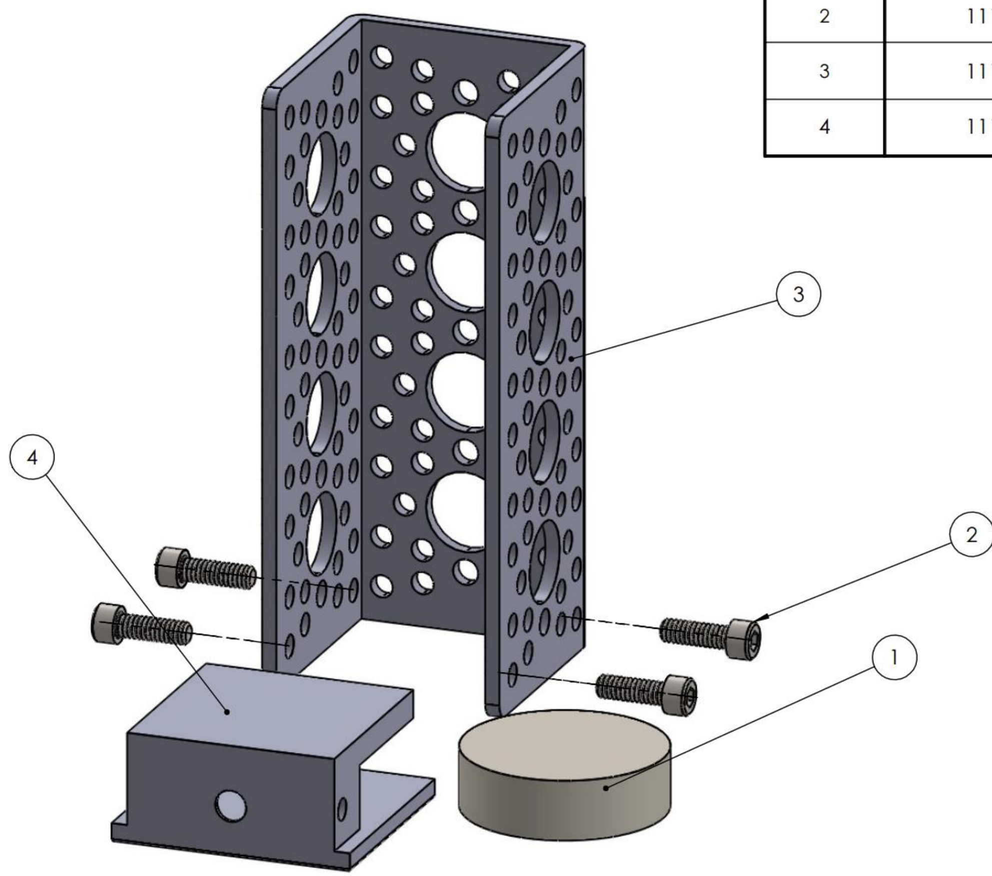
- **11600-1** – Generator
- **11500-6** – Painted Short Screws
- **11500-5** – Motor Mount
- **11500-3** – Motor Board
- **11500-1** – Shaft Coupler
- **11500-10** – RCY Lead

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	11300	Base Plate Assembly	1
2	11200	9 Hole Pillar Assembly	2
3	11400	Drive Train Components	1
4	11500	Motor Input	1



Cal Poly Mechanical Engineering Senior Project Design		Exploratory Activity Sample Configuration	Drwn. By: Jack Cerron
		Date: 2/19/21 | Scale: 1:2	Drwn. Number: 11000

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	11100-1	Magnet	1
2	11100-4	6-32 x 0.375" Head Screw	4
3	11100-3	4 Hole U-Channel	1
4	11100-2	Magnet Mount	1



Cal Poly Mechanical Engineering		4 Hole U-Channel Assembly	Drwn. By: Jack Cerron
Senior Project Design		Date: 2/19/21 Scale: 2:1	Drwn. Number: 11100

Part Number: 11100-1

DX46 Specification Sheet

Product Specifications

Type: DISC

Dimensions: 1.25 dia x 0.375 thk (in)

Tolerance: All dimensions ± 0.004 in

Material: NdFeB, Grade N42

Plating: NiCuNi

Max Op Temp: 176ºF (80ºC)

Br max: 13,200 Gauss

BH max: 42 MGOe

Performance Specifications

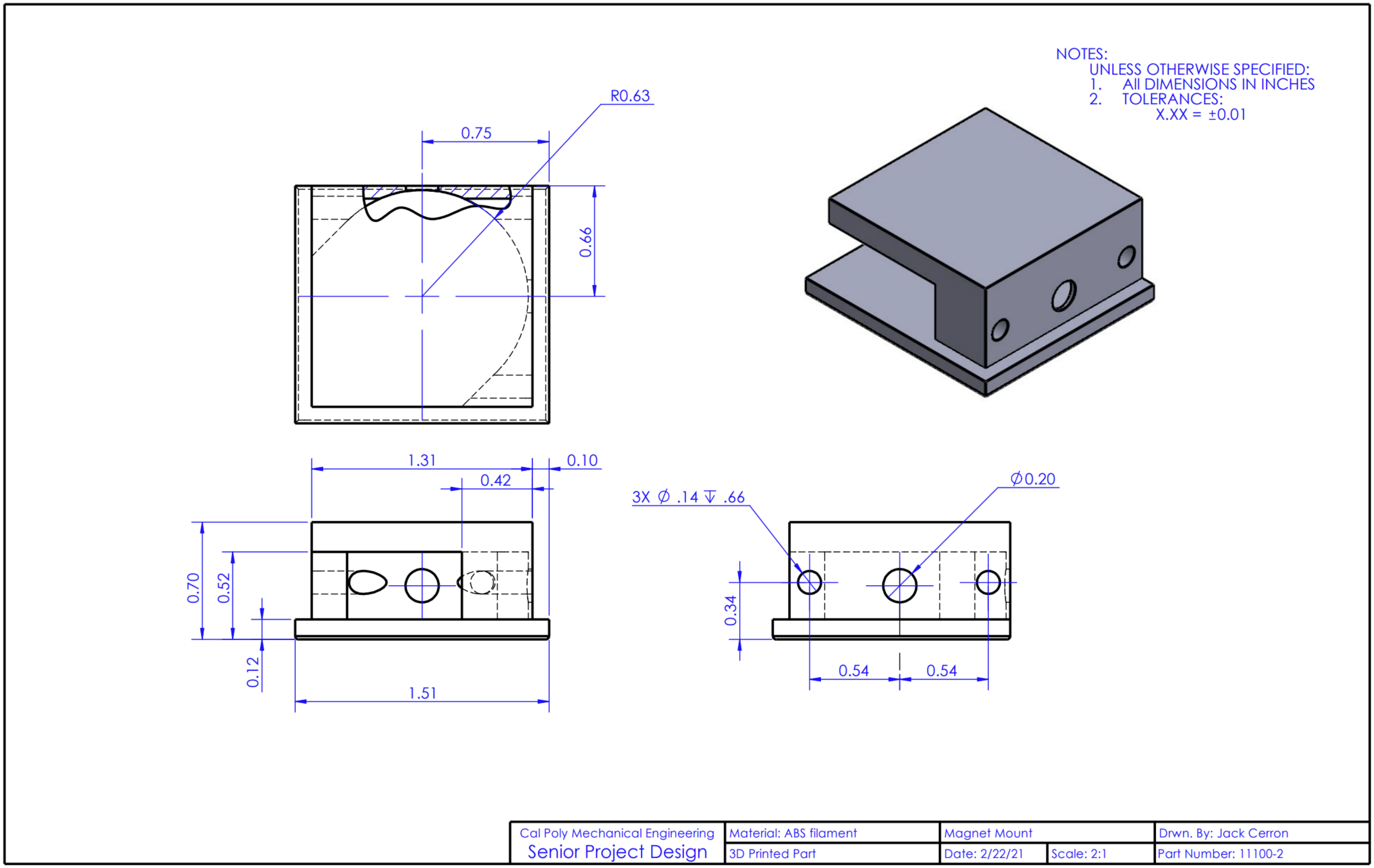
Pull Force, Case 1,

Magnet to a Steel Plate: 48.26 lb

Surface Field values are derived from calculation and verification with experimental testing. These values are the field values at the surface of the magnet, centered on the axis of magnetization. Measurement of the B field with a magnetometer may yield varying results, depending on the geometry of your sensor. Pull Force values are based on extensive product testing in our laboratory. Different configurations of magnets and surrounding ferromagnetic materials may substantially alter your results.

K&J Magnetics, Inc. - www.kjmagnetics.com - 215-766-8055

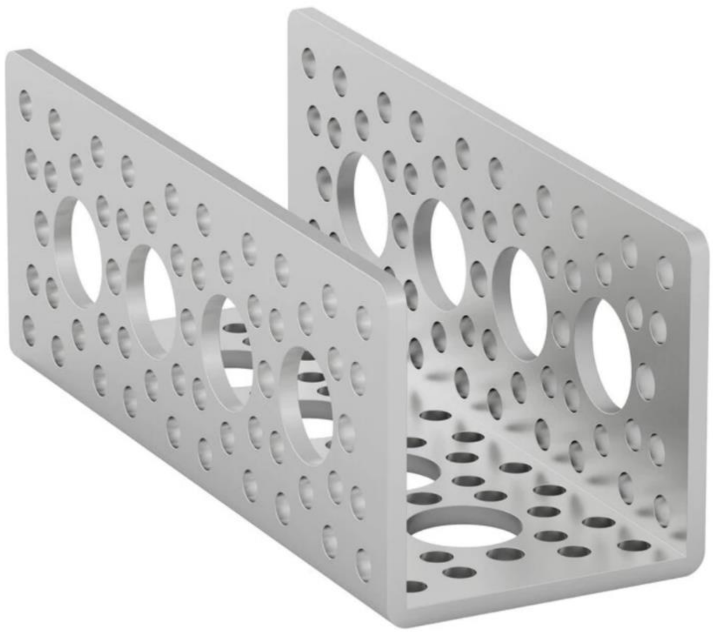
Printed: 02/20/2021


NOTES:
UNLESS OTHERWISE SPECIFIED:
1. All DIMENSIONS IN INCHES
2. TOLERANCES:
X.XX = ±0.01
R0.63
0.75
0.66
1.31
0.10
0.42
0.70
0.52
0.12
1.51
3X ⌀ .14 ↧ .66
⌀0.20
0.34
0.54
0.54
Cal Poly Mechanical Engineering
Senior Project Design
Material: ABS filament
3D Printed Part
Magnet Mount
Date: 2/22/21
Scale: 2:1
Drwn. By: Jack Cerron
Part Number: 11100-2

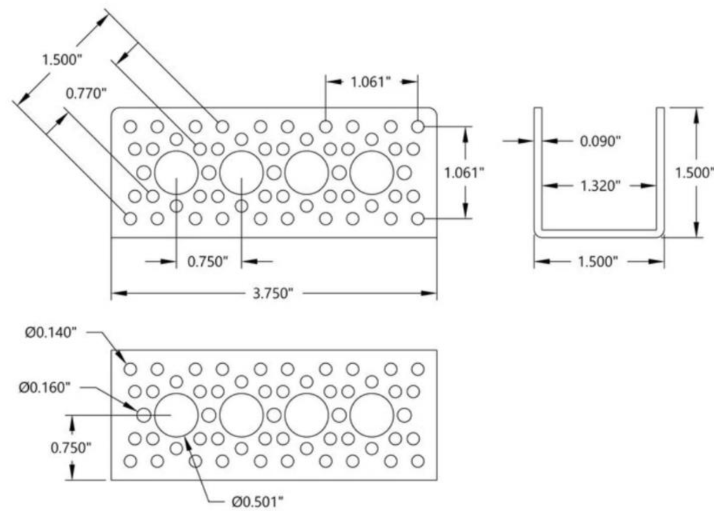
Part Number: 11100-3

U-Channel (4 Hole, 3.75" Length)

SKU: 585443



Patented



Patented

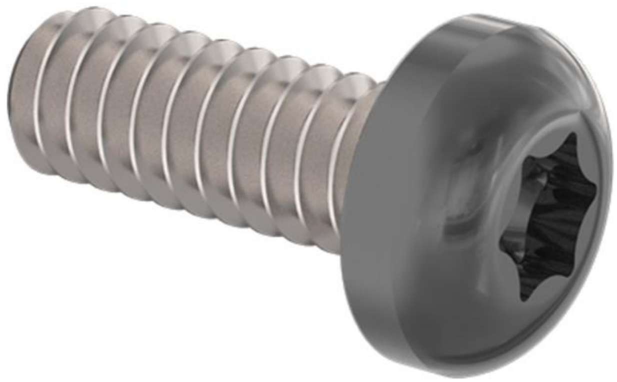
SPECS

Material	Aluminum
Weight	1.56 oz (44g)
Finish	Clear Anodized
IP	Patented

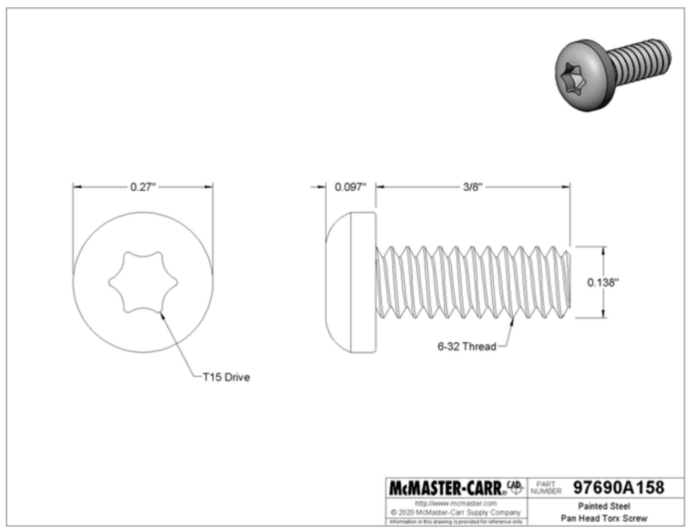
Part Number: 11100-4

McMASTER-CARR.

Painted Steel Pan Head Torx Screw
with Black Head, 6-32 Thread Size, 3/8" Long



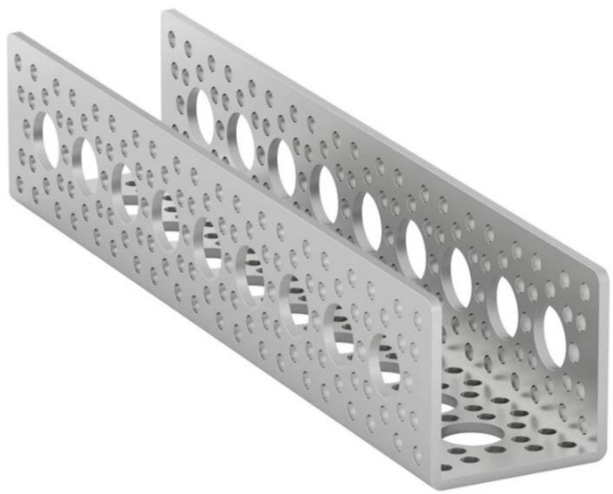
Thread Size	6-32
Length	3/8"
Threading	Fully Threaded
Head Diameter	0.27"
Head Height	0.097"
Drive Style	Torx
Drive Size	T15
Material	Zinc-Plated Steel
Hardness	Rockwell B70
Tensile Strength	Not Rated
Screw Size Decimal Equivalent	0.138"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 2A

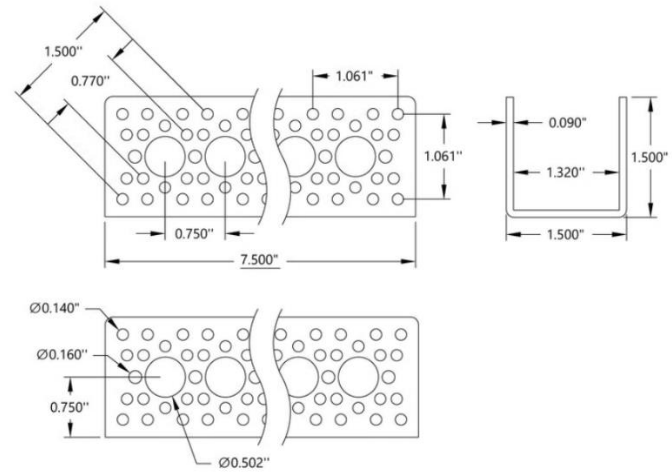


Part Number: 11200-3

U-Channel (9 Hole, 7.50" Length)

SKU: 585448





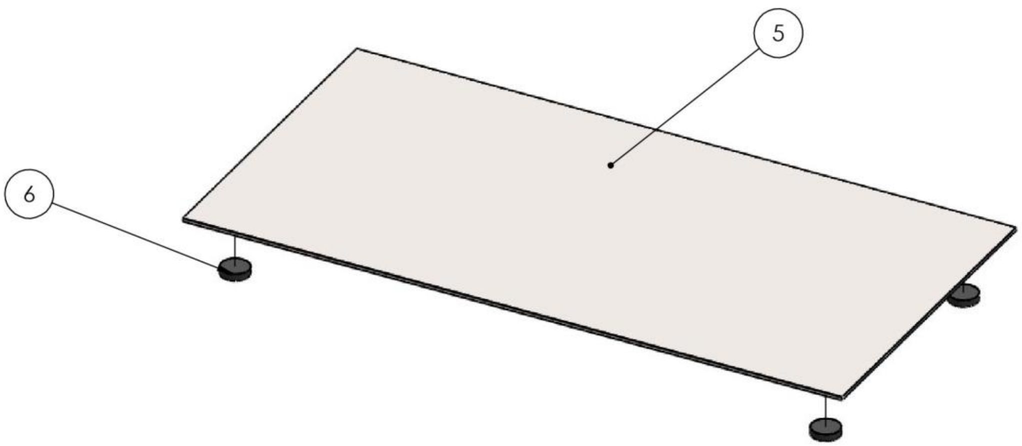
Patented

Patented

SPECS

Material	Aluminum
Weight	3.03 oz (86g)
Finish	Clear Anodized
IP	Patented

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
5	11300-1	Steel Plate	1
6	11300-2	Rubber Feet	4

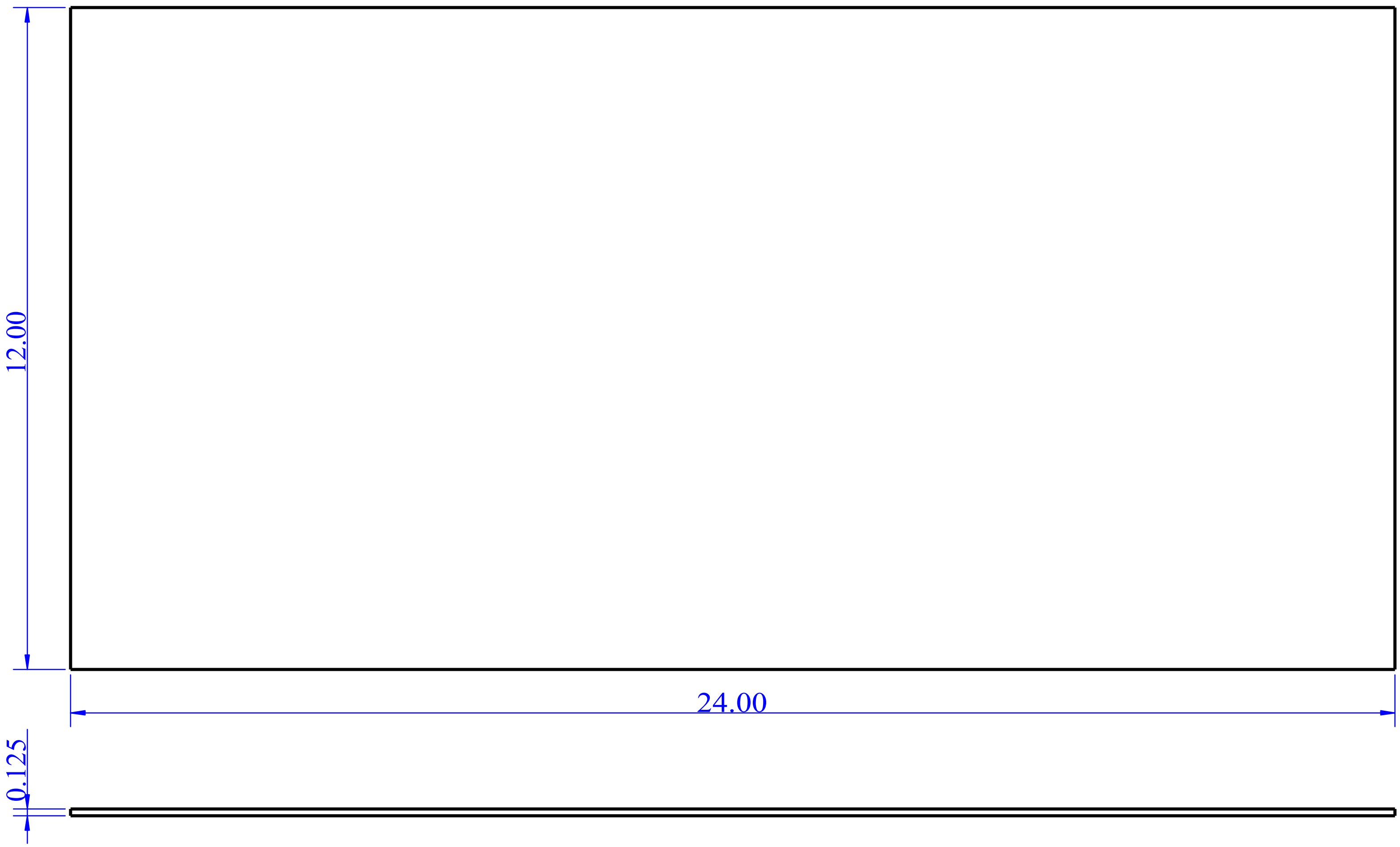


Cal Poly Mechanical Engineering		Base Plate Assembly	Drwn. By: Jack Cerron
Senior Project Design		Date: 2/20/21 | Scale: 1:4	Drwn. Number: 11300

NOTES:

UNLESS OTHERWISE SPECIFIED:

1. All DIMENSIONS IN INCHES
2. TOLERANCES:
   X.XX = + 0.1
3. BREAK SHARP EDGES
4. SPRAY WITH RUST PREVENTATIVE PAINT
5. COVER WITH LAYER OF VINYL



Cal Poly Mechanical Engineering	Material: Mild Steel Sheet A366/1008 C.R.	Base Plate		Drwn. By: Jack Cerron
Senior Project Design	OnlineMetals.com Part #13973	Date: 2/20/21	Scale: 1:2	Part Number: 11300-1

Part Number: 11300-2

The Home Depot – 1-1/2 in. Self-Adhesive Anti-Skid Surface Pads (8-Pack)

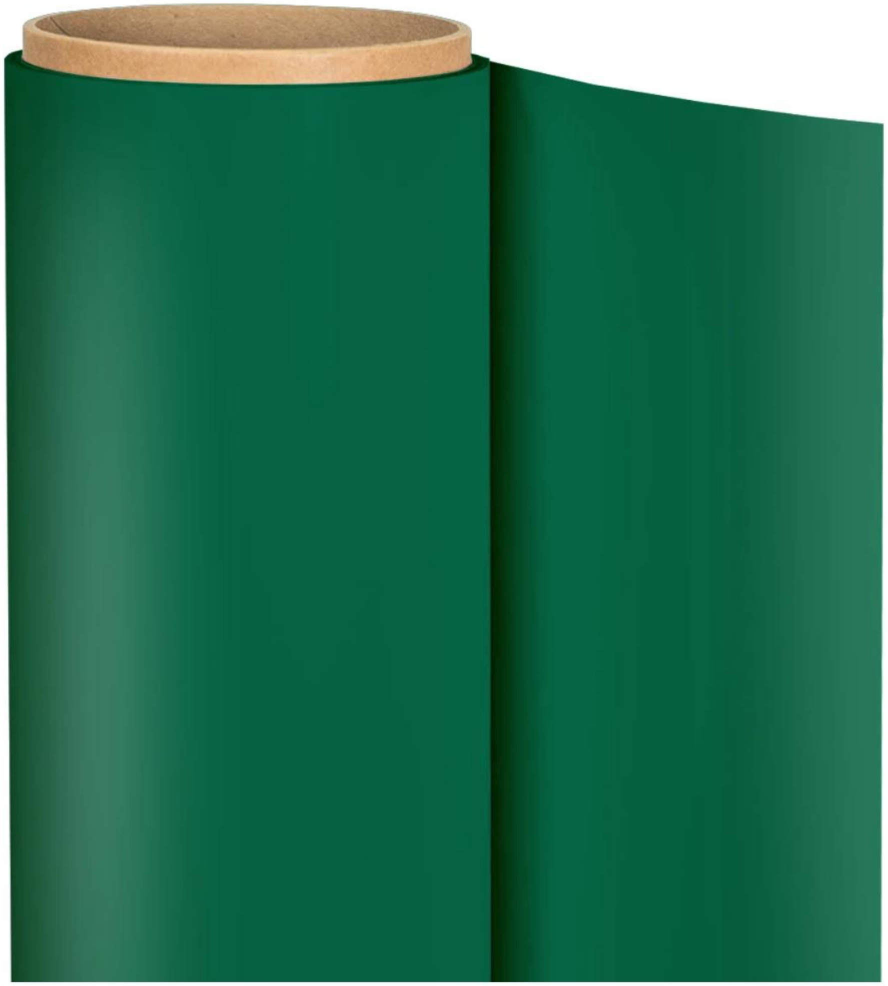
Product Overview

Stop furniture legs from moving and damaging your flooring with the Shepherd 1-1/2 in. Anti-Skid Pads (8 per Pack). These pads stop legs from inadvertent movement. It is made from durable rubber.

- Anti-skid products protect hard surfaces and floors while holding furniture and other items in place for sound and vibration-dampening benefits
- Self-adhesive soft foam pads can be applied to the underside of appliances, office equipment or furniture
- Easy to install - Simply clean, peel, and stick
- Surface preparation is key - Surfaces should be free of dirt & debris and sanded if wooden for maximum performance
- 1-1/2 in. black textured round and thinner 2mm thick anti-skid pads - 8 Pack

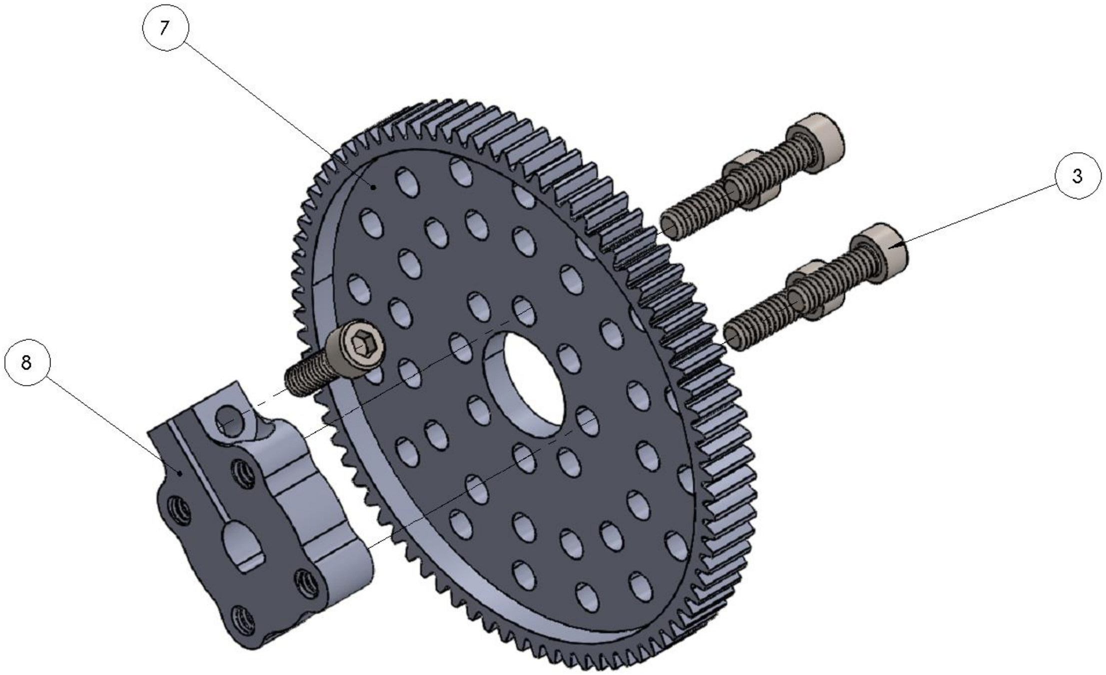
Part Number: 11300-3

Mustang 60 – Vinyl Sticker



15” X 48” minimum

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
7	11410-1	80 Tooth Hub Gear	1
8	11410-2	Hub Mount Assembly	1
3	11410-3	6-32 x 0.375" Head Screw	4

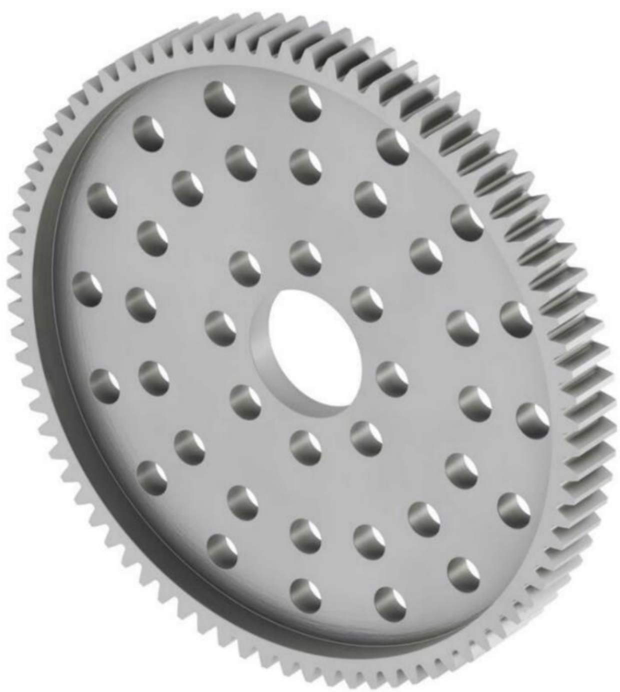


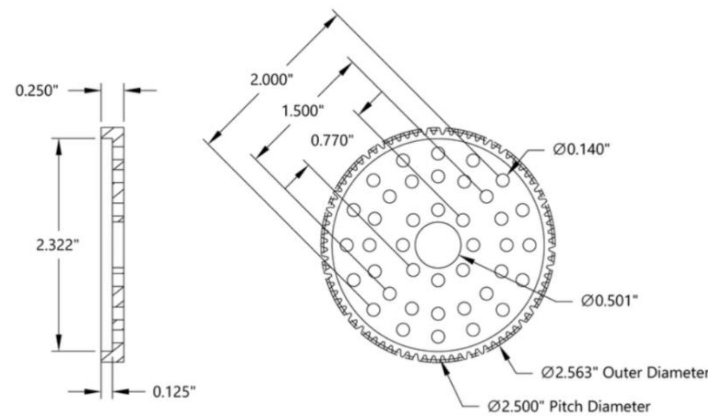
Cal Poly Mechanical Engineering		80 Tooth Gear Assembly		Drwn. By: Jack Cerron
Senior Project Design		Date: 2/21/21	Scale: 2:1	Drwn. Number: 11410

Part Number: 11410-1

32 Pitch, 80 Tooth (.50" Bore) Aluminum Hub Gear

SKU: 615206





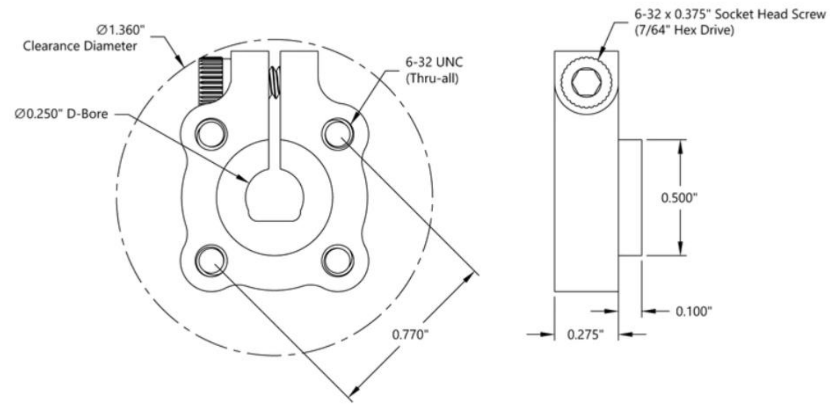
SPECS

# of teeth	80T
Weight	0.92 oz (26g)
Material	Aluminum
Finish	Clear Anodized

Part Number: 11410-2

0.250" Bore Clamping D-Hub (Tapped), 0.770" Pattern

SKU: 545619



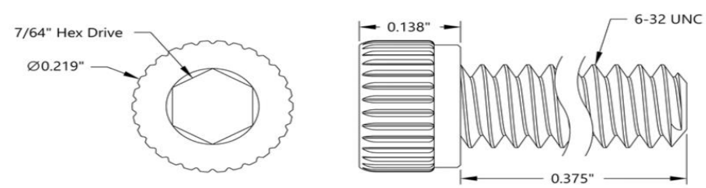
SPECS

Bore	0.250"
Material	Aluminum
Finish	Clear Anodized
Weight	0.30 oz (8.6g)

Part Number: 11410-3

6-32 x 0.375" (3/8) Zinc-Plated Socket Head Machine Screw

SKU: 632110



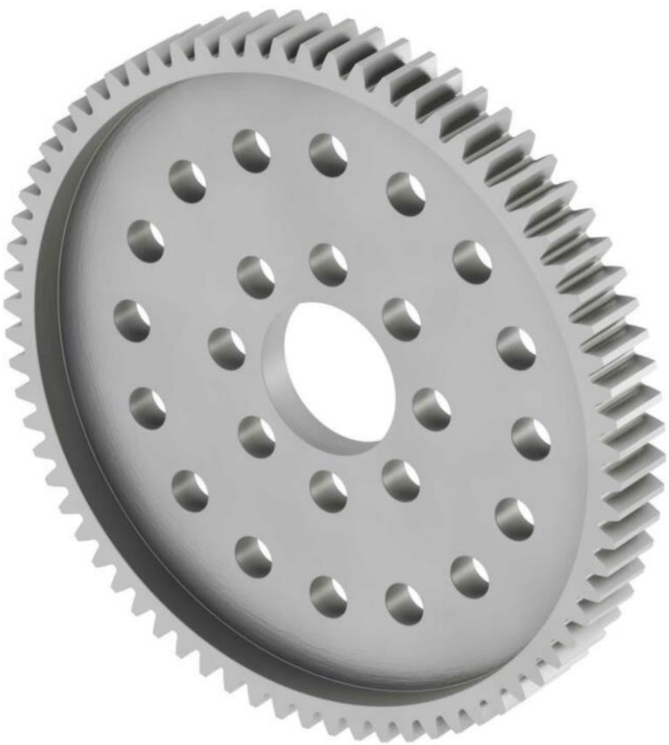
SPECS

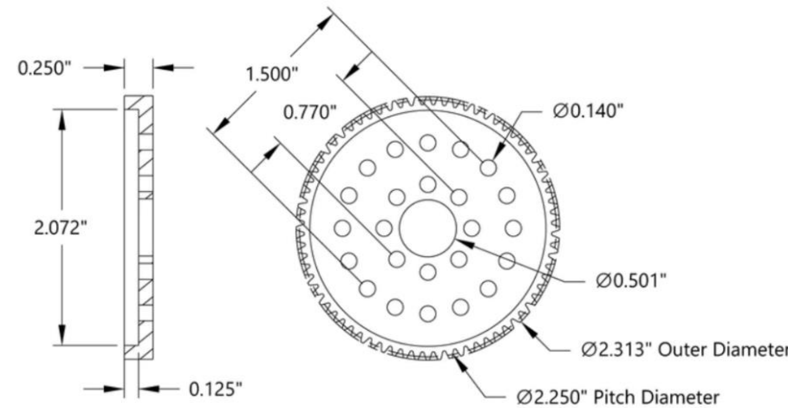
Length	0.375" (3/8)
Material	Alloy Steel
Head Style	Socket
Thread Type	Full Thread
Finish	Zinc-Plated
Thread Size	6-32
Drive Style	7/64" Hex Key

Part Number: 11420-1

32 Pitch, 72 Tooth (.50" Bore) Aluminum Hub Gear

SKU: 615198





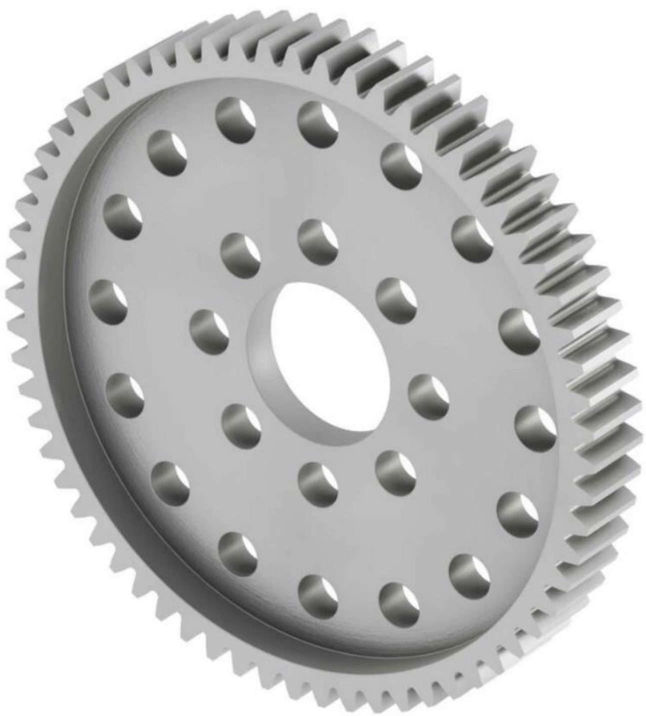
SPECS

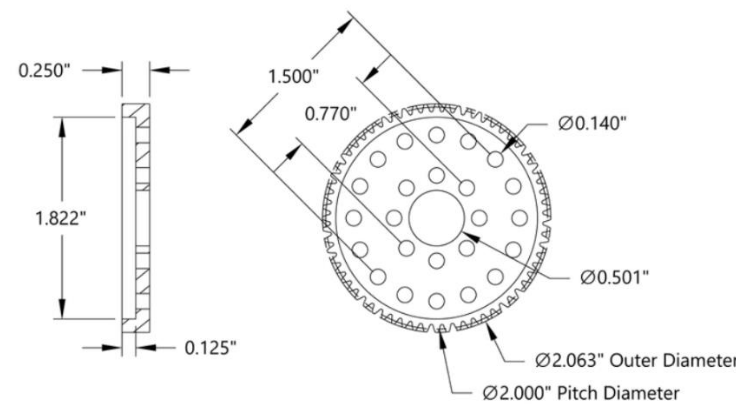
# of teeth	72T
Weight	0.78 oz (22g)
Material	Aluminum
Finish	Clear Anodized

Part Number: 11430-1

32 Pitch, 64 Tooth (.50" Bore) Aluminum Hub Gear

SKU: 615194

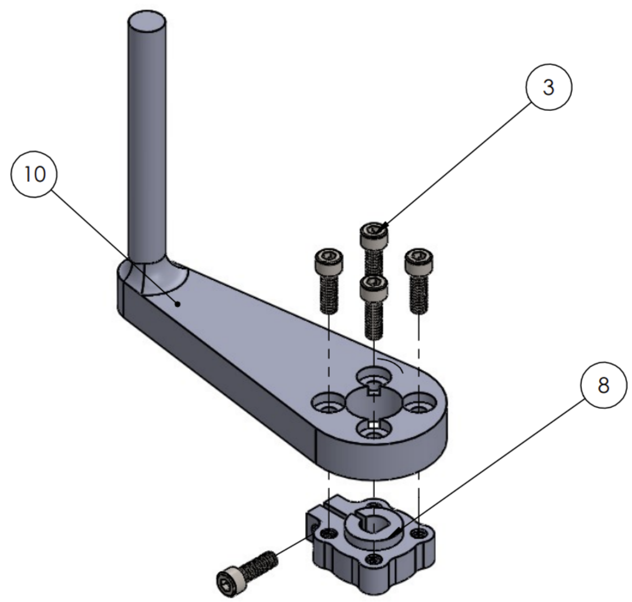




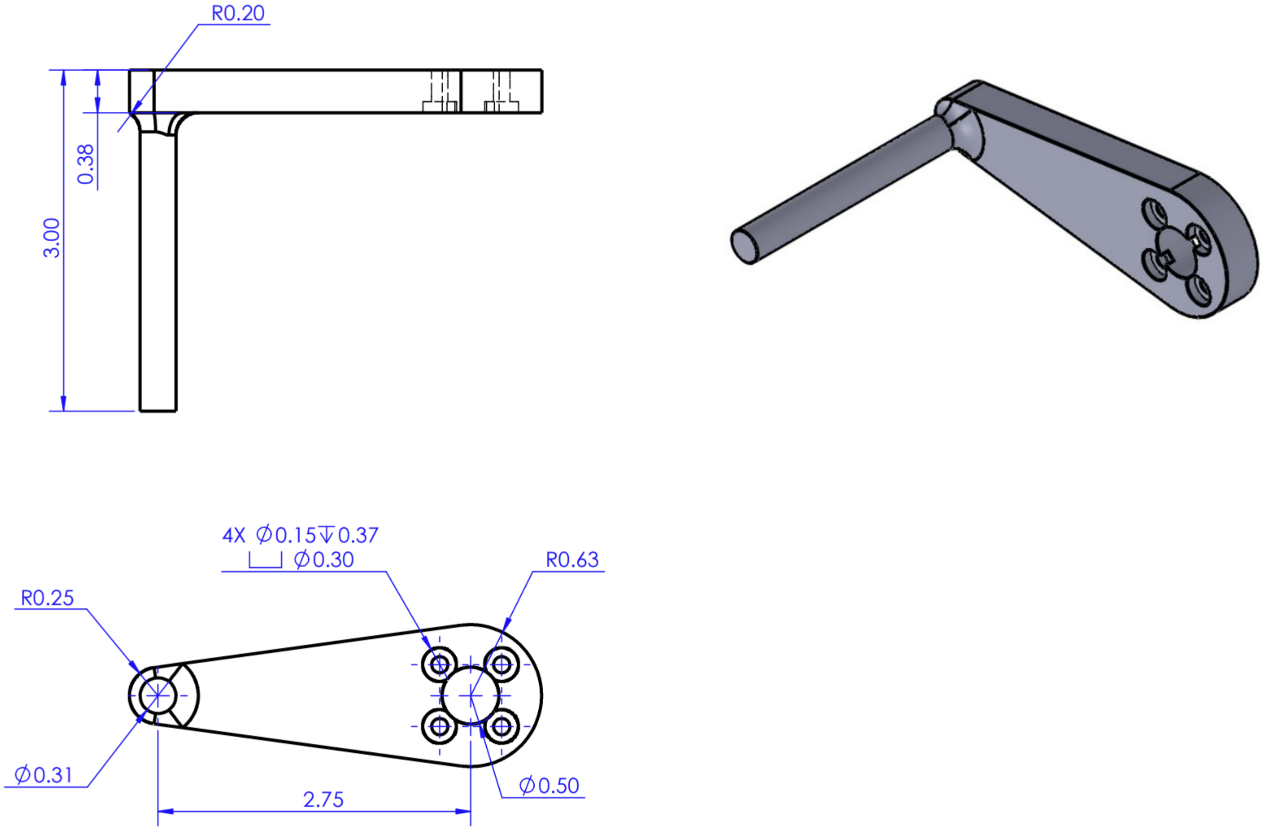
SPECS

# of teeth	64T
Weight	.60 oz (17g)
Material	Aluminum
Finish	Clear Anodized

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
10	11440-2	Crank Arm	1
8	11410-2	Hub Mount	1
3	11140-4	Painted Screws	4



Cal Poly Mechanical Engineering		Hand Crank Assembly		Drwn. By: Jack Cerron
Senior Project Design		Date: 2/22/21	Scale: 1:1	Drwn. Number: 11440

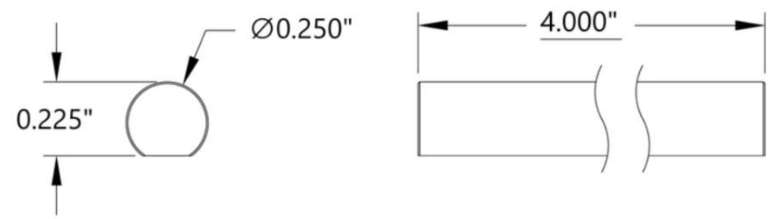


Cal Poly Mechanical Engineering	Material: ABS Filament	Crank Arm		Drwn. By: Jack Cerron
Senior Project Design	3D Printed Part	Date: 2/22/21	Scale: 1:1	Part Number: 11440-2

Part Number: 11450-1

0.250" (1/4") x 4.00" Stainless Steel D-Shafting

SKU: 634080



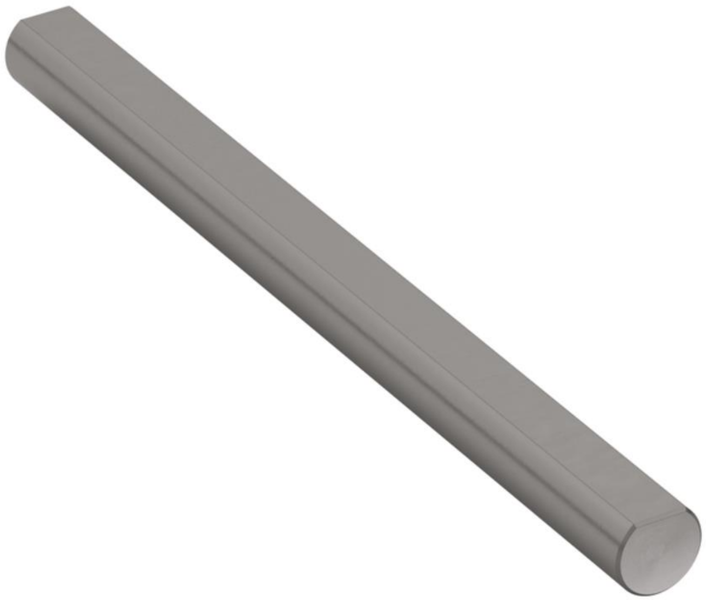
SPECS

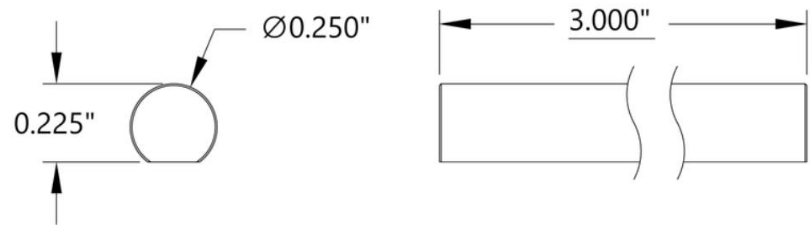
Length	4.00"
Material	Stainless Steel
OD	0.250" (1/4")
Finish	10 RMS Micron rated finish
Weight	0.84 oz (24g)

Part Number: 11450-2

0.250" (1/4") x 3.00" Stainless Steel D-Shafting

SKU: 634078





These 0.250" (1/4") diameter D-shafts are made from stainless steel for superior strength and precision. Rockwell hardness is 83B with a 10 RMS micron rated finish.

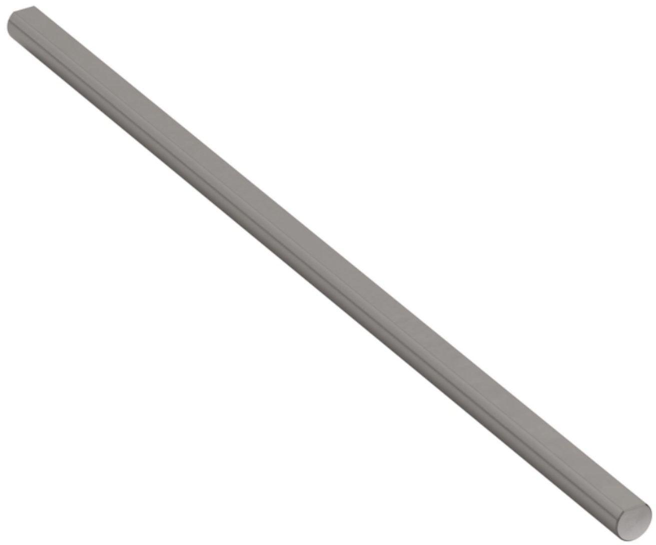
SPECS

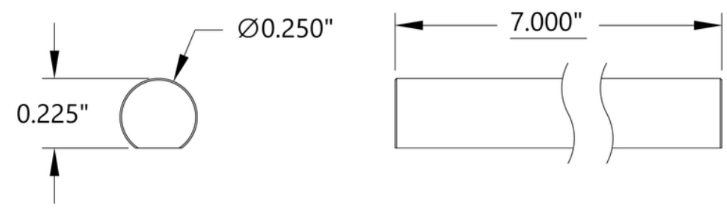
Length	3.00"
Material	Stainless Steel
OD	0.250" (1/4")
Finish	10 RMS Micron rated finish
Weight	0.63 oz (18g)

Part Number: 11450-3

0.250" (1/4") x 7.00" Stainless Steel D-Shafting

SKU: 634086





These 0.250" (1/4”) diameter D-shafts are made from stainless steel for superior strength and precision. Rockwell hardness is 83B with a 10 RMS micron rated finish.

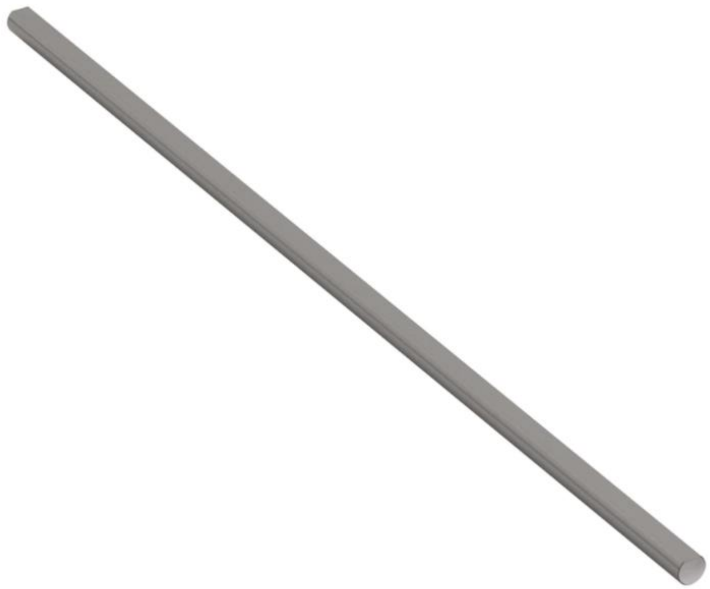
SPECS

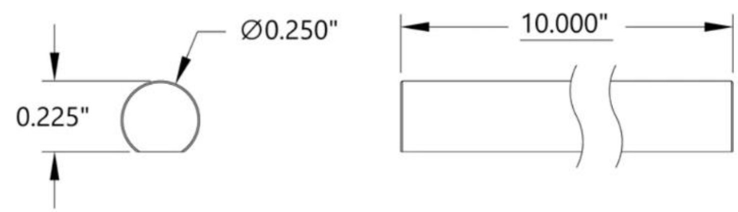
Length	7.00"
Material	Stainless Steel
OD	0.250" (1/4")
Finish	10 RMS Micron rated finish
Weight	1.47 oz (42g)

Part Number: 11450-4

0.250" (1/4") x 10.00" Stainless Steel D-Shafting

SKU: 634092





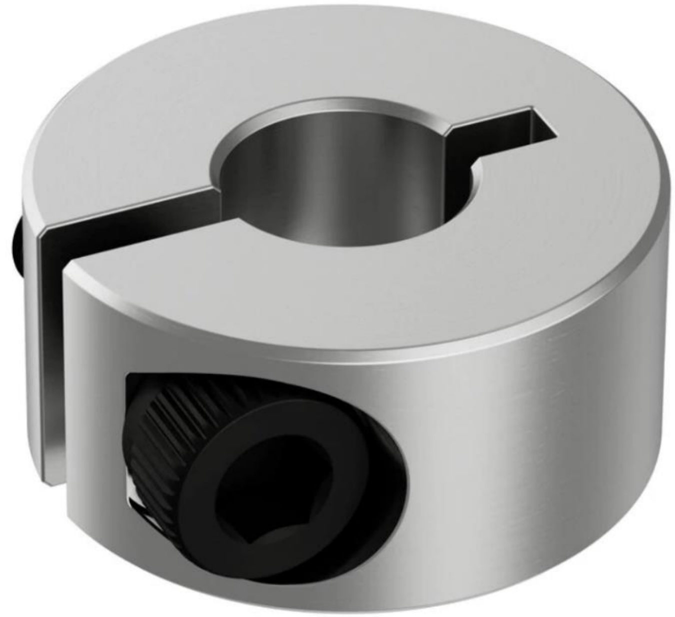
SPECS

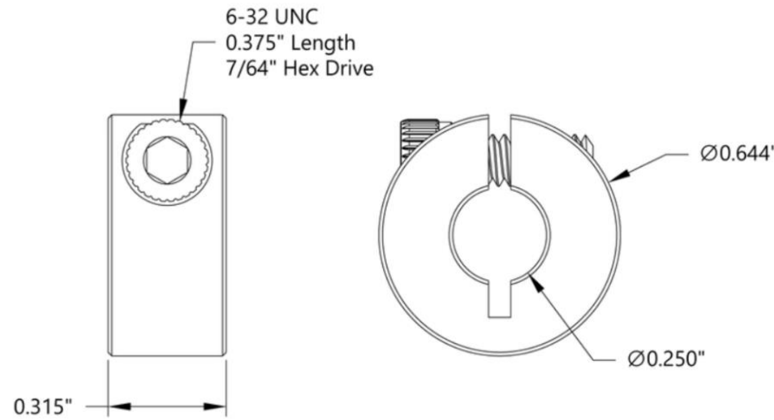
Length	10.00"
Material	Stainless Steel
OD	0.250" (1/4")
Finish	10 RMS Micron rated finish
Weight	2.10 oz (59g)

Part Number: 11450-5

0.250" (1/4) Aluminum Clamp Collar

SKU: 625296





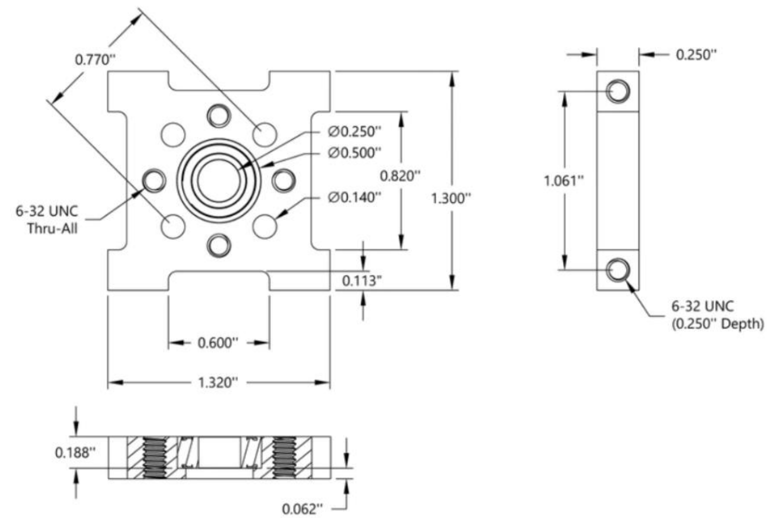
SPECS

Width	0.315"
ID	0.250"
OD	0.644"
Material	Aluminum
Shaft Mount Style	Clamp
Finish	Clear Anodized
Weight	0.15 oz (4.2g)

Part Number: 11450-6

1/4" Bore Side Tapped Pillow Block

SKU: 535130



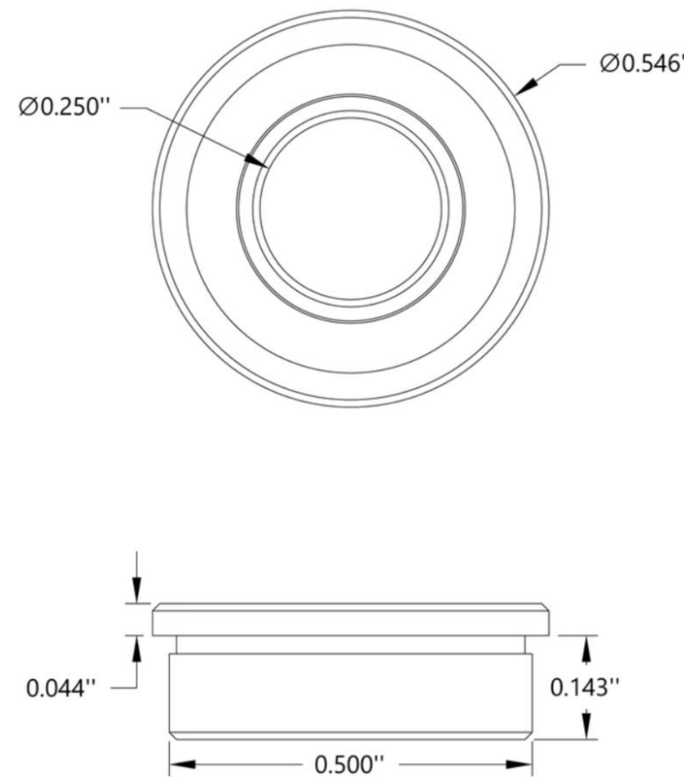
SPECS

Material	Aluminum
Weight	0.46 oz (13g)
Static Load	84 lbs
Max RPM	50,000
Bearing ID	.250"
Dynamic Load	186 lbs

Part Number: 11450-7

1/4" ID x 1/2" OD Flanged Ball Bearing (2 pack)

SKU: 535198



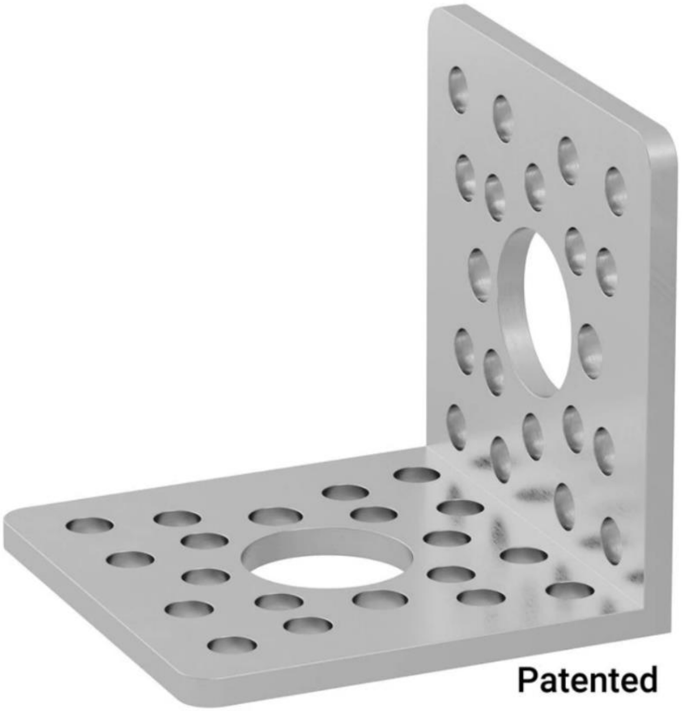
SPECS

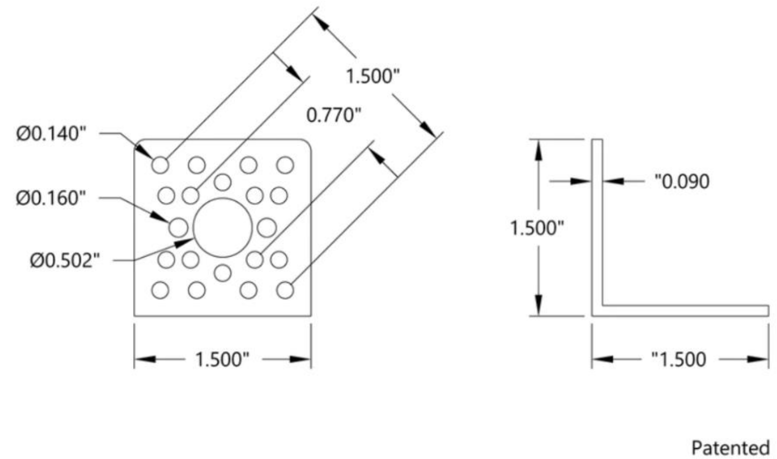
Weight	0.08 oz (2.2g)

Part Number: 11450-8

90° Single Angle Pattern Bracket

SKU: 585424





SPECS

Length	1.50"
Material	Aluminum
Weight	0.47 oz (13g)
IP	Patented

Part Number: 11450-10

6-32 Zinc-Plated Wing Nut - 6 Pack

SKU: 632164

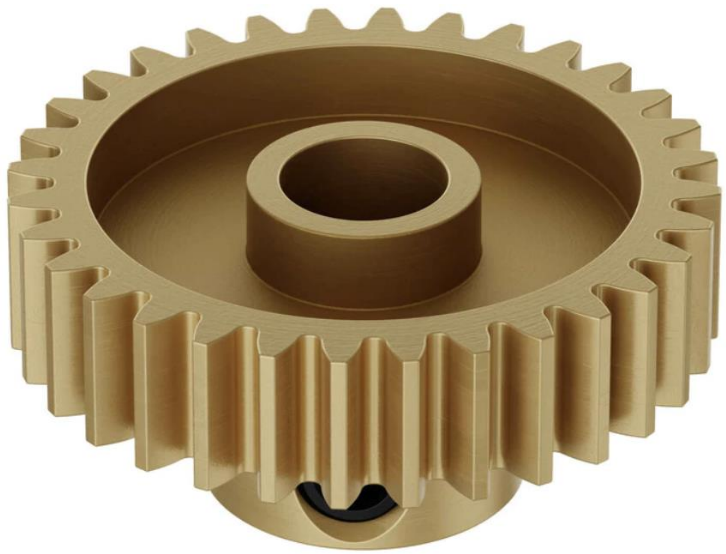
SPECS

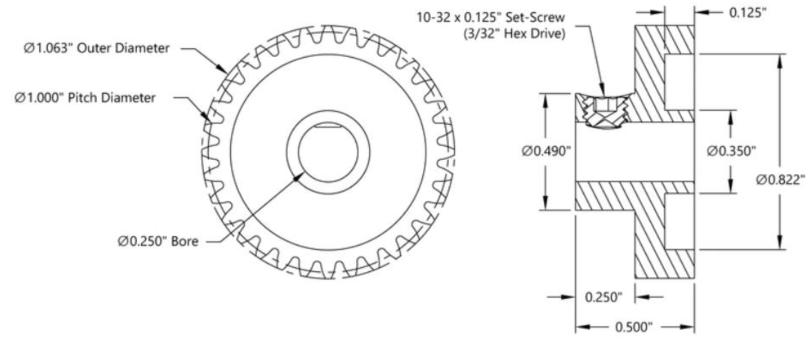
Thread Size	6-32
Material	Steel
Finish	Zinc-Plated
Type	Wing

Part Number: 11450-11

32T, 0.250" (1/4) Bore 32P Shaft Mount Pinion Gear

SKU: 615254





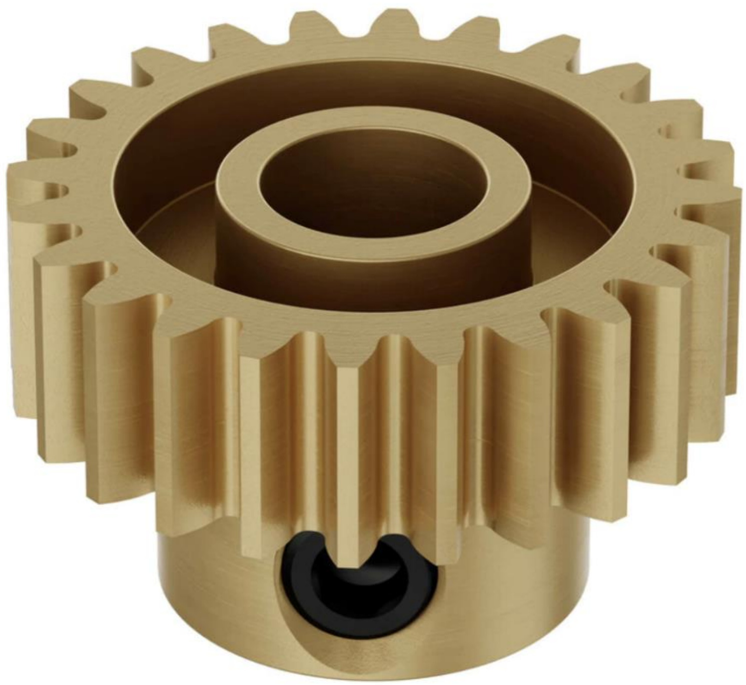
SPECS

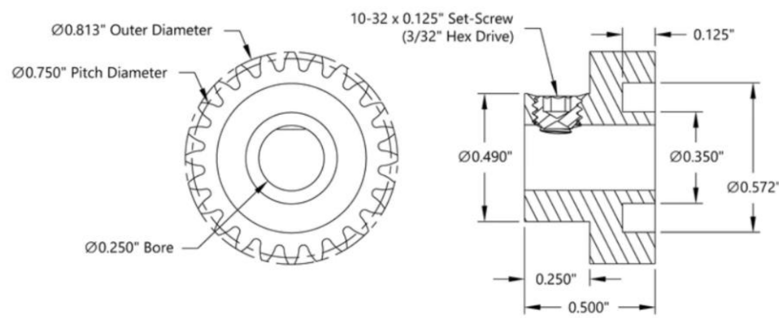
# of teeth	32T
Weight	0.79 oz (23g)
Material	Hardened Brass
Pressure Angle	20°

Part Number: 11450-12

24T, 0.250" (1/4) Bore 32P Shaft Mount Pinion Gear

SKU: 615250





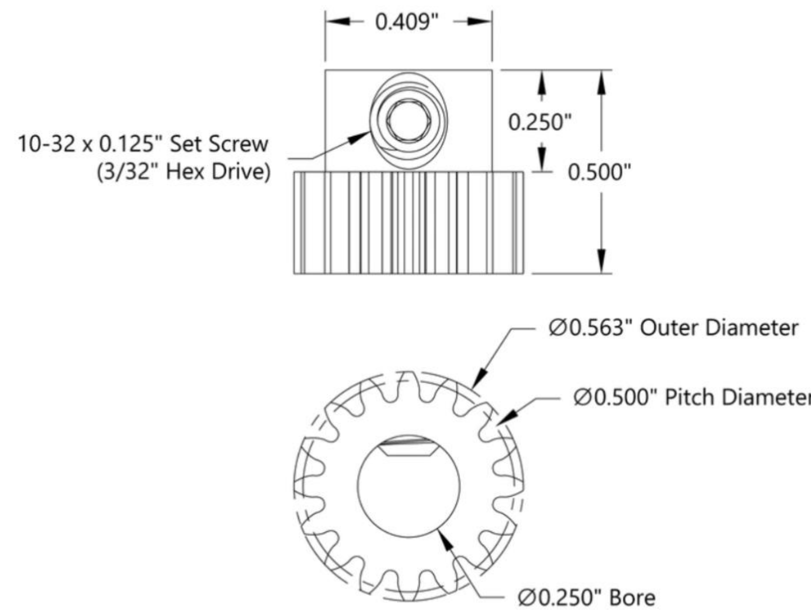
SPECS

# of teeth	24T
Weight	0.54 oz (15g)
Material	Hardened Brass
Pressure Angle	20°

Part Number: 11450-13

16T, 0.250" (1/4) Bore 32P Shaft Mount Pinion Gear

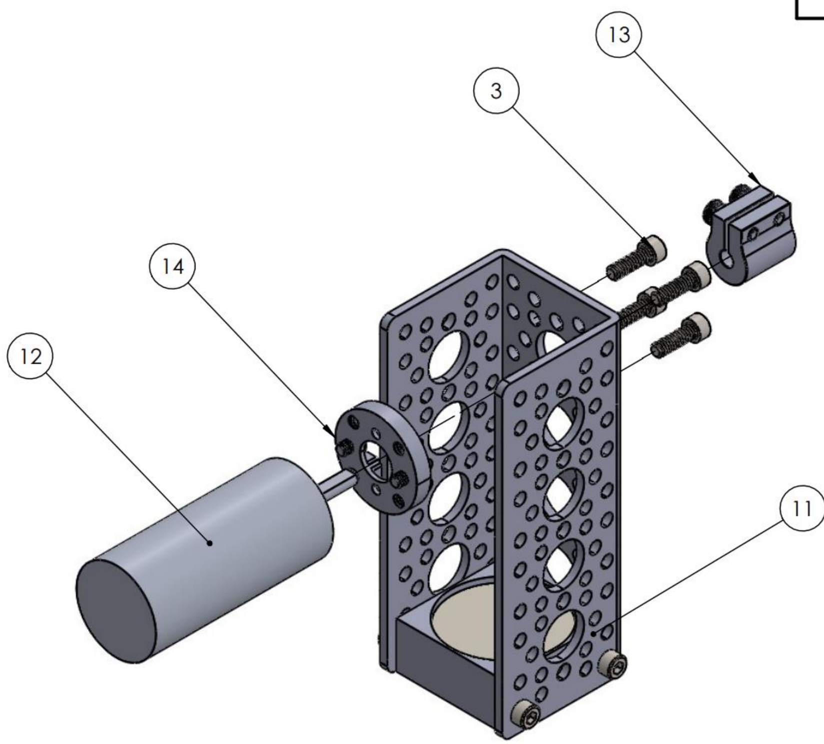
SKU: 615242



SPECS

# of teeth	16T
Weight	0.28 oz (8g)
Material	Hardened Brass
Pressure Angle	20°

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
3	11500-6	Painted Short Screws	4
11	11100	4 Hole Pillar Assembly	1
12	11500-3	124 RPM Motor	1
13	11500-1	Shaft Coupler	1
14	11500-5	Motor Mount	1

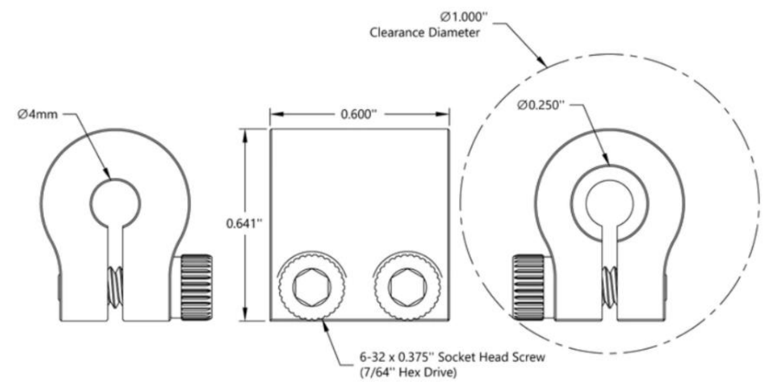


Cal Poly Mechanical Engineering		Motor Input Assembly		Drwn. By: Jack Cerron
Senior Project Design		Date: 2/23/21	Scale: 1:1	Drwn. Number: 11500

Part Number: 11500-1

0.250" to 4mm Clamping Shaft Coupler

SKU: 625049



SPECS

Bore	0.250" to 4mm
Material	Aluminum
Finish	Clear Anodized
Weight	0.26 oz (7.3g)

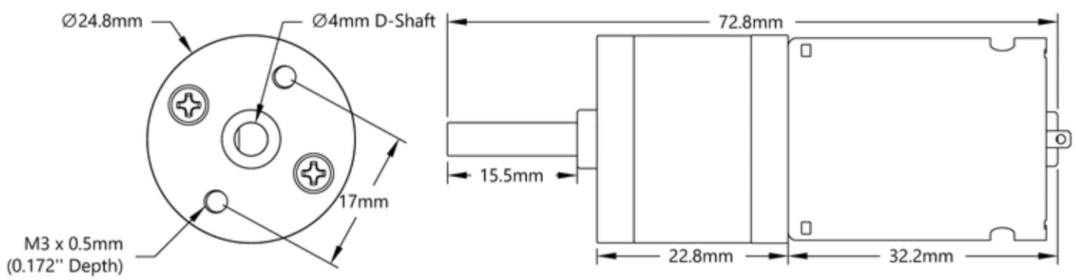
Part Number: 11500-2

124 RPM Econ Gear Motor

SKU: 638352

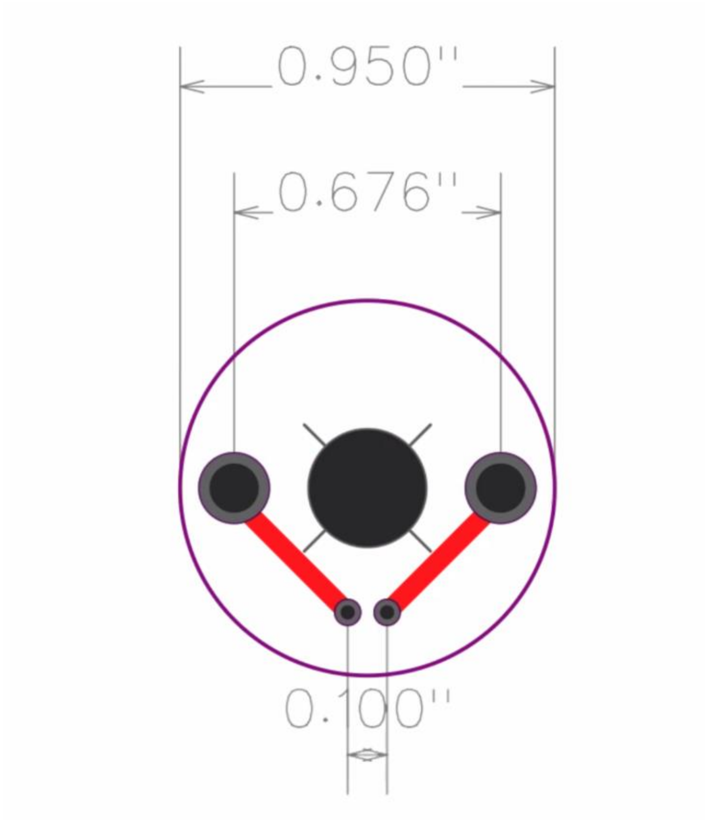
SPECS

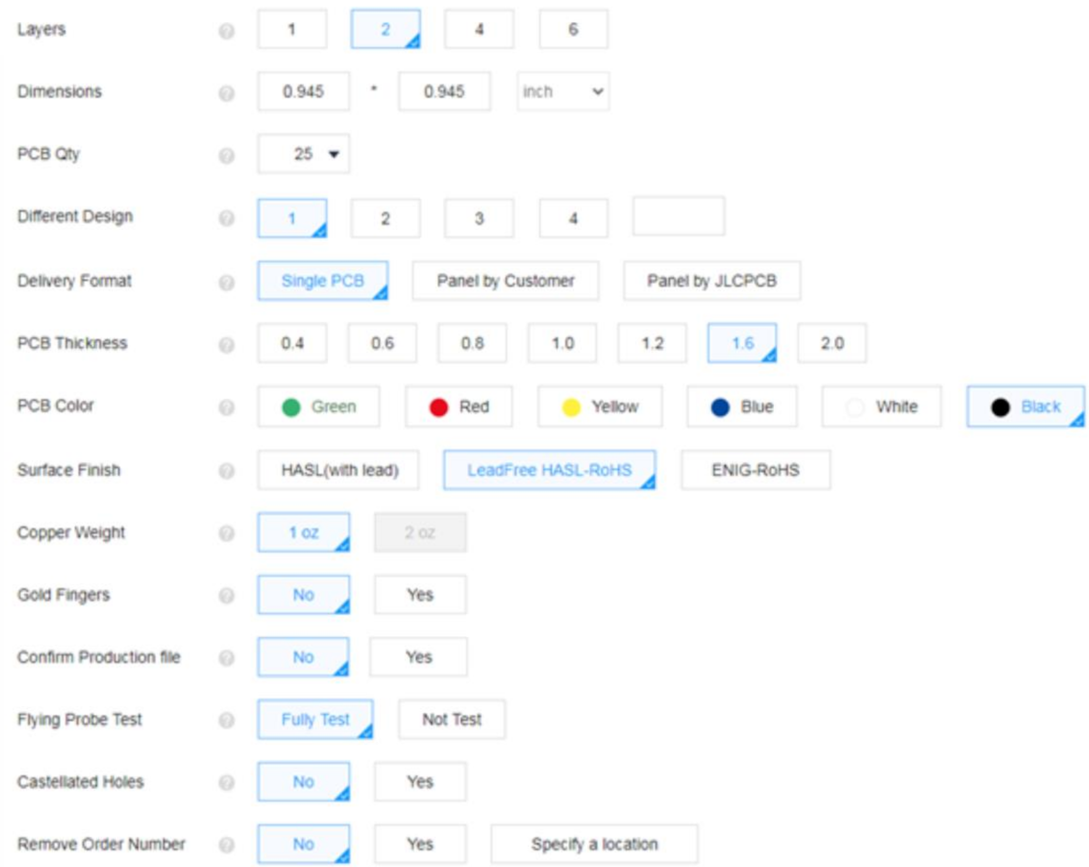
Output Shaft Style	D-shaft
Motor Type	Brushed DC
Output Shaft Support	Bushing
Gear Material	Metal
Weight	3.25 oz (92g)
Voltage (Nominal)	12V
Speed (No Load @ 12VDC)	124 rpm
Current (No Load @ 12VDC)	0.10A
Current (Stall @ 12VDC)	3.8A
Torque (Stall @ 12VDC)	419 oz-in (30.20 kgf-cm)
Gearbox Style	Straight Cut Spur
Connector Type	Male Spade Terminal
Gear Ratio	78:1



Part Number: 11500-3

Custom Motor Board





Layers	1	2	4	6			
Dimensions	0.945	*	0.945	inch			
PCB Qty	25						
Different Design	1	2	3	4			
Delivery Format	Single PCB	Panel by Customer	Panel by JLCPCB				
PCB Thickness	0.4	0.6	0.8	1.0	1.2	1.6	2.0
PCB Color	Green	Red	Yellow	Blue	White	Black	
Surface Finish	HASL(with lead)	LeadFree HASL-RoHS	ENIG-RoHS				
Copper Weight	1 oz	2 oz					
Gold Fingers	No	Yes					
Confirm Production file	No	Yes					
Flying Probe Test	Fully Test	Not Test					
Castellated Holes	No	Yes					
Remove Order Number	No	Yes	Specify a location				

To order PCB, go to https://docs.easyeda.com/en/PCB/Order-PCB and follow the steps.

This link https://cart.jlcpcb.com/?edaOrderUrl=https:%2F%2Feasyeda.com%2Forder&electropolishingOnlyNo=no&achieveDate=72 has PCB details from image above.

Part Number: 11500-4

JST Switch

SKU: 607019

SPECS

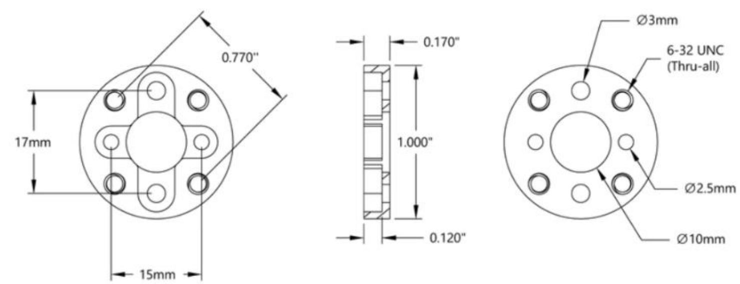
Weight	0.25 lbs

JST RCY 2-pin connectors

Part Number: 11500-5

Aluminum Motor Mount F

SKU: 555104



SPECS

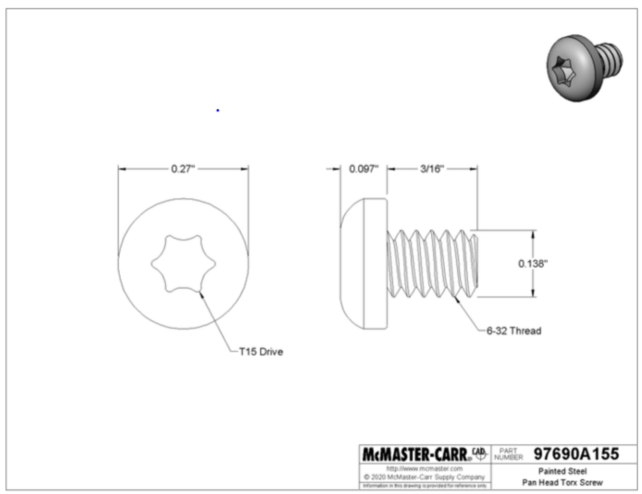
Material	Aluminum
Weight	0.15 oz (4.3g)

Part Number: 11500-6

McMASTER-CARR

Painted Steel Pan Head Torx Screw
with Black Head, 6-32 Thread Size, 3/16" Long

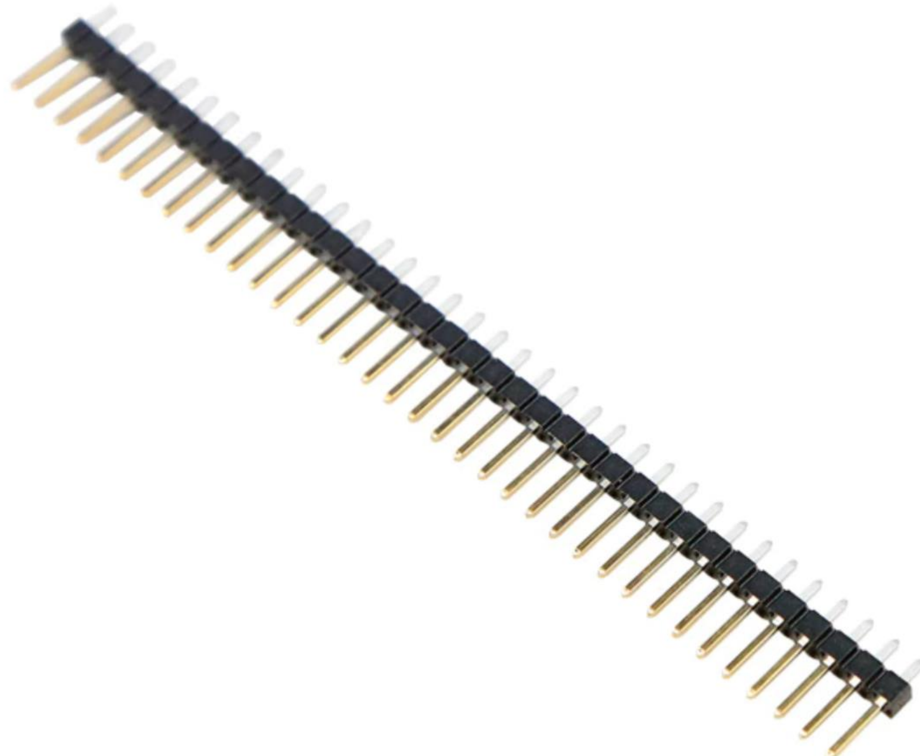
Thread Size	6-32
Length	3/16"
Threading	Fully Threaded
Head Diameter	0.27"
Head Height	0.097"
Drive Style	Torx
Drive Size	T15
Material	Zinc-Plated Steel
Hardness	Rockwell B70
Tensile Strength	Not Rated
Screw Size Decimal Equivalent	0.138"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 2A
Thread Direction	Right Hand



Part Number: 11500-7

Single Header Row Pin

SKU: HPS-100-36



These .100" header row pins have the same spacing as a standard servo connection. Row pins have gold plated contacts and are able to be "snapped" to the appropriate length. 36 contact positions.

SPECS

Weight	0.01 lbs

Part Number: 11500-8

Alligator Clip to Banana Plug Extension Set

SKU: X24231

SPECS

Connector	Alligator Clip / Banana Plug
Wire Length	(Red) 150mm / (Black) 200mm
Weight	0.80 oz

Part Number: 11500-9

Heat Shrink Tubing (560pc Assortment Pack)

SKU: 3201-0005-0001

ASSORTMENT PACK CONTENTS:

Color	ID	Length	Qty
Black	2mm	38mm	50
	4mm	38mm	30
	6mm	38mm	30
	8mm	38mm	30
Red	2mm	38mm	50
	4mm	38mm	30
	6mm	38mm	30
	8mm	38mm	30
Yellow	2mm	38mm	50
	4mm	38mm	30
	6mm	38mm	30
	8mm	38mm	30
White	2mm	38mm	50
	4mm	38mm	30
	6mm	38mm	30
	8mm	38mm	30

For those not afraid to modify! This assortment pack consists of 560 pieces of 38mm length heat-shrink in various diameters and colors stowed away in a plastic case to keep things organized.

Part Number: 11500-10

Male JST RCY Male Leads (20AWG)

SKU: JST20M

SPECS

Connector Type	JST RCY
Gender	Male
Wire Length	4"

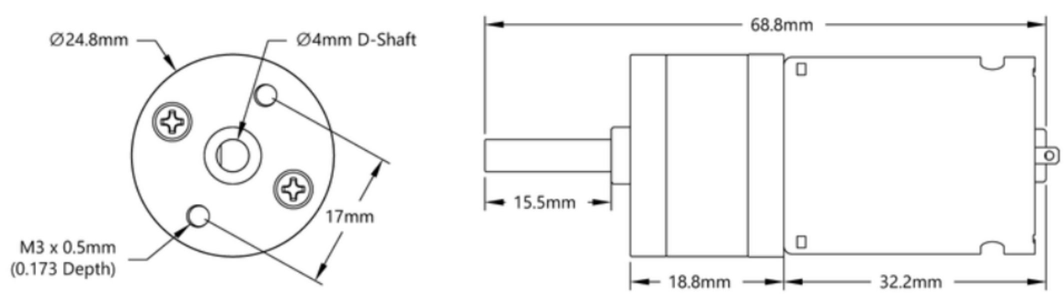
Part Number: 11600-1

970 RPM Econ Gear Motor

SKU: 638358

SPECS

Output Shaft Style	D-shaft
Motor Type	Brushed DC
Output Shaft Support	Bushing
Gear Material	Metal
Weight	3.07 oz (87g)
Voltage (Nominal)	12V
Speed (No Load @ 12VDC)	970 rpm
Current (No Load @ 12VDC)	0.10A
Current (Stall @ 12VDC)	3.8A
Torque (Stall @ 12VDC)	53.1 oz-in (3.83 kgf-cm)
Gearbox Style	Straight Cut Spur
Connector Type	Male Spade Terminal
Gear Ratio	10:1



Part Number: 11700-1

AGPtek® Professional Digital Laser Photo Tachometer Non Contact RPM Tach

Visit the AGPTEK Store

699 ratings | 51 answered questions

Amazon's Choice for "agptek digital laser"

Color: **DT-2234C+**

Brand	AGPTEK
Item Dimensions LxWxH	4.91 x 2.76 x 1.14 inches
Item Weight	0.39 Pounds

Specifications:
Display: 5 digits, 18 mm (0.7¡± inch) LCD with Function Annunciation.
Testing Range: 2.5 ~ 99,999 RPM (rate / min).
Resolution:
0.1 RPM (2.5 ~ 999.9 RPM) .
1 RPM (over 1,000 RPM).
Accuracy: (0.05 % + 1 digit).
Sampling Time: 0.8 seconds (over 60 RPM).
Test Range Selection: Automatic.
Memory: Maximum value, Minimum value and Last Measured value.
Detecting Distance: 50 ~ 500 mm (2 ~ 20 inch) (Laser).
Time base: Quartz Crystal.
Circuit: Exclusive one-chip of microcomputer LSI circuit.
Power: 9V PP3 Battery.
Operating Temperature: 0 ~ 50 ¡ãC (32 ~ 122 ¡ãF).
Dimension: approx. 131 (L) x 70 (W) x 29 (D) mm (5.16¡¯ x 2.76¡¯ x 1.14¡¯ inch).
Weight: approx. 160g

Package Content:
1 x New Digital Laser Photo Tachometer Non Contact RPM Tach
1 x English Manual
1 x Carrying Bag
3 x approx. 20cm of reflective stripes

Part Number: 11700-2

Milky Multimeter from Amazon.com

Milky House

Milky House Digital Pocket Multimeter

Electrical Troubleshooting Necessities

This Digital Multimeter with Backlight LCD Voltmeter Ohmmeter Ammeter meets your various demands! It is designed to safely and accurately troubleshoot a variety of automotive and household electrical problems.

It's easy and safe to operate for measuring current, voltage, and resistance, as well as continuity, transistor, and diode testing, which is both for automotive and household use and is a basic assistant to test.

Newest design and high quality. Please rest assured to buy!

Features:

- √AC/DC Voltage
- √DC Current
- √Resistance
- √Low Battery Indication
- √Backlight Display
- √Overload Protection
- √Continuity
- √Diode

Specification:

- 15mm high LCD Display
- DC Voltage: 200mV/2V/20V/200V ±0.5%, 600V ±0.8%
- AC Voltage: 200mV/2V/20V ±1.0%, 200V/600V ±1.2%
- DC Current: 200μA/2mA/20mA ±1%, 200mA ±1.5%, 2A/10A ±3.0%
- AC Current: 200μA/2000μA/20mA ±1.8%, 200mA ±2.5%, 2A/10A ±3.0%
- Resistance: 20ω±3.0%, 200ω/2Kω/20Kω±1.0%, 200Kω/2Mω/20Mω ±1.5%
- Fuse protection: F-200mA/250V
- Operating Temperature: -0℃ to 40℃
- Over Range Indication: Only figure "1" on the display
- Polarity Indication: "-" displayed for negative polarity
- Low Battery Indication: - /+ display
- Battery: 9V
- Dimension: Approx 147mm x 69mm x 34mm
- Weight: 226g

Part Number: 11800-1

Michael's – 3 Tray Storage Box by Artist's Loft™

Item # 10998650

Details:

- Black
- 16" x 8.75" x 8" (40.64cm x 22.225cm x 20.32cm)
- Has 3 compartments
- Plastic

Part Number: 11900-1

The Home Depot – 9/64 in. Ball-End Journeyman T-Handle Hex Key 6 in.

Internet #203195182 Model #JTH6E09BE

Specifications

Dimensions

Product Depth (in.)	0.5	Product Height (in.)	7
Product Width (in.)	2.75	Tip Size	9/64 in

Details

Hand Tool Type	Hex Key	Hex Key Type	T Handle
Individual/Set	Individual	Measurement Standard	SAE
Number of Pieces	1	Returnable	90-Day
Tools Product Type	Hand Tool		

Part Number: 11900-2

The Home Depot – 7/64 in. Ball-End Journeyman T-Handle Hex Key 6 in.

Internet #203195178 Model #JTH6E07BE

Specifications

Dimensions

Product Depth (in.)	0.5	Product Height (in.)	7
Product Width (in.)	3	Tip Size	7/64 in

Details

Hand Tool Type	Hex Key	Hex Key Type	T Handle
Individual/Set	Individual	Measurement Standard	SAE
Number of Pieces	1	Returnable	90-Day
Tools Product Type	Hand Tool		

Part Number: 11900-3

McMASTER-CARR®

Ball-End Two-Tip T-Handle Key

3/32" Hex Size, 6-7/8" Overall Length

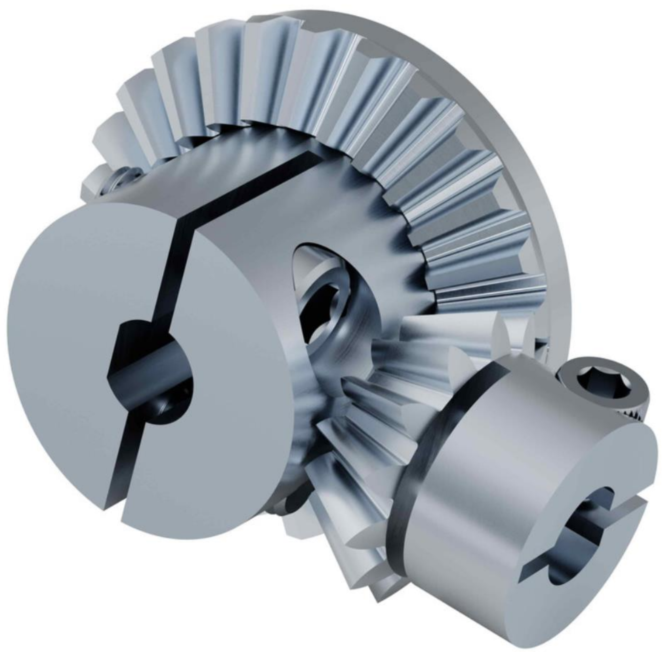
Item #6286A13

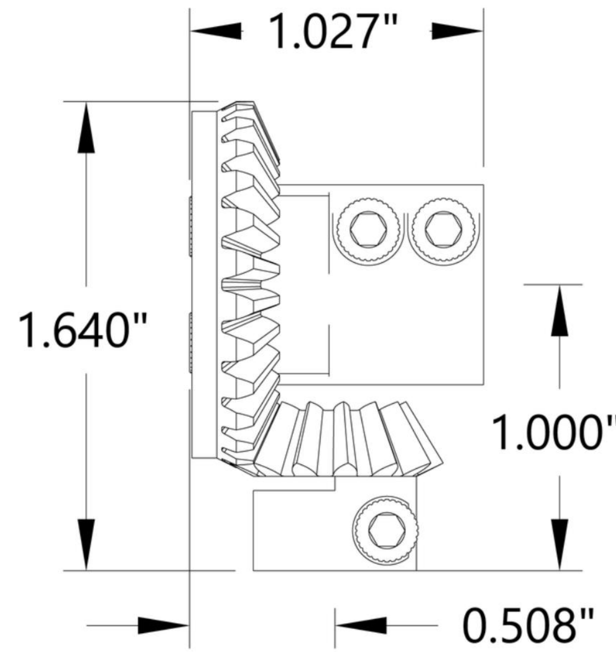
For Drive Style	Hex
Size	3/32"
Length	
Long Shaft	5 3/4"
Short Shaft	1/2"
Overall	6 7/8"
Overall Shaft Width	1/8"
Maximum Access Angle	20°
Material	Chrome-Plated Steel
Handle Material	Plastic
Grip Style	Ultra Grip
Tip Style	Ball
Driver Style	T-Handle
Driver Type	Standard
Individual/Set	Individual
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (06/25/2020, 209 SVHC) Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	Germany
Schedule B	820411.0060
ECCN	EAR99

Part Number: 111000-1

2:1 Bevel Gear Set (1/4" Bore Pinion, 1/4" Bore Spur)

SKU: 637222





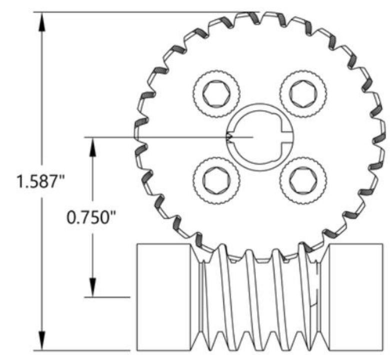
SET INCLUDES:

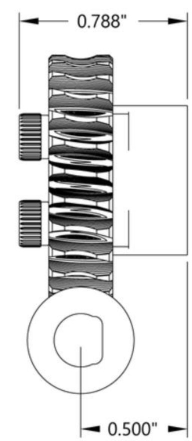
Qty	SKU	Product Description
1	615460	26T, 1/4" Bore, 20 Pitch, Hub Mount Bevel Gear
1	615456	13 Tooth, 1/4" D-Bore, 20 Pitch, Shaft Mount Bevel Gear
1	545694	Steel 1/4" D-Bore Barrel Hub for Worm Gear

Part Number: 111000-2

27:1 Worm Gear Set (1/4" Bore Worm, Hub Mount Worm Gear)

SKU: 637225





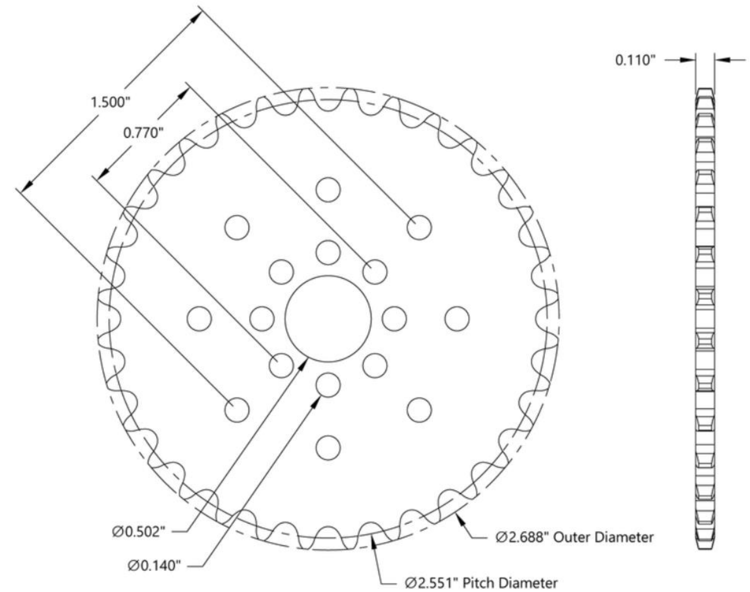
SET INCLUDES

Qty	SKU	Product Description
1	615464	27 Tooth Brass Hub Mount Worm Gear
1	615462	1/4" D-Bore Stainless Steel Worm
1	545694	Steel 1/4" D-Bore Barrel Hub for Worm Gear

Part Number: 111000-3

32 Tooth 0.770" Aluminum Hub Mount Sprocket 0.250 Pitch

SKU: 615114



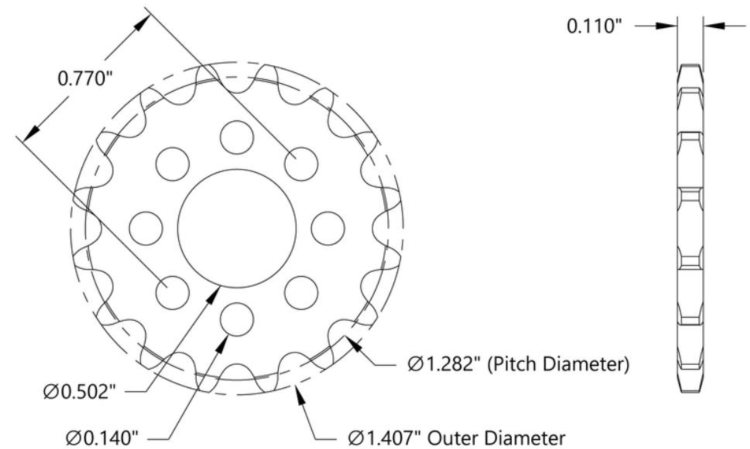
SPECS

# of teeth	32T
Weight	0.78 oz (22g)
Material	Aluminum

Part Number: 111000-4

16 Tooth 0.770" Aluminum Hub Mount Sprocket 0.250 Pitch

SKU: 615102



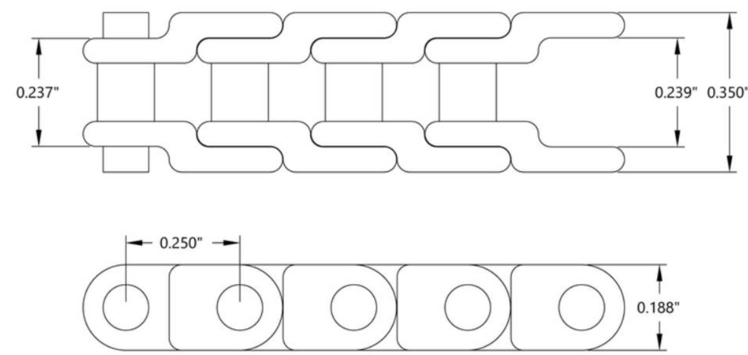
SPECS

# of teeth	16T
Weight	0.16 oz (4.5g)
Material	Aluminum

Part Number: 111000-5

0.250” Pitch Plastic Chain (48 Links, 1ft)

SKU: 615150



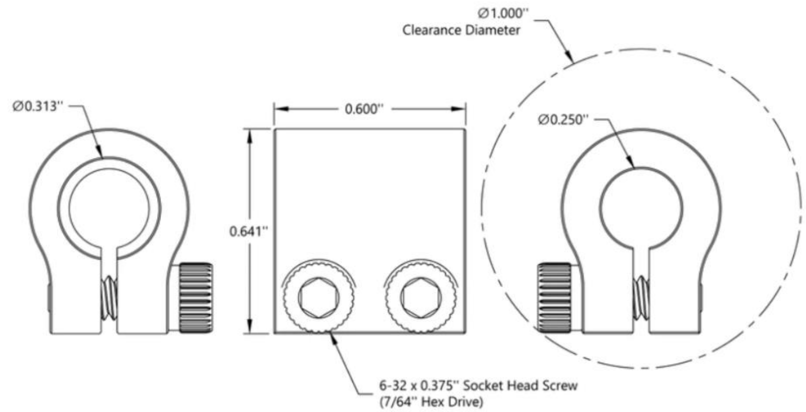
SPECS

Material	Plastic
Weight	0.32 oz (9.0g)
Pitch	0.25"
ANSI No.	25

Part Number: 1111000-2

0.250" to 0.3125" Clamping Shaft Coupler

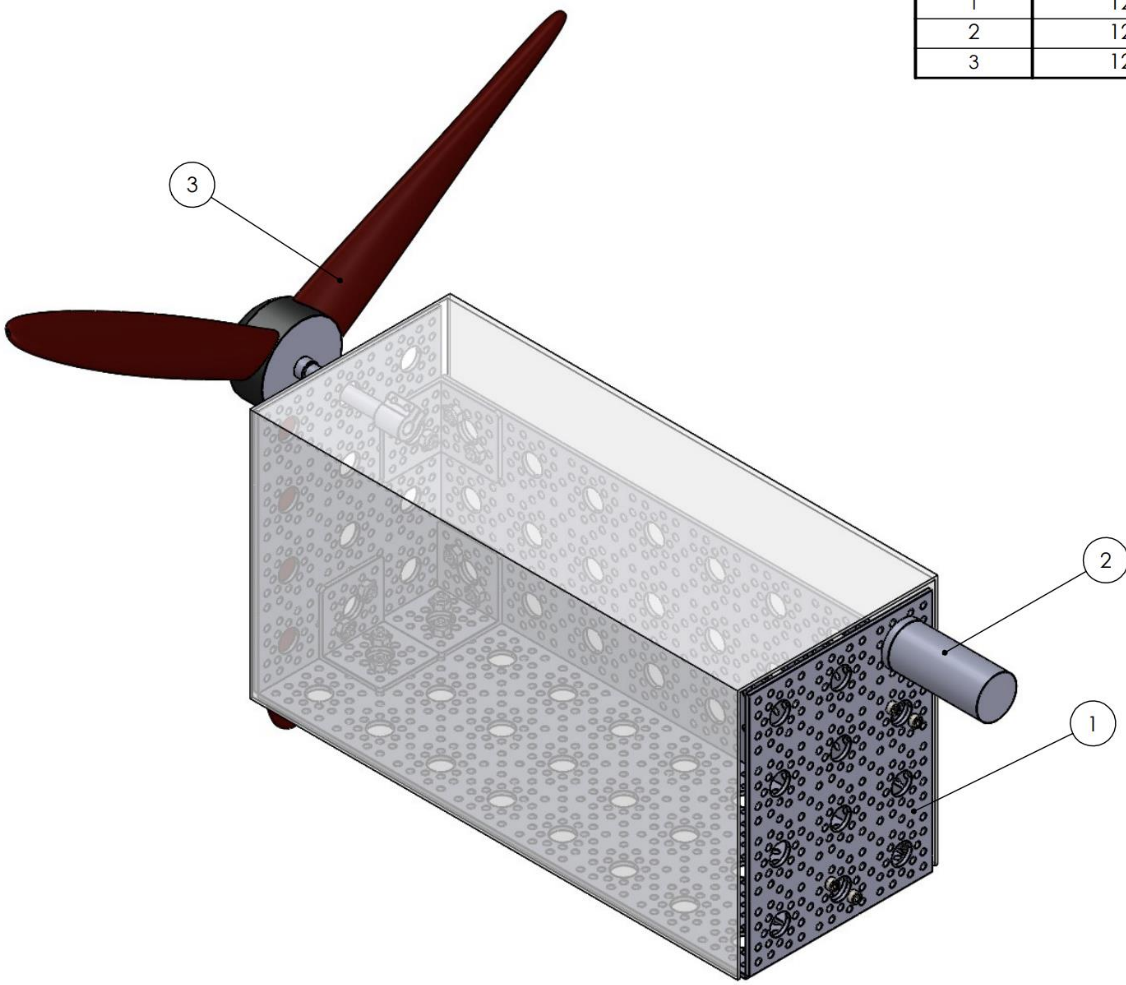
SKU: 625046



SPECS

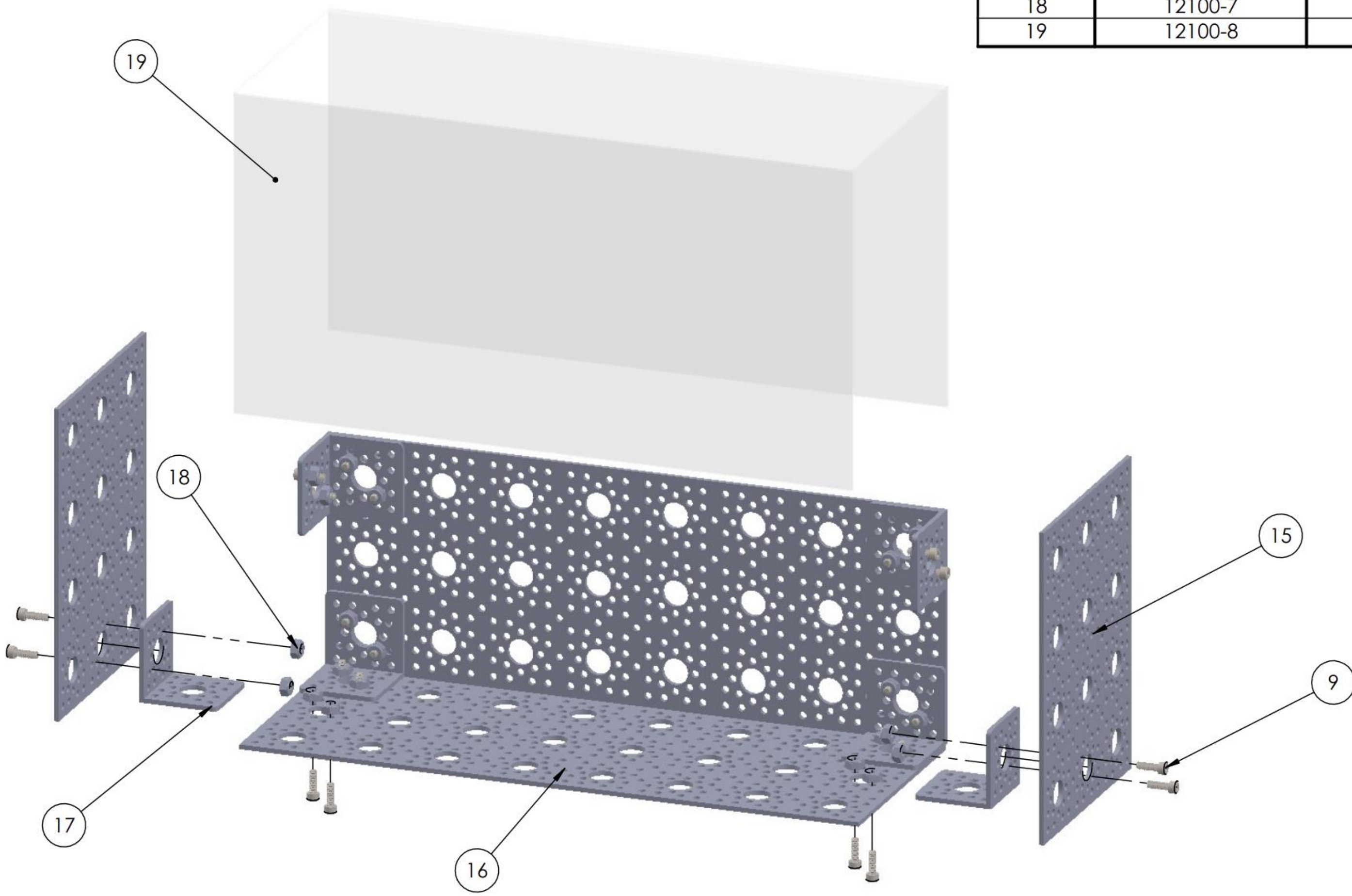
Bore	0.250” to 0.3125"
Material	Aluminum
Finish	Clear Anodized
Weight	0.23 oz (6.6g)

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	12100	Housing Assembly	1
2	12300	Output Generator Assembly	1
3	12200	Input Blade Assemly	1



Cal Poly Mechanical Engineering		Wind Turbine Assembly		Drwn. By: Jack Cerron
Senior Project Design		Date: 05/04/21	Scale: 1:2	Drwn. Number: 12000

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
15	12100-1	3x4 Hole Pattern Plate	2
16	12100-2	3x8 Hole Pattern Plate	2
17	11450-8	Angle Brackets	6
9	11410-3	Head Screw	40
18	12100-7	6-32 Lock Nuts	40
19	12100-8	Acrylic Cover	1



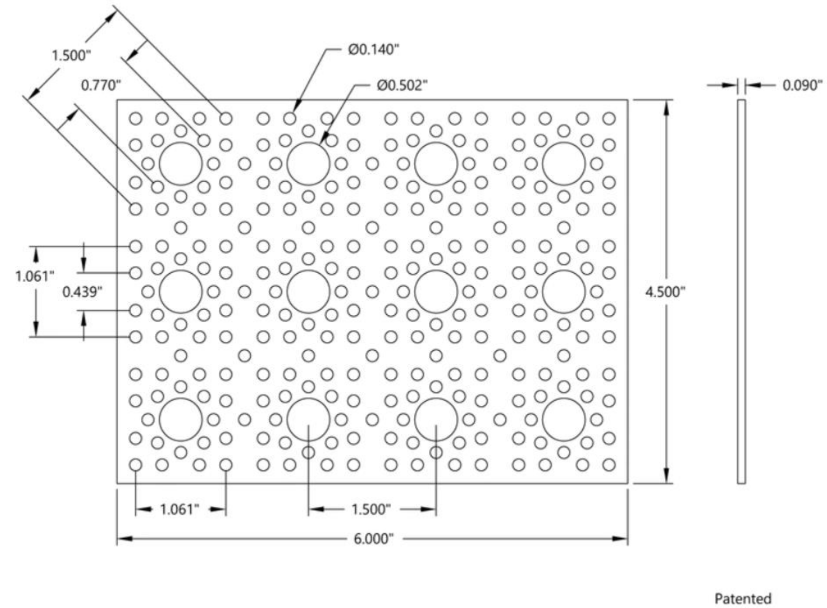
Cal Poly Mechanical Engineering		Housing Assembly		Drwn. By: Jack Cerron
Senior Project Design		Date: 2/23/21	Scale: 1:2	Drwn. Number: 12100

Part Number: 12100-1

3 x 4 Hole Pattern Plate (4.50" x 6.00")

SKU: 585002

Patented



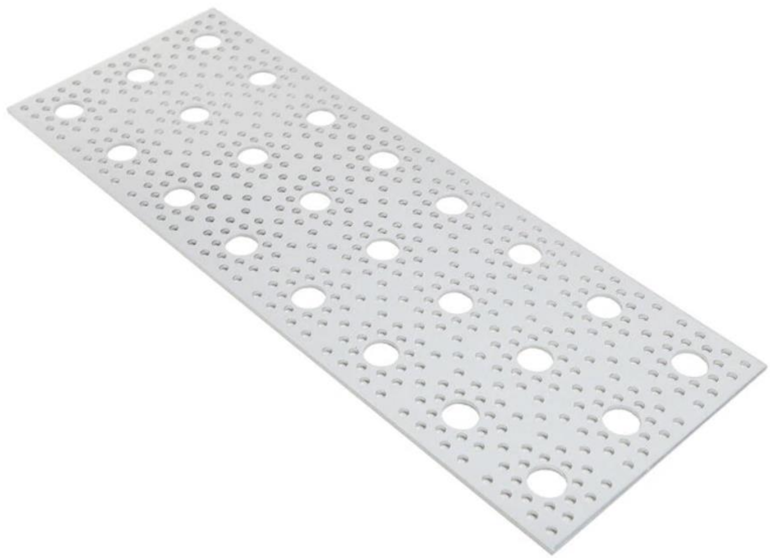
SPECS

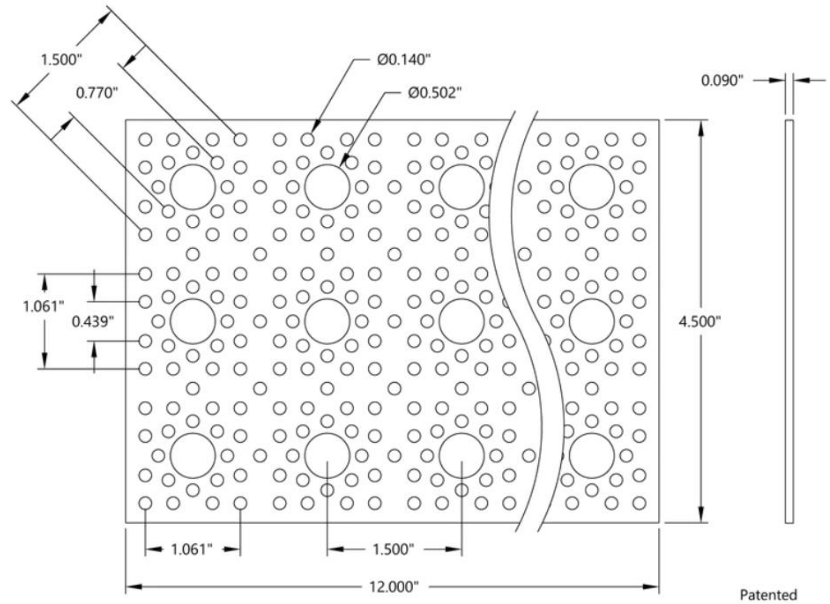
Weight	2.89 oz (82g)
Finish	Clear Anodized
Material	Aluminum
IP	Patented

Part Number: 12100-2

3 x 8 Hole Pattern Plate (4.50" x 12.00")

SKU: 585004





Patented

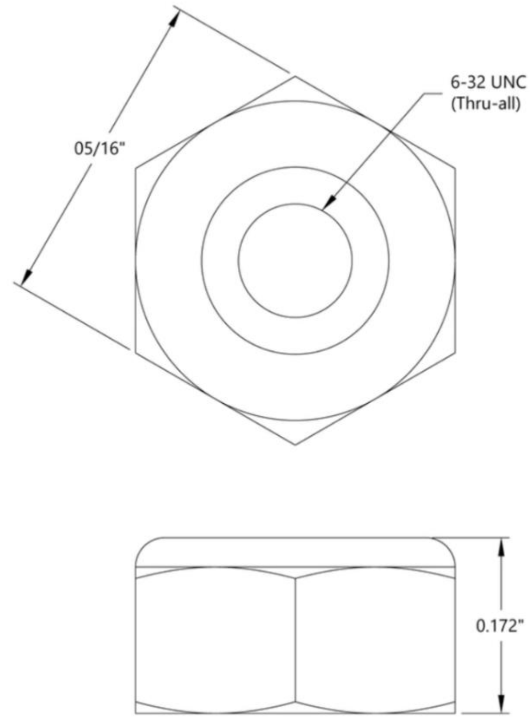
SPECS

Material	Aluminum
Weight	5.77 oz (164g)
Finish	Clear Anodized
IP	Patented

Part Number: 12200-1

6-32 Nylock Nuts Pack (25 pack)

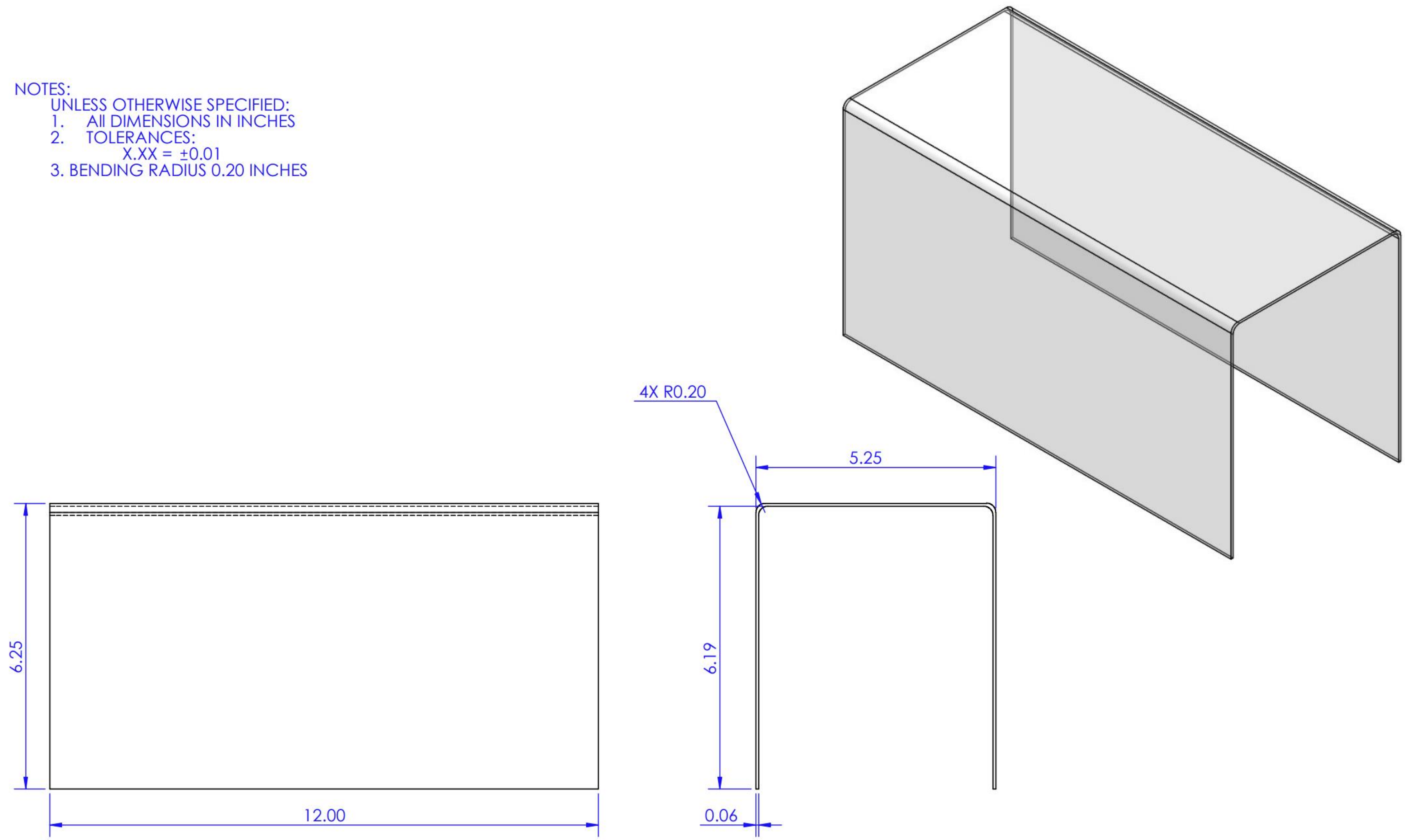
SKU: 632142



SPECS

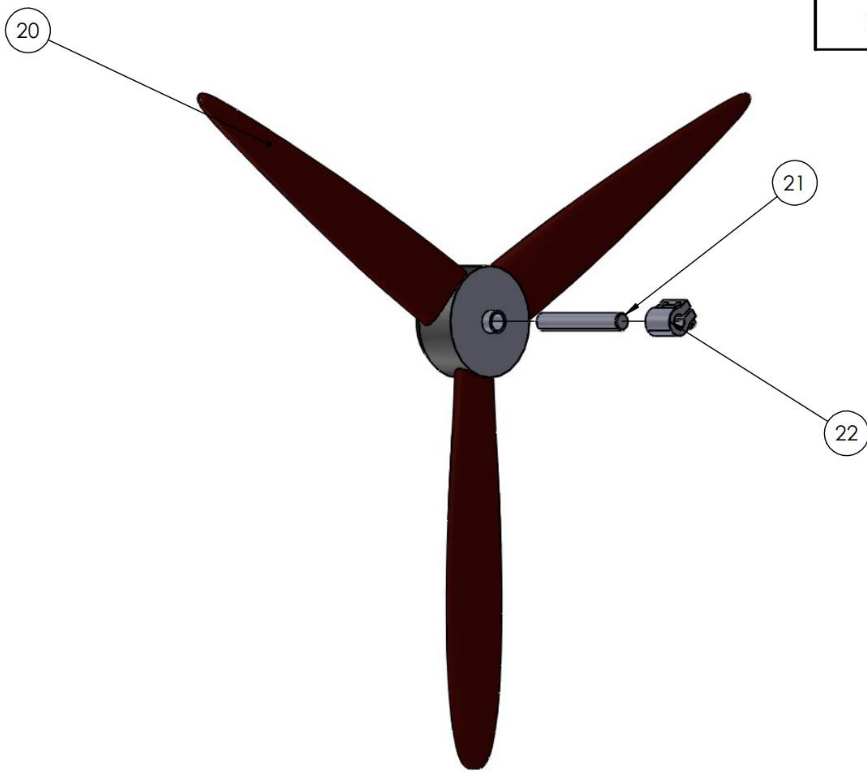
Material	Alloy Steel
Weight	0.051 oz.
Finish	Zinc-Plated
Type	Nylon Insert Locknut

NOTES:
UNLESS OTHERWISE SPECIFIED:
1. All DIMENSIONS IN INCHES
2. TOLERANCES:
X.XX = ±0.01
3. BENDING RADIUS 0.20 INCHES



Cal Poly Mechanical Engineering	Acrylic Clear Sheet	Acrylic Housing Cover	Drwn. By: Jack Cerron
Senior Project Design		Date: 2/23/21 / Scale: 1:2	Part Number: 12100-8

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
20	12200-2	Blades	1
21	12200-3	2" 5/16 Round shaft	1
22	111100-2	5/16 to 1/4 Shaft coupler	1



Cal Poly Mechanical Engineering		Input Assembly	Drwn. By: Jack Cerron
Senior Project Design		Date: 2/23/21 Scale: 1:2	Drwn. Number: 12200

Part Number: 12200-1

Harbor Freight – 20 In. High Velocity Floor Fan

SPECIFICATIONS

SKU(s)	57880	AC Volts	120
Brand	CENTRAL MACHINERY	Certification	ETL
Diameter	20 in.	Flow rate	4800 CFM Low - 5300 CFM Medium - 6000 CFM High
Housing material	Metal	Number of speeds	3
Power cord (ft.)	7 ft.	Product Height	23 in.
Product Length	24 in.	Product Weight	10.5 lb.
Product Width	8.75 in.	Shipping Weight	13.66 lb.
Sound rating (dB)	61.6 dB	Wattage (watts)	164

Part Number: 12200-2

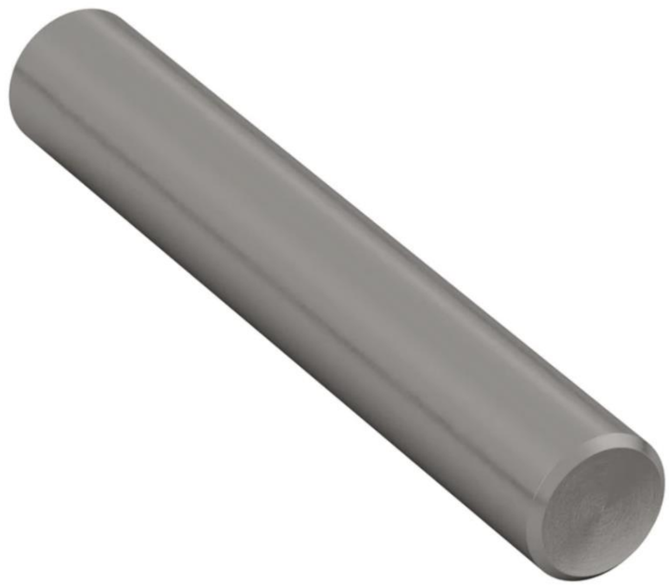
Master AirsScrew 3-Blade - 16x8 Propeller

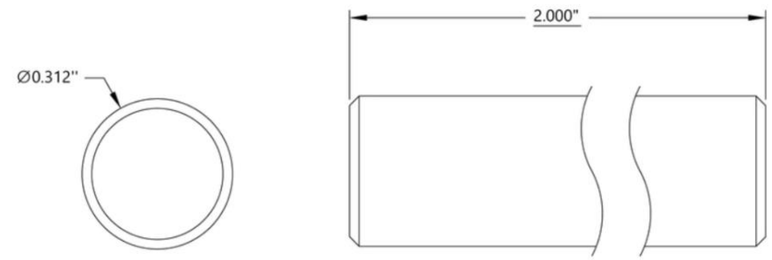
Propeller diameter	16" / 406mm
Propeller pitch	8" / 203mm
Hub thickness	3/4" / 19.1mm
Shaft diameter	5/16" / 7.94mm **
Propeller Weight	3.84oz / 108.9g
Direction of rotation	Normal / Tractor
Material	Glass Fiber R Composite
Color	Black

Part Number: 12200-3

0.3125" (5/16") x 2.00" Stainless Steel Precision Shafting

SKU: 634182





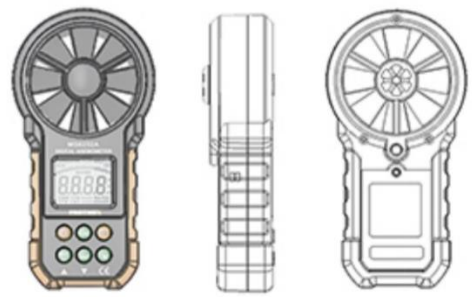
SPECS

Length	2.00"
Material	Stainless Steel
OD	0.3125" (5/16")
Finish	10 RMS Micron rated finish
Weight	0.69 oz (20g)

Part Number: 12200-5

Digital Anemometer B019RU17XC

Specification	Range	Accuracy	Resolution
Wind Speed	0.80-30.0 m/s	±(2.0% reading + 50)	0.01 m/s
	80-59000 ft/m	±(2.0% reading + 50)	1 ft/m
	1.40-108.0 km/h	±(2.0% reading + 50)	0.01 km/h
	0.90-67.20 mile/h	±(2.0% reading + 50)	0.01 mile/h
	0.8-58.30 Knots	±(2.0% reading + 50)	0.01 knots
	1.30-98.50 ft/s	±(2.0% reading + 50)	0.01 ft/s
Wind Flow	0-99990 CFM	(Area) 0-9.999 ftp^2	\
	0-99990 CMM	(Area) 0-9.999 m^2	\
	0-9999 CMS	(Area) 0-9.999 m^2	\
Feature			
Data Hold	√		
Max/Min	√		
Auto Power Off	√		
Backlight	√		
Low voltage indicator	√		



Product Specification:

- m/s (meter per second): 0.80~30.0 ±(2.0% reading + 50)
- ft/s(feet per second): 1.3-98.5 ±(2.0% reading + 50)
- ft/m (feet per minute): 80~5900 ±(2.0% reading + 50)
- km/h (kilometer per hour): 1.4~108.0 ±(2.0% reading + 50)
- mile/h(mile per hour): 0.9~67.0 ±(2.0% reading + 50)
- Knots(nautical miles per hour): 0.8~58.0 ±(2.0% reading + 50)
- CFM: 0 to 99990 0 to 9.999ft2
- CMM: 0 to 99990 0 to 9.999ft2
- CMS: 0 to 9999 0 to 9.999 m^2