Collegiate Wind Competition
Turbine Prototype

Final Report

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Project Sponsor:	W.L. Gore & Associates
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DISCLAIMER

EXECUTIVE SUMMARY

This capstone team is an embodiment of NAU’s participation in the Colligate Wind Competition (CWC), as the group members will be participating in two major competitions. The first of these competitions is the mechanical test turbine, in which the participants are working together to design and build a functional small scale wind turbine to be tested at the competition. The second primary group will oversee developing a theoretical 100MW wind farm/ power plant in the western half of South Dakota. Both teams have intermingled participants represented by the whole of the capstone team; however, this report is only a documentation of the efforts of the mechanical test turbine team. These students will use information obtained in the competition, from the provided resources, and faculty to adapt solutions to complete each of the following primary objectives.

The mechanical test turbine competition will be composed of multiple deliverables throughout the year. It will also be subject to multiple variant tests during competition. While each team may opt. in or out of any individual tasks, our team currently plans to participate in all five testing deliverables. The first of which is the cut in wind speed task, which our team has decided to optimize for with the use of an in-house modified swash plate to control pitching of the blades at 0 rotations per minute (rpm). The second task is to optimize power generation for two specific wind speeds, 5m/s and 11m/s. Our team will do this by optimizing our airfoils to produce maximum energy at 11m/s, this will further be enhanced by the appropriate choice of generator to translate the kinetic energy to usable power. Thirdly, the next task is to control rated power and speed. The team will be able to do this through the use of our disk brake design to dissipate energy and by creating a program to overpitch our blades to reduce effective forces back to what would be expected at lower speeds. Fourthly, the team must be able to perform a full brake in the safety task. Representative of a power surge or disconnection, the team's connection with the turbine will be broken in the test, and the turbine must be able to stop itself on its own accord. We will accomplish this with internal power storage such as battery to actuate the brakes when not told to stay open by the open code. Fifth and finally, the team must perform in the durability task. While relatively impractical to subject the turbine to extended use during a single competition, this task will require the turbine to perform under various conditions, which will be compared with previously attained power curves. This primarily means that the direction of airflow will be changed, and the team must be able to yaw their device to the correct direction, which will be done exclusively by our passive yaw. By using the forces of the disrupted airstream, the yaw will be able to re-align the turbine to equilibrium/operating state.

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1 BACKGROUND

1.1 Introduction

The Collegiate Wind Competition (CWC) is an academic competition that includes the design, fabrication, and testing of a micro-wind turbine. Thanks to our client our team is able to participate in the 2021 competition taking place in the beginning of June. The objective for this project was to present to our client a suitable micro wind turbine that meets the engineering requirements needed for it to perform well in the 2021 competition. The sponsors for this competition include the United States Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL). The U.S. Department of Energy created the rules and hosts the contest for all the contestants. NREL is the competition organizer that leads a fair competition and provides appropriate industry contacts. Upon completion of the project, the team can provide new breakthroughs in the clean energy sector that gives back to the community. Northern Arizona University (NAU) is a stakeholder for the team. The team is studying at NAU in the Mechanical Engineering program. When the project outcome is successful, it provides positive publicity for the university. The team will also affect different areas in societal impacts such as shifting away from fossil fuel dependency, cleaner air and water, and increase in technical jobs for a more skilled economy.

1.2 Project Description

The original project description provided by the sponsor:

> "… "research, design, and build a turbine for deployment in highly uncertain times (with a great degree of unknown risks and delays)" [1]. The background information about the competition given to the team is: "The competition contributes to the creation and maintenance of American leadership in the transition to a global clean energy economy. Specifically, the competition's objective is to prepare students from multiple disciplines to enter the wind energy workforce by providing real-world technology experience" [1]. The team also has objectives given by the sponsors to create "an effective mechanical, electrical, and aerodynamic wind turbine and load design that is safe and reliable for testing in an on-site wind tunnel," The project description given directly from the sponsors gives the team a clear understanding of what is expected to be produced."

Due to COVID-19, the team will no longer be attending an on-site competition. The team will not be able to test the micro wind turbine due to this. To accommodate for these times, the team has prepared to conduct testing in Flagstaff, Arizona.

2 REQUIREMENTS

For the Collegiate Wind Competition, the team is required to create an effective mechanical, electrical, and aerodynamic wind turbine/load design that can be safely tested through personal car testing.

2.1 Customer Requirements (CRs)

Customer requirements include the creation of a wind turbine with an effective design, safe and reliable electrical design, and has and aerodynamic construction that can withstand 22 m/s wind speeds as well as continuously last through 13m/s wind speeds. The competition requires the wind turbine to have geometries within a 45x45x45 cm^3 cube and require no further assembly after being moved through the door of the wind tunnel.

2.1.1 Customer Requirements (CRs) Breakdown

The customer requirements for the test turbine are listed below. These requirements were generated after carefully listing to our client in multiple meetings. As well as understanding contest rules and constraints listed in [1].

1. Cost within budget: The team must be able to design and produce a turbine with the allotted budget given to the team by the University and the various sponsors.

2. Durable and Robust design: The turbine must be able to be able to hold up to high wind speeds (22 m/s) and be able to withstand multiple tests in the field.

3. Reliable design: The testing must be repeatable with mostly the same parts such as generator, tower and nacelle.

4. Safe to operate: The turbine must be able to operate without injury of staff personal and the testing team.

5. Turbine baseplate needs to be no thinner than 16.1 mm and able to withstand 50 N-m of torque

6. Voltage must be DC at the PCC and be at or below 60 volts

7. Must have an emergency stop button that halts within 7 seconds

8. Stop when electrically disconnected from the load which can never carry more than 3 A and will stop the turbine

9. No batteries of any type that exceed 10 J of energy storage

10. An adequate generator: This will produce the power that is required in testing for the turbine.

11. Blade rotation start up at low wind speeds

12. Stable power output at wind speeds between 5 and 11 m/s

2.2 Engineering Requirements (ERs)

All the requirements listed below directly correlate to the to the customer needs. All units are in relatable engineering terms.

1. Cost in USD
2. Output in Watts
3. Readability in Volts
4. Speed control in RPM
5. KV rating of 150 – 170 for generator
6. Thickness of base plate needs to be less than 16.1 mm
7. Active pitch system and/or unique blade geometry

2.3 Functional Decomposition

To allow the team to start research into the projects, it is necessary to break down the project. The Black Box Model and Functional Model will provide the team with the breakdown of the systems. These models will be the starting point for the team's literature review which will progress into the project's subsystem concepts.

2.3.1 Black Box Model

The different figures below show the main components for both the Mechanical test turbine. All the components were taken directly from the main rules that have been posted by the U.S. Department of Energy. The team created the two different models to help focus on the importance of the project to achieve not only a high rate of success, but also to help the team score well in the overall competition.

The figure below shows the main points of interest for the design as well as creation for the mechanical test turbine portion of the project. With the different inputs listed below, there are several main topics that are being covered with significant importance for the final design. The black box model shows not only the different sections of the project. It also highlights the final design that the team is trying to accomplish, which is an effective micro wind turbine.

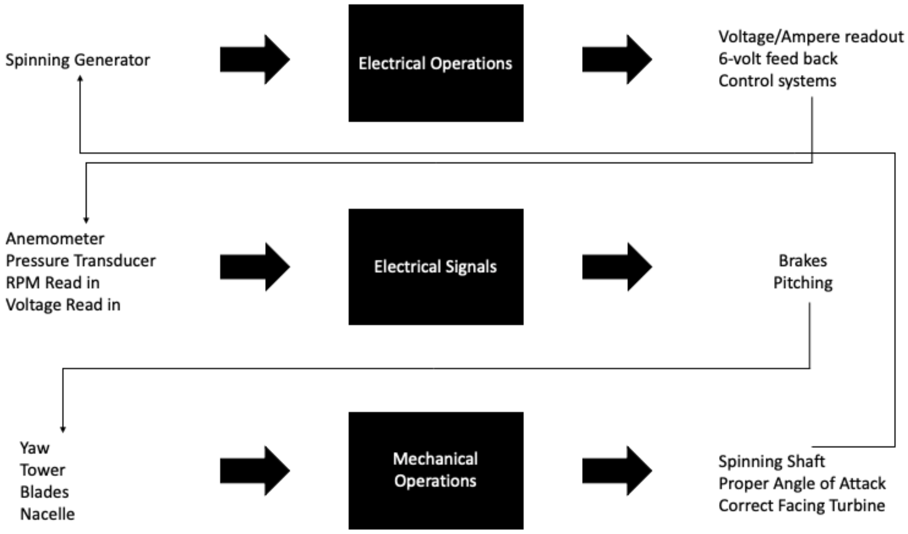


Figure 1: Mechanical Test Turbine Black Box Model

The figure above shows how the team must have various signals inputs to the turbine that are then transformed into different sources of energies and inputs for the turbine. The turbine is supposed to be self-sufficient and be able to run on its own power that it has generated and stored. For example, the only way for the turbine to start up is the read the various electrical signals and through those signals the turbine will then determine what operation it needs to be in and from there it will read again allowing for the turbine to be constantly producing power and going through the repeated cycle of reading the inputs going into the proper operating condition, and devolving power.

The team will use this Blackbox model to make sure the different energy inputs to the turbine are relevant to the project and the competition. These will be further broken down into spaller pieces that can be handled much more readily. For many of the electrical systems the team will employ help of Electrical Engineering students for this portion of the project.

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

After finding an initial black box design, the team was able to determine functional models. These models showed various points per breakdown method explained above. When looking at the mechanical test turbine and the many main inputs to the overall design, each of these design standpoints can been broken down into further points. For example, the brakes need to be able to stop the wind turbine, as well as the overall actuation system for the brakes. This is just one of the main points; however, all the points are broken down in the functional model in Figure 2**.** This includes the electrical portion of

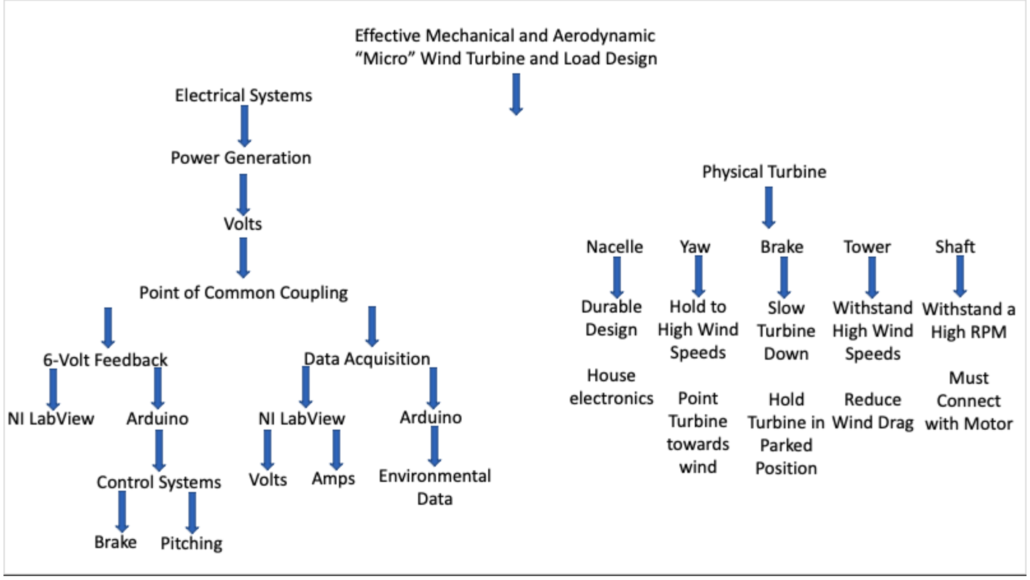
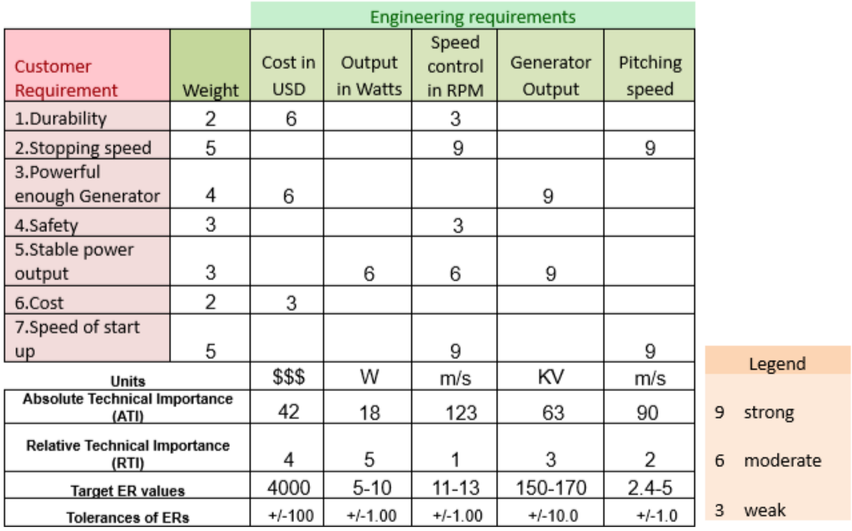


Figure 2: Mechanical Test Turbine Development Functional Decomposition

The figure above describes the various breakdowns of the problems that the turbine team must solve and account for. The main issue the team must deal with is the breakdown of the electrical systems that has to be brought back into the system to either power the turbine control system or the various data acquisition systems. This voltage also must be recorded with a DAQ then the one used to collect environmental data. The physical side of the turbine is mainly making sure the turbine can hold up to the various wind speeds.

2.4 House of Quality (HoQ)

The importance of the customer requirements is scaled from one to five. Five equals an elevated level of importance and one equals a low level of importance. In the main room of HoQ, the team harmonized the customer needs with engineering requirements to identify which requirement can satisfy the customer needs the best. After the calculations, the team found energy production is the most crucial factor and terrain quality is the least crucial factor of our design process. The last two rows represent our target values. Target values are decided by the team members after agreed with the client. Figure 5 is the Mechanical Test Turbine HoQ.



		Engineering requirements				
Customer Requirement	Weight	Cost in USD	Output in Watts	Speed control in RPM	Generator Output	Pitching speed
1.Durability	2	6		3		
2.Stopping speed	5			9		9
3.Powerful enough Generator	4	6			9	
4.Safety	3			3		
5.Stable power output	3		6	6	9	
6.Cost	2	3				
7.Speed of start up	5			9		9
Units		$$$	W	m/s	KV	m/s
Absolute Technical Importance (ATI)		42	18	123	63	90
Relative Technical Importance (RTI)		4	5	1	3	2
Target ER values		4000	5-10	11-13	150-170	2.4-5
Tolerances of ERs		+/-100	+/-1.00	+/-1.00	+/-10.0	+/-1.0

Legend	
9	strong
6	moderate
3	weak

Figure 3: HoQ for the Mechanical Test Turbine

The team target for total component cost is $2,000 with a budget of $4,000 overall. We chose a 150-170 KV motor for our design because the wind speeds are not high enough for a 200 KV. The most important design constraint that we found was for the speed control system because both the start-up speed and the braking speed are some of the most important aspects of the design, both for this competition and when it is factored in that these two extremes will be representative of the range in which the turbine must operate. To assist with these crucial conditions, in the start-up and braking speed, the team is using a pitching mechanism that will enable better performance, by systematical vectoring the forces to mitigate losses on startup and overdraw at breaking speed. The pitching mechanism will be operated via electromechanical components, consisting of Arduino computing and stepper motor actuation. The team will continue exploring opportunities to combine these actuators alongside the braking system to minimize components and complexities. In the case of pitching failure, the team is prepared to redesign the wings to increase start up lift forces.

The testing procedures that will be done with the engineering requirements is the suable power output. This will be done with car testing by mounting the turbine to the top of a car and have various other testing apparatus to test the turbine. Output in watts will be tested by the use of a PCC box and through various resistor setups and analog and digital readouts. The generator output as well as the speed control of the turbine will be tested through the car testing. Pitching speed will be tested through static testing and the use of an Arduino control system. When the device is asked to pitch the team will start the stopwatch and test the time it takes to rotate.

2.5 Standards, Codes, and Regulations

The largest standard that the team will be held to is the initial team contract. This contract lays out all of the different points that the team will have to follow, how to work with others in the group, as well as how to create an overall timeline for the project.

All the codes that the mechanical test turbine will be following the ASME code regulations. One of the main codes that the team will be following PTC11-1984, this code if the code set for fans and fan blades. Even though this code is more for ceiling fans and fan blades, the overall principal can be shown.

The next code that the team will have to follow is PTC42-1988(R1998). This code directly relates to wind turbines. This code bases off the windspeed vs power curve. This will be useful to the team as a guideline for creating the turbine, with the consideration of power production based off the relative wind speeds the turbine with endure.

The third main code that the team will have to follow will be PTC46-1997. This code is a basis for overall power plant performance. This will be helpful not only for the mechanical testing team, but also the Siting team. This code will need to be referenced for the Mechanical team due to the overall power production of the turbine. The team will need to make sure that no wires are exposed as well as a grounding node is attached to the final design to make sure no excess current is left in the turbine. [2]

The final code that we as a team will have to be following is the overall engineering code of ethics. This code states that under no circumstances will the team or team members jeopardize the final design from a safety standpoint. This is important because when the turbine is spinning there exists the possibility that the blades could break and potentially hurt not only the team members but the people watching the overall tests as well.

Table 1: Mechanical Test Turbine Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASME PTC-11-1984	Fan blades	The team will be analyzing the different airfoils around the turbine. This code depicts how to measure them
ASME PTC-42-1988(R1988)	Wind turbines	This code shows how general wind turbines will be created, and how they need to be structured within a power grid as well as a turbine array
ASME PTC-46-1997	Power plant Design	The final turbine will have to emit a positive current there for generating power. This code creates a foundation for wiring as well as the overall power transfer to the “grid”
Engineering Code of Ethics	Ethics	All the team members must follow these guidelines and make sure the turbine and everyone operating the turbine is safe for people testing and watching the test.

3 DESIGN SPACE RESEARCH

The team has taken different tasks to achieve customer needs and competition guidelines. Every member of the CWC has read their required portion of the textbook, "Wind Energy Explained" and has taken measures to implement this information into the project design. The team has also researched different materials including but not limited to System Advisory Model, Continuum 3, Arduino, MATLAB, and Google Earth to better the team's turbine and siting design. Each team member has undergone various research to understand and fulfill different goals.

3.1 Literature Review

The mechanical team has started overall research in: blade designs, generator selection, braking systems. These different subsystems are helpful for the overall power production as well as the stopping of the turbine design. The different blades were looked at, analyzing different airfoils and the overall coefficients of lift to the blade design. The Breaks team looked at different break designs as well as creating a dynamic break calculator to find the time to stop. The final point was the generator, the team was looking into different methods, as well as the power production for different motors based off the overall kV rating of the different motors. The team had to develop a functional brake model and overall nacelle and internals for the nacelle. The selected design for the brakes is one actuated brake pad that contact a floating disk to static pads mounted to the nacelle of the turbine. The liner actuator and the active pitching mechanism will be controlled by an open-source Arduino coder and the shaft will be designed through a dynamic calculator with the aid of equations out of Shingley's Mechanical Engineering Design mostly to find the minimum diameter to be within safety specifications. Many of the equations used to calculate torque and brake force are from the SAE Brake Design and Safety. Many of the torque calculations were derived from Wind Energy Explained to get equations to get the brake force equal to the torque created from the blades so that the turbine may stop. All the calculations were then plugged into MATLAB to get physical properties of the design of the turbine subsystems. Once the physical specifications are created it then will be modeled in a 3D CAD program SolidWorks. Once it is all modeled in the 3D CAD program it will then be put into drawings and sent to a machine shop. This will result in acquisition of physical pieces of the turbine, so then it also may be assembled and tested.

3.2 Benchmarking

In this section, the team has evaluated various designs of turbine blades, generator selection, and a yawing system for the team's current turbine designs and research.

3.2.1 System Level Benchmarking

3.2.1.1 Existing Design #1: Physical Design

The overall turbine has five amin physical designs that need to be looked at. The first main one will the tower and this piece holds up the entirety of the turbine. The next piece that will be looked at is the nacelle which connects to the tower and holds all of the electrical subsystems and the other physical designs. This is the main crucial piece to the turbine it serves as the connecting point for all of the other function of the turbine.

3.2.1.2 Existing Design #2: Electrical Systems

The next major function starts at the generator of the turbine. When the turbine is spinning it will generate a voltage from the three-phase motor then it will go through many different rectifiers and circuits to generate a power that is useful to the team and the turbine this will be described in mor in depth.

3.2.1.3 Existing Design #3: Data Acquisition

The team has a point of common coupling box (PCC) which houses NI LabView and various electrical circuits. The voltage from the turbine comes from a voltage booster developed by the Electrical Engineers and then is tapped and put into the PCC box that allows for the reading of the voltage. Then once the voltage is read it also goes into a DC load that measures the amperes coming of the turbine with that specific load. The data acquisition will also be done through an Arduino and this will collect various environmental data.

3.2.2 Subsystem Level Benchmarking

3.2.2.1 *Subsystem #1:* Pitching and Yawing

The team's main expectation is to design a turbine that will allow it always to be in the direction of the free-flowing velocity. Through the free-flowing velocity, it can make the most power. This can be done through the active pitching system and the passive yawing system.

3.2.2.1.1 Existing Design #1: Passive Yawing System

The passive yawing system was designed with a large fin in the rear that will push the turbine in the proper direction facing the wind. This fin is a simple large hemisphere plate that is attached to the back of the turbine.

3.2.2.1.2 Existing Design #2: Active Pitching System

The active pitching system is done through the use of the Arduino data actuation system and the control systems done by the same Arduino. The team will be using the voltage read in from the turbine and from that read in it will determine the condition of the turbine and through those conditions it will pitch the blades at a certain angle.

3.2.2.2 Subsystem #2: Data Collection

The team is required to collect data to share and display to the judges of the Colligate Wind Competition. This data will also allow the team to trouble shoot the turbine and make adjustments throughout based on the received data from the two DAQ systems.

3.2.2.2.1 Existing Design #1: National Instruments LabView

The National Instruments with LabView will be reading the voltage after the boost converter coming off of the turbine. It will then spit and go into a shunt resistor that will read the current. Both of these variables will be input to the LabVIEW and displayed through the user interface and recorded to excel. Also, with the variables other calculations can be made such as the power produced. The NI and LabView will also be reading the wind speeds directly next to the turbine to verify the conditions that the turbine is in.

3.2.2.2.2 Existing Design #2: Arduino

The Arduino will be reading environmental data around the turbine and some various parts of the turbine. The main data that will be collected is the temperature which will be collected by a MAX 31855 chip and a K-type thermocouple and the pressure around the turbine at a certain altitude as well as the temperature again from a 3115A2 Altimeter Chip. This will give all the necessary environmental data required by the client and the CWC. For the team's personal use, the Arduino will be reading an IR sensor underneath the shaft that will show the RPM value that the turbine is rotating.

3.2.2.3 Subsystem #3: Electrical Subsystem

This subsystem will describe the voltage and how it will be used once it is produced by the turbine.

3.2.2.3.1 Existing Design #1: Point of Common Coupling Box

Once the voltage had been generated by the turbine it will go into a point of common coupling box which includes a boost converter from the turbine. Then once it leaves the boost converter it will enter the PCC box which houses the two DAQ systems.

3.2.2.3.2 Existing Design #2: Control Systems

The control systems will be controlled through the same Arduino that reads environmental data and turbine data. The data read from the Arduino will then go through data processing and at certain conditions it will have the turbine go into a startup, operational, and stall condition, Of the three conditions the first two, the startup and the stall, the brake will be retracted. In the final condition the brake will be extended, and the blades will be put into stall condition, this will happen when the turbine is moving too fast, or a button is manually active.

3.2.2.3.3 Existing Design #3: Wiring

The wiring from the turbine part of the system to the various other subsystems was done through the use of a slipring and multiple wires. The slipring is designed for the turbine to rotate in any direction no matter how many rotations and still be connected to the rest of the system. The slipring was then connected to the various controls systems in the turbine such as the brakes and the pitching system and well as the three phases for the motor. This will then go to the rest of the electrical subsystems in the PCC box and Arduino.

4 CONCEPT GENERATION: Mechanical Turbine

In the early stages of the project many of the components were unrefined and thus had to go through several iterations before coming to a suitable design for our turbine.

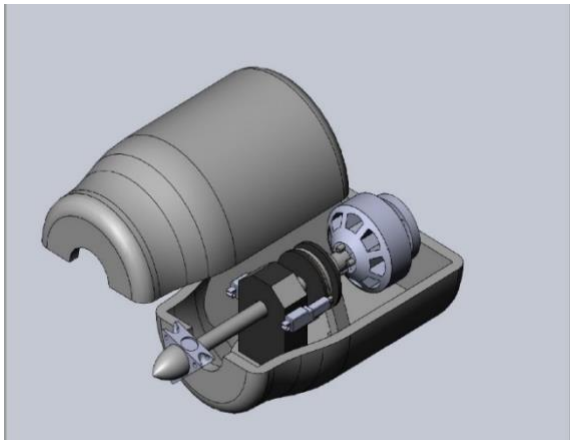


Figure #4: Initial Nacelle design 1

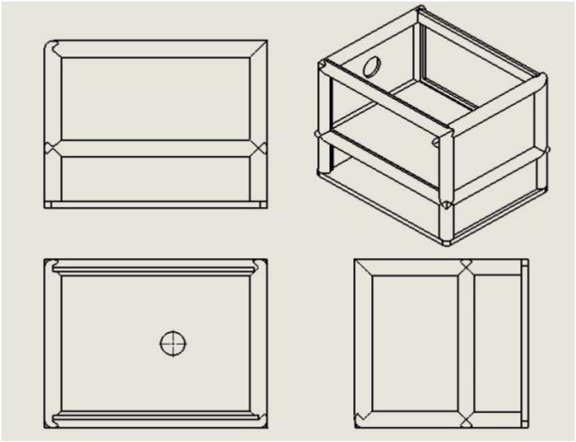


Figure #5: Initial Nacelle design 2

The overall view of the initial nacelle designs. Design 1 is bottle shaped to be more aerodynamic, and large enough to hold the initial components of the turbine. Design 2 was a box shape to allow for ease of construction and deconstruction.

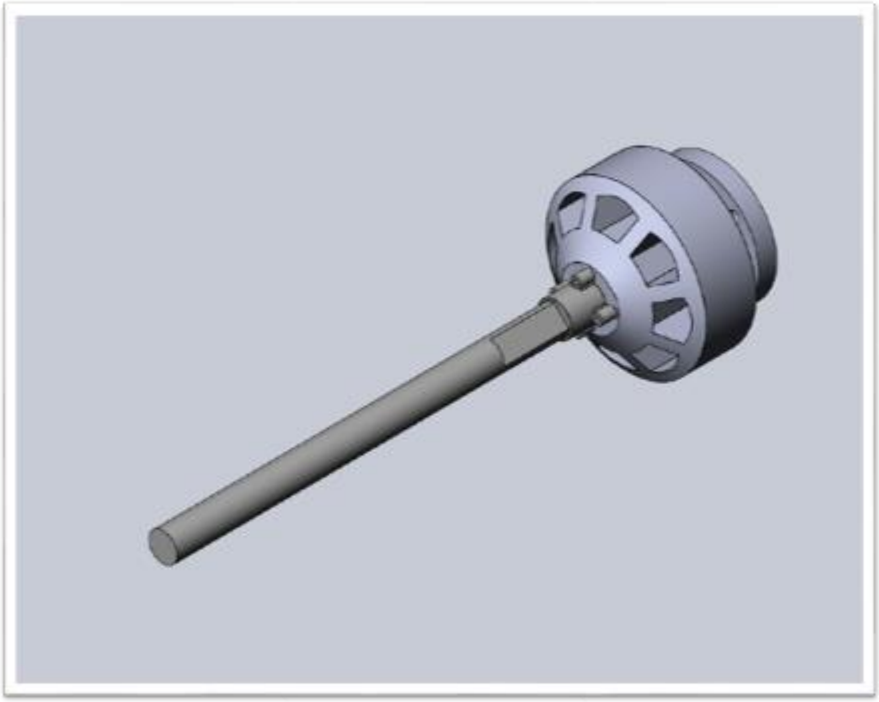


Figure #6: Initial Shaft and Motor Design

The basic shaft and motor design that will transfer the torque of the blades to the generator and turning into voltage.

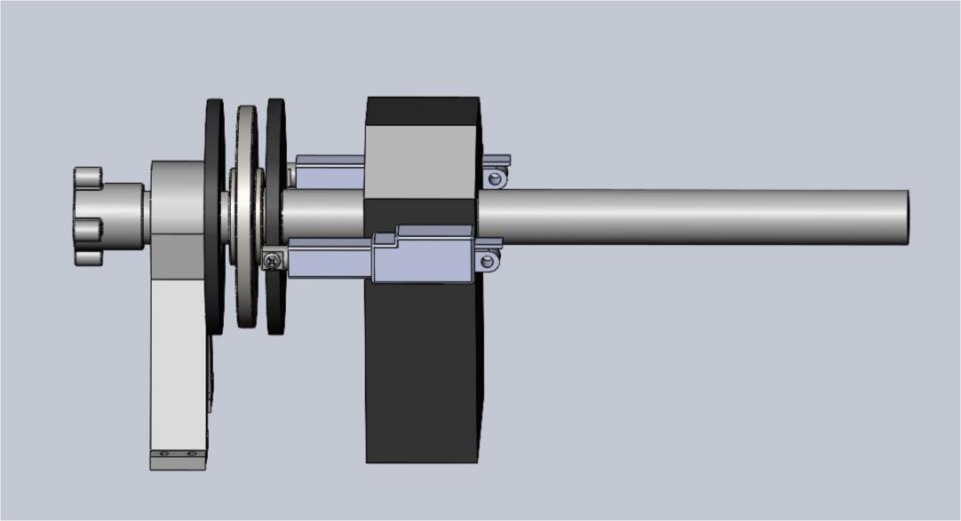


Figure #7: Initial Shaft and brake design

The basic design of the brakes on the shaft and the mounting to the nacelle.

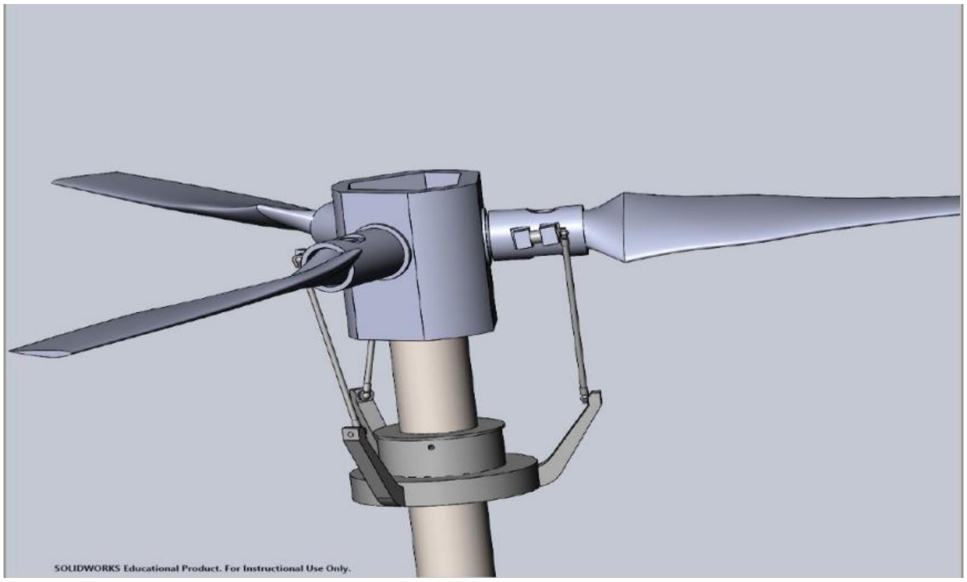


Figure #8: Initial Pitching swash plate mechanism (initial idea)

The basic design for the active pitching mechanism using a swash plate to rotate the blades.

4.1 Full System Concepts

The only major decision that would guide the entire design of the wind turbine is that of horizontal vs vertical turbine orientation. This alone changes the maxims we should use in our design and building process. As such, we have documented our reasoning for our decision below. In section 4.2 we will elaborate on minor changes to the system that differ between designs.

4.1.1 Full System Design #1: Horizontal Axis Wind Turbine with Pitching

The most basic decision that the group needed to make was what style of turbine to use. Horizontal or vertical axis (HAWT or VAWT) was the most overarching category that the team needed to decide upon. The identifying advantage of VAWTs is the turbine's ability to operate in an erratic flow field, while their obvious disadvantage is the presence of a retarding vane causing a decrease in net torque produced by the machine. Since the competition will have testing for pitching that is rather predictable, the versatility of a VAWT is unneeded, therefore the HAWT with its superior efficiency characteristics was chosen.

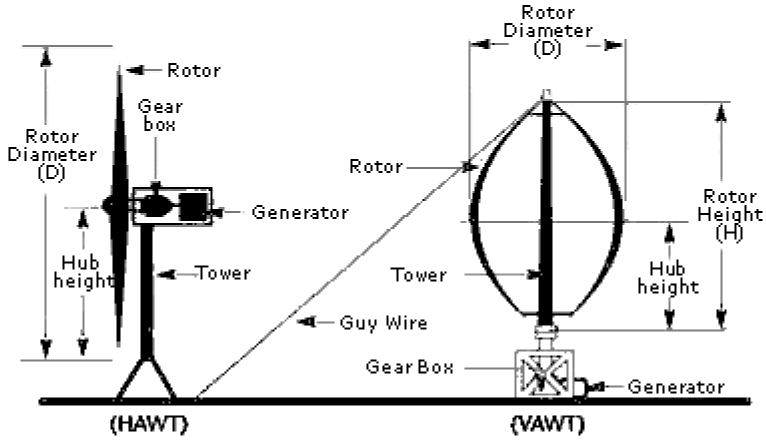


Figure 9: HAWT vs VAWT Diagram

Pros of HAWTs:

- High efficiency
- Well documented design methodology
- Positive torque produced throughout the entire configuration.

Cons of HAWTs:

- Poor start up characteristics.
- Susceptible to erratic flow fields
- Manufacturing techniques are difficult compared to VAWTs.
- Elevated nacelle is required.

4.2 Subsystem Concepts

The subsystems indomitably considered for our turbine were the blades subsystem, brake subsystem, and yawing subsystem. While many other components of our design were considered and iterated on throughout the design process, these three far exceeded any others in complexity of choices and tradeoffs. In contrast, the other subsystems did not require extreme sacrifice or tradeoffs during their design. Those honorable mentions requiring in depth study regimes, but yielded inscrutable solutions include the tower, nacelle, motor, and data acquisition subsystems.

4.2.1 Subsystem #1: Blades

The designing of the blade's subsystem required use to utilize iterative solvers due to the variant nature of options available alongside the binary decisions of design. In our binary decisions, we primarily focused on the pitching mechanism as we would need to utilize one to succeed in the start up competition. Secondarily, we had to use iterative solvers to converge on blade designs that could operate most efficiently at high speed while maintaining their usability at low-speed operations as well.

4.2.1.1 Design #1: Active Pitching

Pros of Active Pitching:

- Turbine can cut in at lower wind speeds
- Can design blade geometry at just the rated wind speeds
- Overcome cogging torque easier

Cons of Active Pitching:

- High Power Draw
- Very complicated swash plate mechanism
- May be hard to code

4.2.1.2 Design #2: BEM iterator without wake rotation

Pros of BEM iterator w/ out wake rotation:

- Easier to code

Cons of BEM iterator w/ out wake rotation:

- Inaccurate fluid flow description
- Unreliable values for coefficient of power

4.2.1.3 Design #3: CFD approach instead of BEM

Pros of CFD:

- Considers 3D effects of fluid flow around airfoil and next to hub
- More accurate around hub and tip of blade

Cons of CFD:

- Very high computational cost
- Much more complicated than BEM

4.2.2 Subsystem #2: Brakes

The primary system for stopping the turbine's rotation during operation.

4.2.2.1 Design #1: Single Caliper

There is a single caliper that actuates to a floating disk that contacts another brake pad therefore stopping the turbine.

Pros of Single Caliper:

- Low power draw
- Easily Coded

Cons of Single Caliper:

Long time to stop

Uneven distribution of load

Not powerful enough to stop torque of blades

4.2.2.2 Design #2: Double Caliper

The double caliper design will have two linear actuators that have brake pads on both actuators lined up to the outer ring of a fly wheel and when the brakes need to be applied it will clamp the fly wheel to two other brake pads that are statically mounted to the nacelle of the turbine forcing the blades to stop.

Pros of Double Caliper:

Short time to stop

Even distribution load

Can be designed with floating disk

Cons of Double Calipers:

Large power draw

Takes large portion of nacelle

4.2.2.3 Design #3: Round Caliper

The round caliper is supposed to be fitted to the outside of a disk then when the brake system is actuated the round rubber pad will be contacted with the floating disk and brough track to a static rubber pad which will allow the turbine to stop.

Pros of Round Calipers:

High surface area

Quick time to stop

Cons of Round Calipers:

High power draw

Overly complicated design

Takes large portion of nacelle

4.2.2.4 Design #4: Clamping

The clamping mechanism will be like that of a mountain bike in which an actuator will pull a cable and a clamping force will be applied to a disk which will then stop the turbine

Pros of Clamping:

Takes less space within the nacelle

Less power draws

High clamping force

Solid mounted disk on shaft

Cons of Clamping:

Unreliable

Needs system of pulleys

Does not face disk linearly

4.2.2.5 Design #5: Double Clamping

The double clamping will be like the single clamping mechanism however it will be on either side of the disk that is mounted to the shaft.

Pros of Double Clamping:

- Low time to stop
- High clamping force

Cons of Double Clamping:

- Large pully system
- Lots of space taken within nacelle
- High power draw

4.2.3 Subsystem #3: Yaw

Passive mechanism to keep the turbine angled in the direction of the wind.

4.2.3.1 Design #1: Double Yaw Tail (Trapezoid)

The Double tail method showcases a turbine with two tails that can act independently to apply force, but in conjunction to balance said forces. These paddles at the end of the turbine are responsible for two important things. The first of which is keeping the turbine aligned with the streamlines of the air. The second importance of this system is to produce a reduction method for backdraft/ pressure discontinuities along the turbine and ultimately into the blades. The backdraft from the blades can negatively affect the overall efficiency of the turbine.

Pros of Double Yaw Tail:

- Ability to keep turbine in correct airflow
- Wind control

Cons of Double Yaw Tail:

- Gap in between blades
- No support for backdraft
- No overall support on yaw system
- Extended tail

4.2.3.2 Design #2: Single Small Yaw (Trapezoid)

The single tail system, this system sits on a tail towards the rear of the turbine design. This design also helps correct the direction of the turbine and produces a stable environment for the turbine to operate within, it acts as a counterbalance for the turbine. However, this design does not prevent the overall back draft of the wind airfoils from the turbine.

Figure 10: Small single yaw system[Y1]

Pros of Single Small Yaw:

- High efficiency
- No gap between parts

Cons of Single Small Yaw:

- Extended tail
- No support for backdraft
- No overall support on yaw system
- Extended tail

4.2.3.3 Design #3: Large Single Yaw (Trapezoid)

The trapezoidal system will be a large trapezoid that sets directly being the mounting point for the generator. The trapezoidal Yaw system will create a slanted wall for the air to evenly flow over the system, this will also create a barrier at the rear of the trapezoid for the backdraft to be caught on and prevent it from flowing back into the system.

Pros of Large Single yaw:

- High efficiency
- Creates a path for the airfoils to travel over.

Cons of Large Single yaw:

- Bulky
- Must be in one piece for optimum efficiency.

4.2.3.4 Design #4: Single Yaw (Square)

The square single yaw system would be a thin square attached to the rear of the turbine so that it can act as a passive yawing system.

Pros of Single Yaw (Square):

- Easily designed
- Easily installed

Cons of Single Yaw (Square):

Not appropriately aerodynamic.

4.2.3.5 Design #5: Single Yaw (Circle)

The circle single yaw system would be a thin square attached to the rear of the turbine so that it can act as a passive yawing system.

Pros of Single Yaw (Square):

Easily designed

Easily installed

Cons of Single Yaw (Circle):

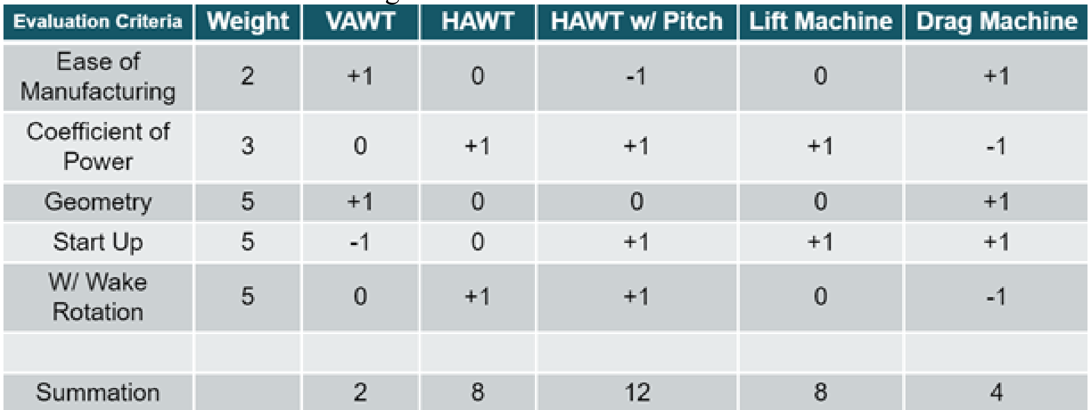
Not appropriately aerodynamic.

5 DESIGN SELECTED – First Semester

5.1 Technical Selection Criteria

Table 6 represents the Pugh chart that was used to aid in the selection of the classification of the wind turbine the group would produce. These turbine designs are very general, breaking the decision down to whether a horizontal or vertical axis turbine will be used (the distinction between lift and drag machines are also included for even further general analysis of the design problem). The important evaluation criteria are limited to the geometry and startup of the turbine as they will directly affect the scoring of the turbine in the competition. Other key factors include consideration for wake rotation and the potential coefficient of power. Another factor of slightly less importance is the ease of manufacturing. This criterion is not scored in the competition at all, so it received the lowest ranking.

Table 2: Pugh Chart for the Class of Wind Turbine

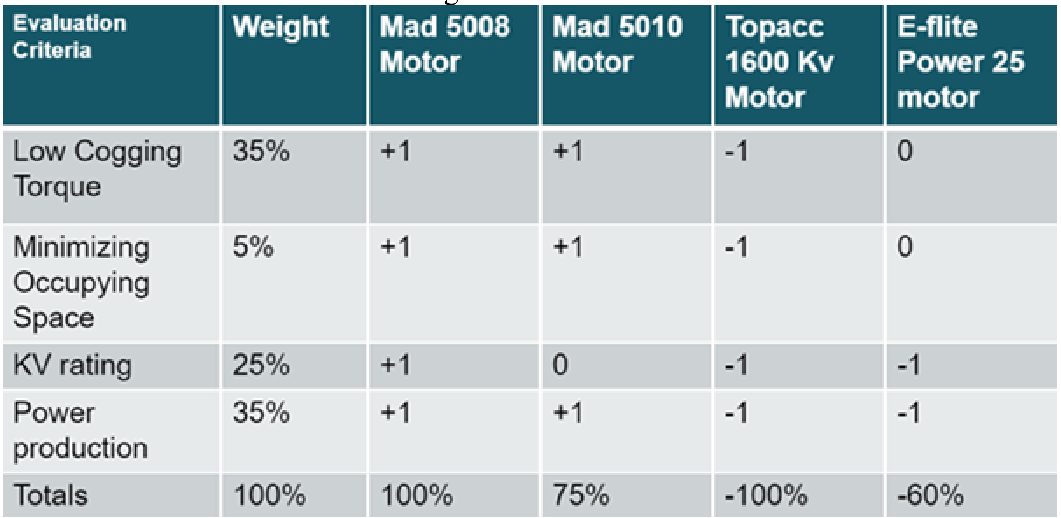


Evaluation Criteria	Weight	VAWT	HAWT	HAWT w/ Pitch	Lift Machine	Drag Machine
Ease of Manufacturing	2	+1	0	-1	0	+1
Coefficient of Power	3	0	+1	+1	+1	-1
Geometry	5	+1	0	0	0	+1
Start Up	5	-1	0	+1	+1	+1
W/ Wake Rotation	5	0	+1	+1	0	-1
Summation		2	8	12	8	4

The lowest scoring design option is the VAWT. Although it had superior manufacturing options, it falls short in other key areas such as the coefficient of power and the startup ability it possesses. The designs that tied for second have a remarkably similar design, in the fact that the classifications are not mutually exclusive (i.e., lift machines can be HAWTs). They both scored well because of their design flexibility and their tendency to have a coefficient of power that approaches the Betz limit well. But they both fall short of the HAWT with pitch; although this design can be considered a classification of a HAWT, the benefits of the inclusion of pitch have benefits that can be seen within the Pugh chart that are not properly displayed under its general HAWT classification, particularly, its ability to start up well despite conditions outside of the BEM theory's design parameters.

Table 7 represents the decision making for the generator. The generator was selected from four main criteria. These were having a low ideal cogging torque based off the number of coils and magnetic poles, a small motor to minimize space in the nacelle, being within the ideal kV rating for the turbine, as well as being able to maximize the overall power production from the motor. The different motors that were examined in the Pugh chart were the three motors mentioned above. From this Pugh chart the team has selected the MAD 5008 (Figure 10) motor based on all the requirements from the Pugh chart.

Table 3: Pugh Chart for the Generator



Evaluation Criteria	Weight	Mad 5008 Motor	Mad 5010 Motor	Topacc 1600 Kv Motor	E-flite Power 25 motor
Low Cogging Torque	35%	+1	+1	-1	0
Minimizing Occupying Space	5%	+1	+1	-1	0
KV rating	25%	+1	0	-1	-1
Power production	35%	+1	+1	-1	-1
Totals	100%	100%	75%	-100%	-60%

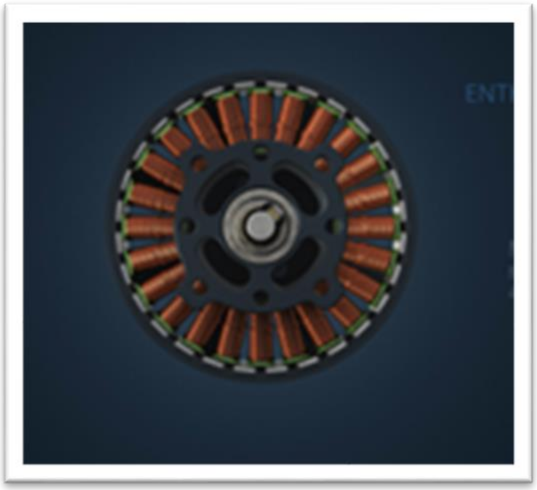
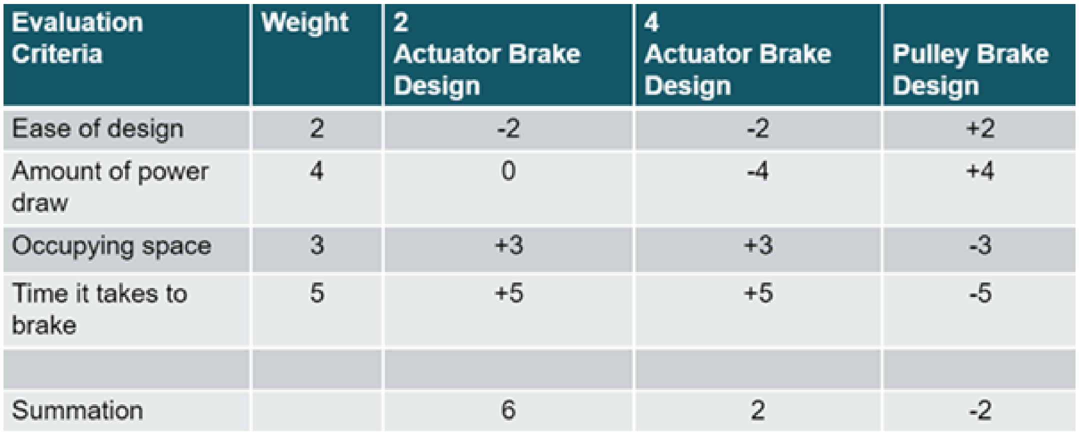


Figure 11: MAX5008 kV Generator

Table 8 weighs between the functionality of the 2-actuator brake, 4-actuator brake, and pulley brake design systems regarding the amount of space, amount of power, and time it takes to brake for each system.

Table 4: Pugh Chart for the Brake Design



Evaluation Criteria	Weight	2 Actuator Brake Design	4 Actuator Brake Design	Pulley Brake Design
Ease of design	2	-2	-2	+2
Amount of power draw	4	0	-4	+4
Occupying space	3	+3	+3	-3
Time it takes to brake	5	+5	+5	-5
Summation		6	2	-2

5.2 Implementation Plan

For next semester, the team plans to develop physical prototypes for all the subsystems that have been developed in the CAD model. This includes the subsystems for the brakes, pitching mechanism, generator, yaw, and tower. Additionally, the blades and hub design will be refined as prototyping has already begun for these components. The mechanical test turbine team will be researching more into how to code in Arduino to control the linear actuators utilized in the brake system as well as the stepper motor that we plan to use for the pitching mechanism. The mechanical design systems currently need three Arduino Uno controllers for the pitching, braking, and for the rpm sensor systems. In terms of mechanical and actuation devices, the team is already in possession of a testing generator, L16 linear actuators, and two stepper motors for prototyping purposes. A final selection has already been made for the generator in our turbine and a shaft for the tower is already available, although the tower is likely to undergo some redesign as the team moves through testing over the brake. A nacelle design has been chosen with an open compartment for the mechanical components and a secondary enclosed layer for the electrical components in the turbine.

Currently the team plans to make the final brake disk and hub out of metal that will be outsourced due to the complexity in their designs. Aside from that, the swashplate for the pitching mechanism will need to be remade or adjusted so that it works within our system, as the current design has unchecked degrees of freedom in terms of pitch, roll, and an over extended degree of freedom in the yaw direction. The team will use the NAU machine shop for any manufacturing that is within our skill level and anything else will need to be outsourced. Prototyping still needs to be undergone for most of the sub-assemblies so decisions on where to outsource parts will be addressed over winter break once the team has a more concise list of what needs to be manufactured for the wind turbine. Screws, bolts, bearings, washers, and other mounting or spacing components will be decided on as prototyping commences. The current schedule is to get the brake, pitch, and yaw systems done by the end of December so that final designs can be refined, and necessary parts can be outsourced by end of January or mid-February. Additionally, a current BOM of all the CAD components can be found in Appendix D of this report as well as all of the CAD subassemblies in Appendix A.

5.2.1 Gantt Chart

The team has been following this schedule. Figure 11 showcases the different steps that the Mechanical test team has taken so far this year to complete the final research and design process for creating the micro turbine. These tasks include but are not limited to, designing a BEM iterator for the blades, researching different motors and break designs. The team has also conducted research to ensure that all the airfoils are correct, as well as the breaking forces would be adequate for the final design.

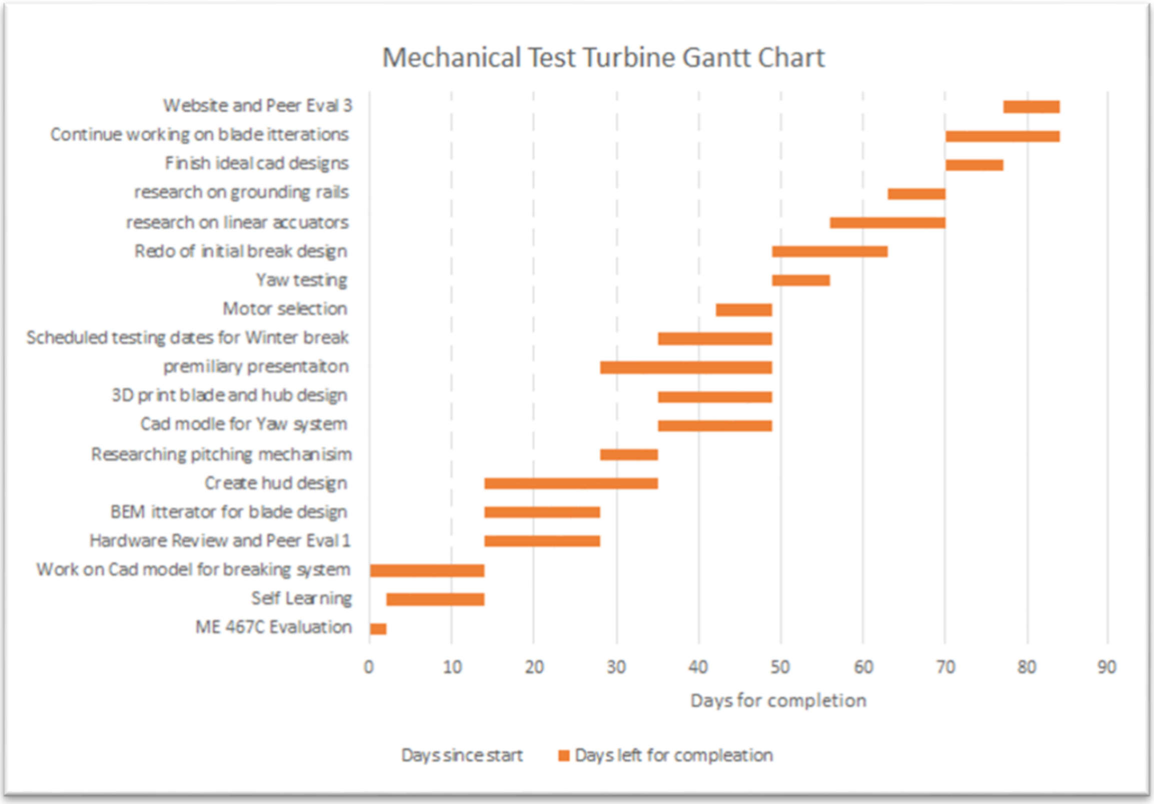


Figure 12: Mechanicals test team Gantt chart.

5.2.2 Computational Fluid Dynamics

The group will be utilizing a rotating mesh simulation in ANSYS to confirm the forces experienced by the turbine. This analysis will not only serve as confirmation of the required material strength but also to test the power produced by the turbine at different oncoming wind speeds and tip speed ratios. These simulations will drive the redesigns of any existing parts.

5.2.3 NAU MakerLab Fabrication

The team will use the MakerLab for all initial designs and prototypes of the turbine. The final design is not created; however, some components may be 3D printed for weight reduction on the overall turbine. The MakerLab also allows for very versatile and rapid design alterations.

5.2.4 Local Hardware Departments

Although difficult to quantify, the group will need fasteners, bearings, joints, tools, among other small components throughout the entirety of the project. Homco is a local hardware and lumber store to Flagstaff that not only carries a large section of the above parts but also has customer service that is willing to work with individuals until the desired parts are located.

5.2.5 Arduino Microcontroller

Within the turbine system there are many mechanical components that will need to interface with a microcontroller, including but not limiting to the pitching mechanism, the brake system, as well as read voltages being output by the turbine. The group will be utilizing an Arduino (Figure 12**)** in considerations of its versatility and cost effectiveness.

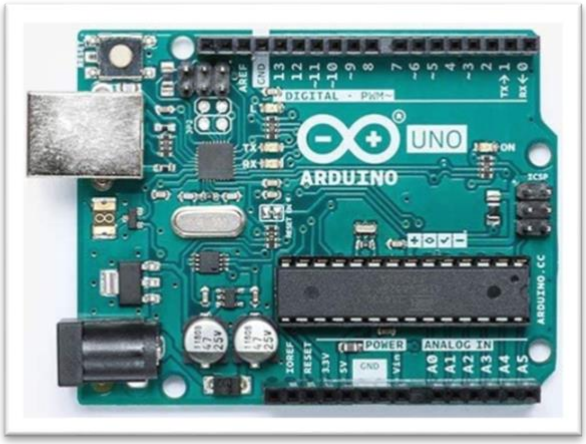


Figure 13: Arduino Microcontroller

5.2.6 NAU Machine Shop

Several members of the group are safety trained to employ the resources available at the on-campus Machine Shop. Some parts that are currently under consideration for machining is the team's original hub designed depicted in Figure 13.

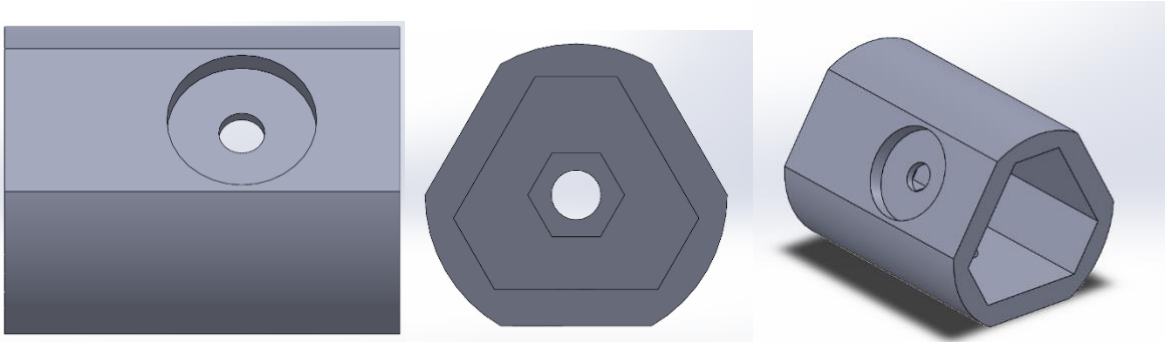


Figure 14: Original Hub Design

The machining shop also accepts work orders, so even if there is advanced geometry desired in the parts that is above the skill level of the trained members, the possibility of fabrication remains.

5.2.7 Outsourcing

The group hopes to refrain from outsourcing too many parts. However, there are several parts of the turbine that are specialized enough that outsourcing would prove far more time efficient than designing the individual parts. Examples of this would be the 3-bladed swash plate that is sold by Align or the MAX5008 170 kV generator.

Figure 15: 3-Bladed Swash Plate from Align

Another possibility for outsourcing is the unforeseen closure of currently available facilities, such as the NAU Machine Shop or MakerLab. With the existing condition of Covid-19 in Flagstaff, Arizona, these events seem unlikely. However, the group recognizes the incredibly dynamic state of the world produced by 2020 and acknowledges the possibility of these events and are prepared to adapt.

6 IMPLEMENTATION – Second Semester

6.1 Design Changes in Second Semester

During the second semester the team made several changes to the overall structure and connection methodology for the turbine. As separate components began to come together, necessary changes became evident to allow the sub-systems to intermesh. As such, adjustments were made to the nacelle, shaft, and blades which in turn necessitated remodeling most of the turbine.

6.1.1 Nacelle Updates

The nacelle has gone through constant change over the last few weeks to adjust for updates in parts, sub-systems, and ease of construction. The Mechanical Bracket and Electrical housing are the final iteration of the nacelle after changes were made to increase the aerodynamics of the housing as well as decreasing unused space. The Mechanical Bracket holds the length of the turbine shaft from motor to hub with the use of bearings to minimize friction losses. In the middle is where the linear actuating-braking system is stationed, and at the front is where the final iteration of the pitching mechanism is housed. The original model for the Mechanical housing was split into three sections due to its complexity but was later conjoined as one to mitigate errors during assembly. Additionally, after all the sub-assemblies were finalized, a cover was added to avoid causing any low-pressure zones.

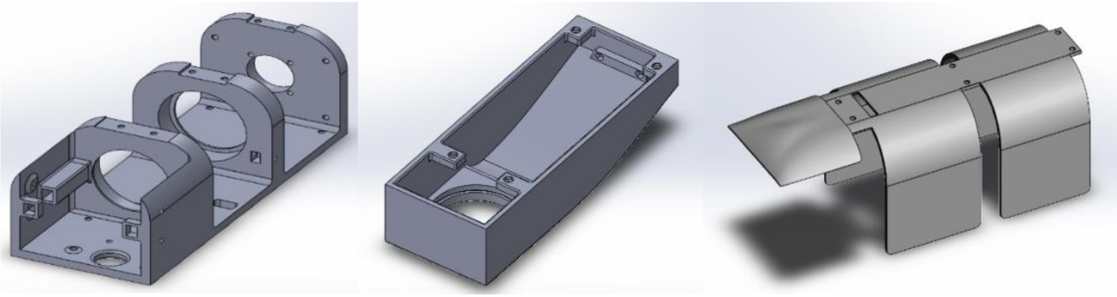


Figure #16: Mechanical Bracket (left), Electrical Housing (middle), Cover (right)

There was concern from our client about the strength of the 3D printed materials we have at and what forces we could potentially see during operation. As such, we did an FEA analysis of the housing and reassured our client that our maximum force would only be around 2.75 MPa at the connection point. Image # and # below show the potential displacement and stresses we expect to see in the electrical housing.

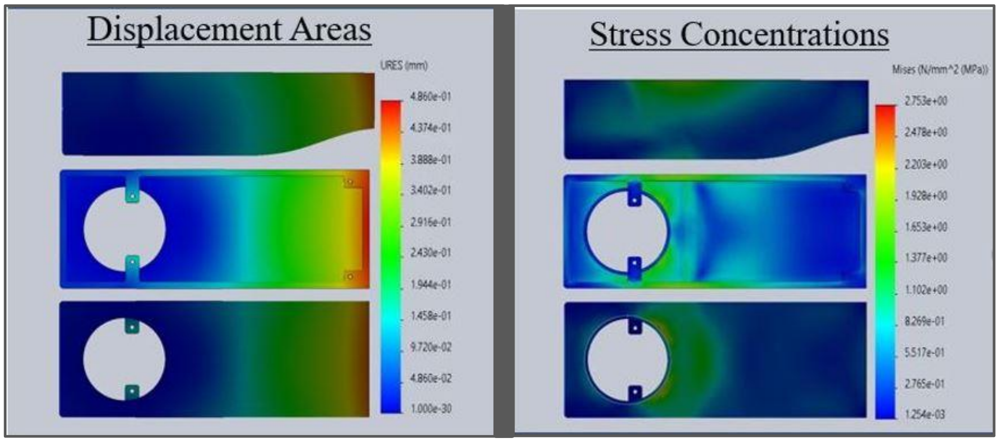


Figure #17: EE housing FEA Analysis

6.1.2 Hub Update

The hub design was adjusted numerous times throughout the semester and the final iteration utilized mounted bearings at the blade connection point to allow for as little friction as possible when pitching the blades. This decision gives our device much more precision when changing the angle of the blades which will allow for us to collect the maximum power in the wind at the optimal position.

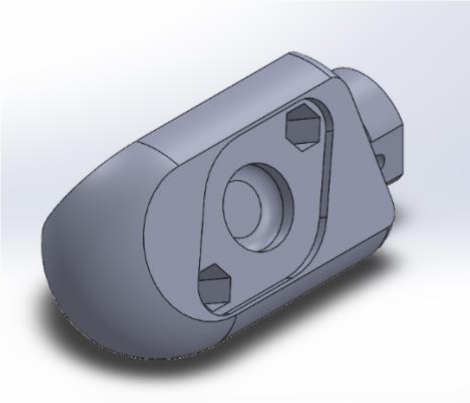


Figure #18: Hub

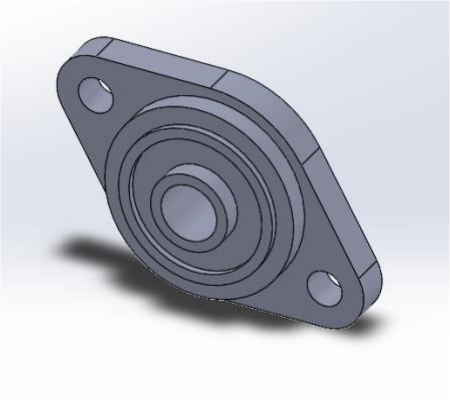


Figure #19: Mounted Bearing

6.1.3 Yaw Fin Updates

The yawing fin has gone from a single fin design to a double fin design as our team realized that the square flat shape of the back of our nacelle was interfering with our turbine's aerodynamics. The use of two fins gets rid of the disconnect from the bracket to the yaw and it increases the torque produced from the wind to turbine.

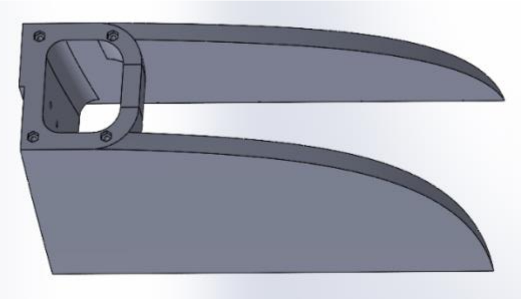


Figure #20: Yaw Top Fin

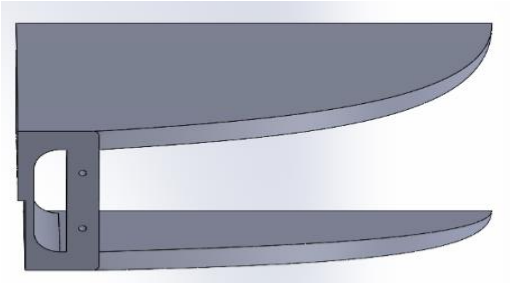


Figure #21: Yaw Bottom Fin

6.1.4 Tower Updates

Last semester our team planned on using a PVC pipe for the tower and the baseplate was to be 3D printed, but due to some concerns from our client we decided to go with a full metal base and tower. The tower and baseplate are both 6010 Aluminum, which we performed an FEA analysis of to make sure that the connection methodology at the top would not compromise during operation.

6.1.4.1 Tower

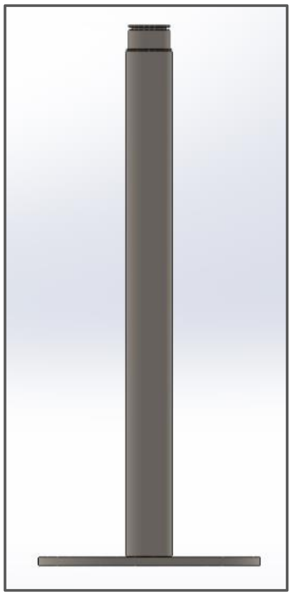


Figure #22: Tower

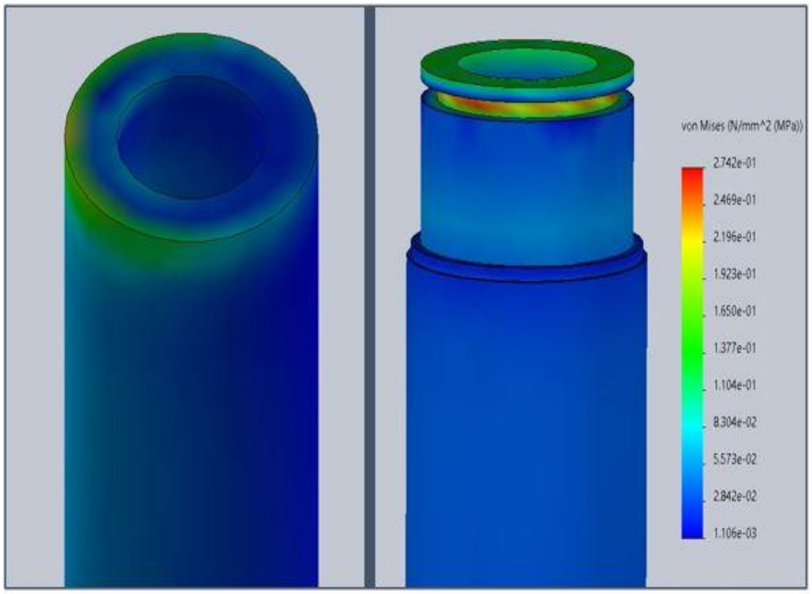


Figure #23: FEA at tower connection

6.1.4.2 Tower Connection Methodology

The top of the tower originally utilized a single bearing system, but the team decided to double it to give extra support to the nacelle. A groove was machined at the top of the tower to make room for the bearings which are secured with the use of a retaining ring to make sure none of our wires become twisted and mangled while the tower is spinning, we utilized a slip ring to at the top of the tower.

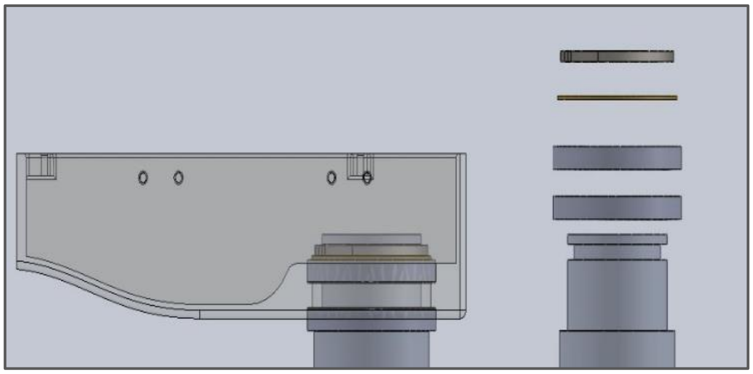


Figure #24: Tower to Electrical Housing connection

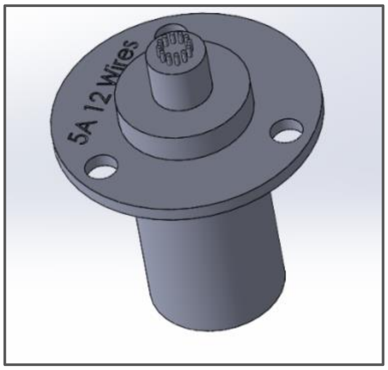


Figure #25: Slip Ring

6.1.5 Blade Update

The blades have changed in design several times to account for changes in the amount of power we need to produce for the competition as well as for the systems in the turbine. The most recent changes in the blades, aside from the general geometry, was the decision to make the coupler and blades one part rather than keeping them separate.

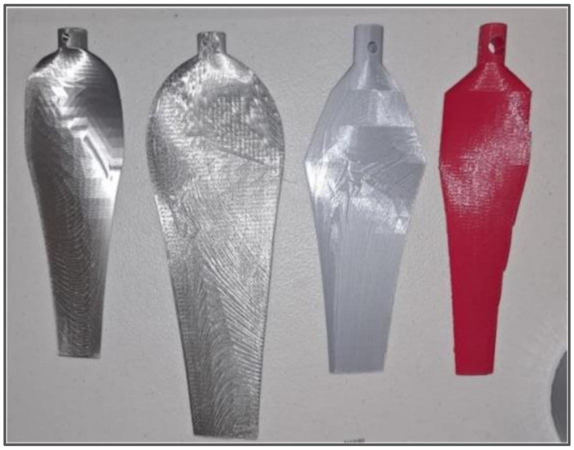


Figure #26: Early Blade iterations

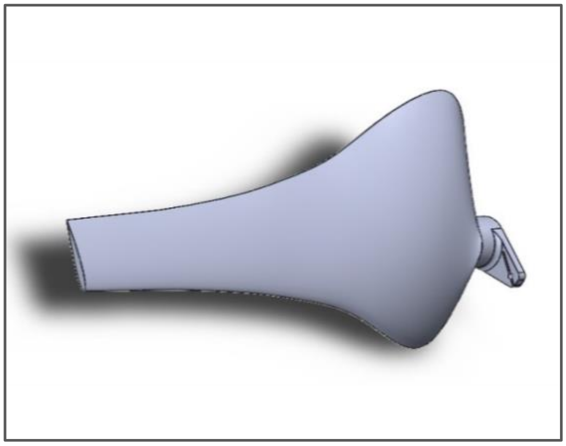


Figure #27: Current Blade(s)

6.1.6 Pitching Sub-System

The Pitching System is one of the most complex parts on the turbine, and as such it has gone through numerous iterations. The most recent changes involved some fine tuning of the stepper motor gear system which is used to push the swashplate forward or pull it back. This motion pivots the blades so that they stay at the optimal position during operation.

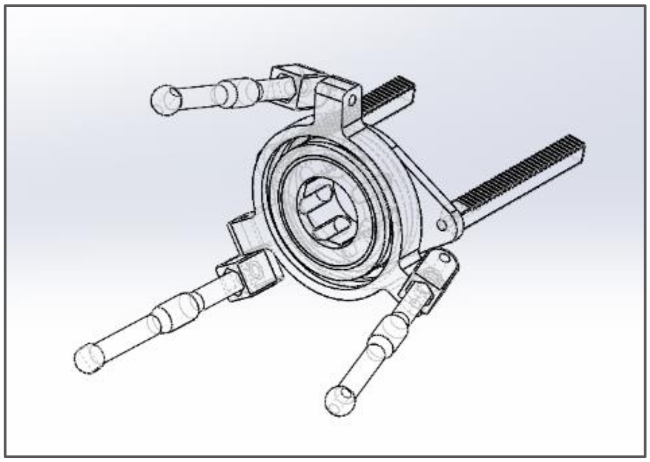


Figure #28: Swashplate Pitching Mechanism Visual

6.1.6.1 Swashplate

The use of a swashplate restricts the degrees of freedom to give us control of the rotation of the blades without inhibiting the rotation of the turbine shaft. Originally our team attempted to buy a swashplate used in RC helicopters, but after not being able to find one that would fit our dimensions our team opted to create our own via 3D printing.

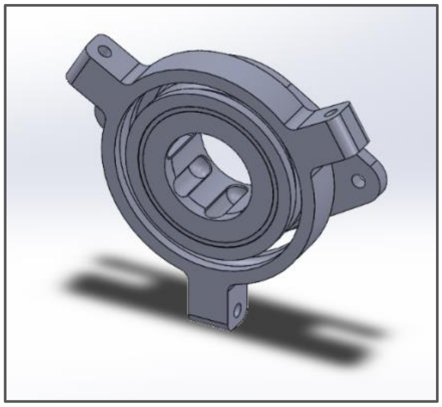


Figure #29: Swashplate Visual

6.1.6.2 Heim Joint & Coupler

Connected to the blades to so that each blade gets positioned at the same angle at the same time.

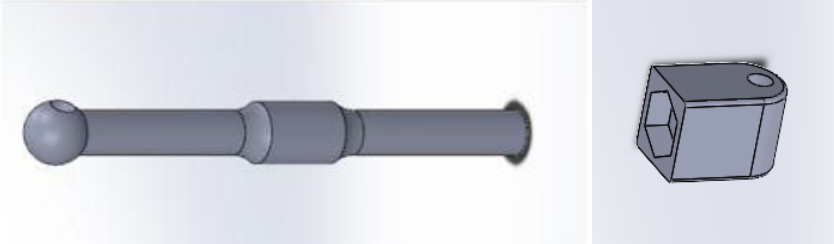


Figure #30: Heim Joint of Pitching Mechanism Visual

6.1.6.3 Gearing

A stepper motor was utilized along with some 3D printed gears to keep the blades pitched at the correct angle. A rack gear is used on each side of the swashplate to keep the force pushing and pulling on the pitching mechanism as even as possible.

Figure #31: Wall, Floor, and Stepper Gear

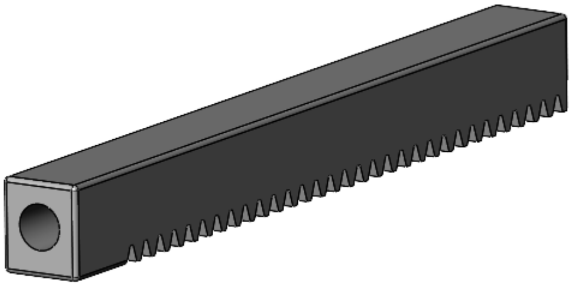


Figure #32: Rack Gear

6.1.6.4 Stepper Motor

A stepper motor was used to increase the precision of the pitching mechanism as it is easier to code a stepper motor to rotate within specified degrees.

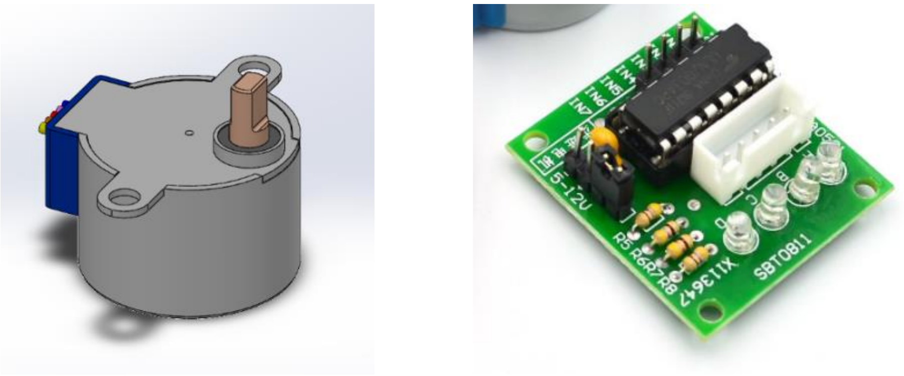


Figure #33: Stepper Motor and Driver

6.1.7 Shaft Update

The shaft has gone from being two parts to one, as it was initially split so that the brake disk could be assembled onto the shaft. We realized that splitting the shaft into two parts gave it less stability during operation, so the part was redesigned as one part with an edited groove for the disk brake to slide on. A coupler was also manufactured for the back of the shaft to allow it to mount onto the motor.

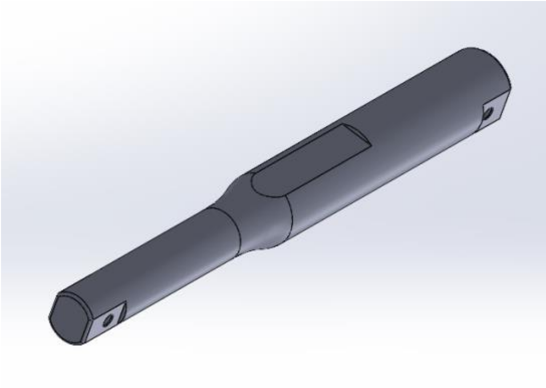


Figure #34: Shaft

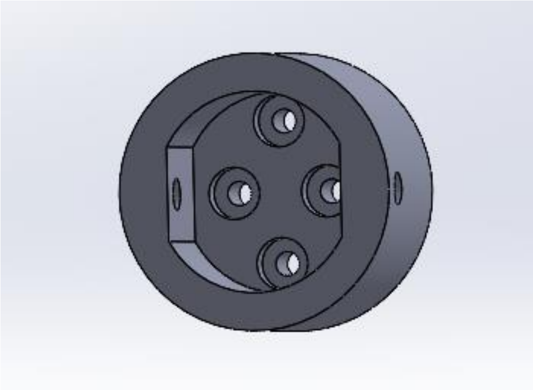


Figure #35: Shaft Coupler

6.1.8 Brake System/Components Update

The original Brake system utilized two linear actuators and a flat circular brake pad on either side of the brake disk to halt the turbine's motion. Since the original iteration, the brake system has been updated to be a single linear actuator on account of not needing as much force to brake. This is primarily thanks to the pitching mechanism's ability to initiate stall, which decreases the force needed, thus allowing us to use less power to stop our turbine.

6.1.8.1 Braking System

The braking system is in place to keep the turbine stopped when not in use as well as to stop the turbine from spinning when the operator does not want it in motion.

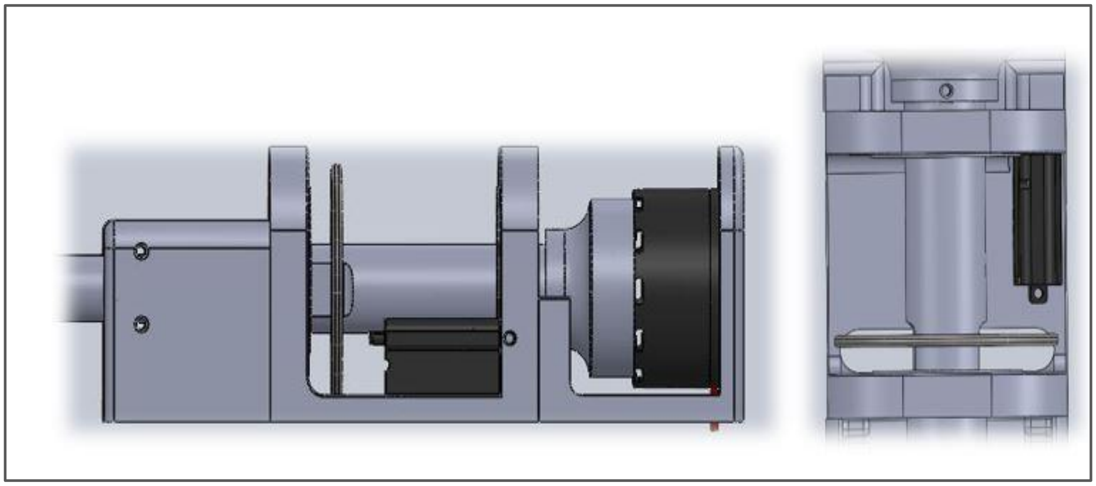
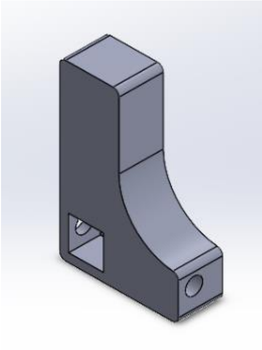


Figure #36: Braking System Visualization



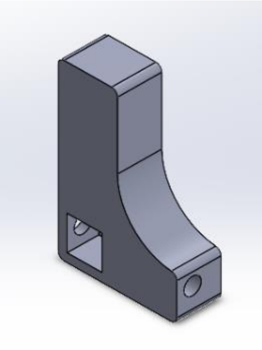


Figure #37: Brake Disk

Figure #38: Linear Actuator

Figure #39: Brake Pad

7 RISK ANALYSIS AND MITIGATION

Looking at the overall top two potential modes for each semester, the team has found ways to help mitigate the potential failure, as well as troubleshooting potential issues that could occur when constructing the final turbine design. Over the break, the team was able to come up with different potential designs options. These new design choices created different failure modes that the team had to account for within the final turbine design. With all these failure modes, the team also came up with ways to mitigate all the potential failures. Within each of the following sections, each of the top four potential failures will be investigated as well as the ways the team planned to migrate those failures for both semesters.

7.1 Potential Failure first semester

Within the first semester the team was initially using a two-part shaft. The idea of this shaft was to help with the placement of different parts such as the fly wheel and the hub/swash plate assemblies. This shaft would use a left-handed thread in order to create an overall self-locking mechanism in the shaft to ensure that it would not separate during operation.

The second most important failure mode that the team examined was also with the shaft. The largest aspect was with the overall seizing of the left-handed thread. This was important to the team due to the overall ability to no longer change out the parts needed, as well as no way to examine any of the other main components of the turbine.

The next two aspects of the turbine that the team were focusing on due to potential failure modes were with the braking system as well as the pitching system. Within the braking system, the team was most concerned with were the brake pads. More importantly the overall impact fatigue on the brake pads. Without the brake pads, the team would have to rely on the pitching mechanism pushing the blades into stall and having the ability to stop the turbine.

With the pitching mechanism, the team had to investigate the overall aspect of the total amount of force the printed 3D filament would be able to withstand. With this aspect in mind the team looked at the different types of fractures. Without the pitching mechanism, the team would not be able to place the blades into the correct position in order to move and generate power, and much like the breaks, if the pitching mechanism were to fail, the team would have to rely on the brake pads in order to bring the turbine to a complete stop.

7.1.1.1 Potential failure rankings first semester

These different rankings were created by using the standard FMEA analysis modes by looking at different potential modes and ranking the overall Severity, Occurrence and detection.

7.1.1.1.1 Shaft design (Force/temperature deformation)

With the shaft design, the team was worried about the potential temperature deformation as well as the overall centrifugal force. The overall severity of this impact was ranked at an 8. This ranking was due to the face that the shaft has been designed to fit inside specific size bearings. If the shaft is deformed in any way, it will no longer fit within the specifications of the bearings which will cause the total internal workings of the turbine to fail.

Next within the overall force deformation of the shaft, the team looked at the overall occurrence of the phenomenon. The team started out with designing for all aspect of the turbine to have an initial factor of safety of two. With the overall design of the shaft, the final factor of safety was around three. This proved that the shaft would have a difficult time deforming in any way. With these numbers in mind, the team decided to give a ranking of 6.

The last aspect of the overall shaft deformation was that of the Detection. With the shaft, any form of deformation would be easily detected by the different team members. This detection would be found by the overall inoperative shaft within the bearing housings. With the overall ability to detect the deformation, the team ranked the detection at a 7.

With these different factors combined, the total score for the shaft while looking at force and temperature deformation, the final scores was 336, which was the highest for all of the FMEA analysis in the first semester.

7.1.1.1.2 Shaft design (Galling and Seizure)

The next part of the shaft that the team looked at, was the overall seizing within the left-handed thread as well as the bearings. The overall severity of the seizure is very high within both aspects. The seizure within the shaft will cause the shaft to stick together, and the team will not be able to interchange the parts within the turbine. In the bearings, this will cause the turbine to fail on all aspects due to not having overall rotational energy for power production. With these aspects in mind, the team ranked this at a 10.

The overall deformation of the shaft will be easy to see on the seizing aspect, without the proper clearances the motor will begin to fail, as well as the braking system will not be able to stop the overall system. Within the left-handed thread, the deformation will be instant, and the shaft will no longer be able to separate which will lead to the turbine nacelle have to be broken in order to get the shaft out. With all these aspects it was ranked at a 4.

The detection for the shaft is very important and will also be able to sense much quicker than a simple examination for the seizure with the overall bearing houses. The team will be able to see the shaft stop moving, as well as be able to smell the burning of the motor. With the seizure in the shaft, the team will not be able to take the shaft out of the nacelle as well as not being able to take the shaft apart. With both factors, the ranking for the detection was 8.

When looking at the overall galling and seizure factors for the shaft design, the final total was 320. This was the second highest aspect that the team had to look forward for turbine production, and even potentially redesigns.

7.1.1.1.3 Pitching System (Brittle Fracture)

Within the overall pitching system one of the main concerns of the team is to ensure that the blade is connected to the pitching mechanism properly. This will help create a safe testing environment. However, if the blade becomes lose withing the connection, it could fly off causing a hazardous object within the testing area. So, to make sure the connection is solid, the team has ranked it at a 9 due to the overall safety factors.

The team also had to look at the overall occurrence as well as what would cause this breaking. The team was able to determine that the main cause of this mechanism to fail would be due to overall high angular velocities within the blade design. These high velocities could cause excess stress not only on the blade design, but also within the connection method due to using 3D printed material. However, the turbine will at a max only see RPM of 3000. With this different information in mind, the team was able to rank this at a three due to the lower RPM experienced within the final design.

The overall detection method of this would be amazingly simple, the team would have to look at the 3D printed material within the blade connections and look for fracturing within the case. With the nature of 3D printing being a brittle material, the team will be able to see cracks. With this, the overall potential of the connection failing the turbine blade, it would fall off the turbine. With these easy detection methods while looking for potential failures, the team was able to rank this at a 10.

The overall factor for the potential failure when looking the aspects of the pitching mechanism the overall total 270. This system was looked at the third highest for potential failure modes when operatizing. The team will have to investigate ways to monitor these failure modes. This has included different redesigns in the overall final design.

7.1.1.1.4 Brake Pads (Impact Fatigue)

When looking at the overall braking system. The main point of concern within the system is the brake pads them self. Most importantly the overall impact fatigue that the brake pads will have to endure. The severity of the potential failure is significant. This can be seen if the brake pads are worn down, the turbine would not be able to slow to a stop and will have to rely on the pitching mechanism to bring the turbine to a stop. This part is a vital aspect of the turbine, and the team ranked the overall severity of this system at a 9.

The overall potential for this to occur is extremely high due to the turbine having to pass through while the breaks are applied multiple times. With this as well, the usage of the breaks will wear down the overall pad which will cause the linear actuator to extend greater distance. With the general wear and tear of the brake pads them self, the team best ranked a potential failure occurrence at a 5

The Detection for this method will be harder to notice. This comes down to an issue of when a suitable time to replace the brake pads are. The team will have to measure the brake pads and determine at what time would be a good time to replace the breaks within the system. The team has decided to give this a ranking of a 6.

With these distinct factors in consideration, the team will need to look at the distinct aspects in which the brake pads would potentially fail. The total of 270 means that from the first semester, this system with the overall potential failures, was ranked the fourth highest to fail.

7.1.1.2 Risk Mitigation first semester

Within in this section, this will look at the factors mentioned above and will discuss and the possible mitigation steps that the team can take to ensure the safety as well as the operation of the turbine design.

7.1.1.2.1 Shaft design

The main way that the team will be able to help to make sure the main part doesn't fail would be the proper utilization of the left-handed thread. This will help the team make sure that no parts are falling off, as well as making sure the overall air foil within the turbine is constant to make sure the final turbine design will have even heat transfer across the top portion of the nacelle. This left-handed thread will also be able to create a strong seal within the turbine housing.

7.1.1.2.2 Shaft design

The other main part of the shaft is that with the usage of the left-handed thread could seize due to a left-handed thread creating a self-locking shaft. However, with is shaft design, the team would also have to make sure the clearance of the bearings is correct to ensure that during operation the shaft does not seize.

7.1.1.2.3 Pitching system

Within the pitching system the multiple members that the team will have to look at, however the main portion is the heim joints within the pitching mechanism. To make sure the final design does not fail; the team will have to look at the overall surface connection with the heim joints. The team will also have to look at the different infills for the 3D printing to look at the different stress testing on the prints to find the best fill for each of the 3d printed parts.

7.1.1.2.4 Brake Pads

The brake pads are going to be worn down regardless due to the nature of the breaking mechanism. The team will have to be able to change out the brake pads in the turbine design. When replacing the brake pads, the team will have to be able to make sure that the new brake pads are the same size as the initial due to saving time be recalibrating the internal code for the braking system.

7.2 Potential failure second Semester

Within the second semester, the team was able to make unique design changed that led to the development of new potential failure modes. These have been added to the initial teams FMEA analysis that can be seen in Appendix B.

With these overall redesigns, the team was able to find multiple new aspects that the team would have to pay attention to with in the overall testing phase of the process. The top four that the team has begun to redesign for were with the electrical connections, pitching connections, Tower connection and the slip ring.

One of the main aspects of the second semester design was looking at the electrical housing and the overall connections between the different components. The main problem that the team had to look at was the overall conduction between the wires as the motor will be spun both in testing as well as the final design.

With the electrical housing, the next main portion of the turbine that needed to be looked at was the slip ring. This is the main point for both the tower as well as the wiring aspect of the turbine to be transfer to the external electrical as well as data acquisition system. This is the main aspects as well due to the slip ring having an internal bearing that allow the wiring to move free within the tower connections.

The next main aspect was the pitching mechanism. Within the pitching mechanism, it contains and external bearing which will aid in the overall ability to pitch the blades into the correct position when moving in-between started operating as well as stall position. This part won't break easily, however the bearing could have the ability to slip off and make the part faulty.

The last part is in unison with the slip ring. The tower connection is important due to it being the main point of connection of the turbine to the tower. This is made of multiple bearing connection as well as a retaining ring. The most important part of this set up it the retaining ring due to the potential failure methods that can happen if the retaining ring is not connected.

7.2.1 Potential Failures rankings second Semester

These different rankings were created by using the standard FMEA analysis modes by looking at different potential modes and ranking the overall Severity, Occurrence, and detection. These were also remade looking at the team newer designs, as well as made with extra input from an electrical engineering standpoint.

7.2.1.1 Electrical Connections (Force/temperature deformation)

Within the second semester design, the team had to look at and focus on the overall electrical housing for the wiring. This is a vital aspect of the turbine not only for monitoring, but also utilizing the overall control systems within the turbine. With these wires, the transfer of electrons will create internal heat within the wire causing it to melt overall. This is a top priority for the team due to the fact of losing all control over the turbine. As well as the potential repercussions the team has ranked this at an all-time high, or a 10.

The occurrence of this phenomenon will happen very frequently, however once it happens, the team will be able to change out the part and create a more complete circuit. Within this, the wiring will have the potential to melt, causing all of the wiring within the control systems as well as leading up to the turbine to melt together causing the entire wiring to be redone. With these different aspects as well as the importance of this part, the team has been ranked at an 8 overall.

Within the turbine detecting the overall potential failures, the team's best detection method will be to run the motor at lower RPM in order to test the overall heat transfer within the wiring setup, this detection will be easy, but also when testing the turbines final design, the detection will be easy when the system is not collecting data. With these solutions as well as very simplistic detection methods, the team has ranked this at a 5.

With all of these different factors the team was able to rank a total of 400. This was the highest within the overall additional designs from the second semester the team will need to be able to create a safe electrical housing as well as have the overall continuity within the electrical housing for the turbine to be both safe and effective.

7.2.1.2 Pitching connection (Brittle Fracture)

Within the overall pitching connection, the 3D print material is not as strong as most of the other locations on the turbine, often being held together very loosely. If this piece were to disconnect from the pitching mechanism and become free floating along the shaft, the pitching system will fail. This factor will hurt the team with testing the turbine within different wind speeds. With these different failures and their implications towards both the design and data collection, the team has ranked the catastrophe level at a 9.

The team has been able to identify that the overall occurrence is very unlikely at lower speed which has led to the conclusion that this would not be a pertinent issue. However, in the higher speed tests, the bearing within this connection can have the opportunity to vibrate which will cause the slip ring to come apart from the pitching mechanism. With these different factors, the unlikely event of low-speed failures, but the chance of high-speed failure, the team has ranked this at a 5. This is because most of the tests will be done at lower wind speeds except for that of stall testing.

The team will have the ability to test this and see any potential failure in two different aspects. The first is creating a test by hand and moving the pitching system by hand and with the code with little to no wind speeds present. The second method of testing is operatizing the pitching mechanism in the yaw test. With this the team will be able to use the code and test the pitching mechanism while moving at potential wind speeds. The team has ranked this at a 4 due to the multiple different ways to look at this system and find any failures within the pitching mechanism.

With the different factors considered when looking at the overall pitching connection point for potential failures, the team gave a total of 180. With this total in mind the team will need to look for other alternative connection methods. This portion with the overall potential failures, the team needs to look at this with top priority due to the overall severity of what this failure could do to the turbine.

7.2.1.3 Tower Connection (Yielding)

Within the tower connection, the tower design of PVC pipe will cause the tower to bend and become brittle. With this consistent yielding, the turbine could be pushed in a direction or even set in a new position that could cause the blades to disturb the intended airfoils. This shift in position will cause the turbine to be ineffective during operation. With this severity in mind the team ranked this at a 9.

The team had to look at the overall occurrence within the tower yielding. This was ranked at a 1 due to the fact that the team would has been able to center the turbine weight as to help avoid the shift in overall position. The team has also made to compensate for the weight of the hub assembly with adding a larger fin to the back of the turbine in order to help push the overall center of mass around the main connection of the turbine.

Within the turbine testing as well as set up, the detection to see if the tower as well as the tower connection the overall detection method for this failure would be very easy to notice. This is simply since the tower would begin to bend at lower speeds which would be very minimal in the data collection systems. However, with the higher speeds, the team would notice a significant bend and potentially a total failure in the tower as well as the connection.

The total when looking at the tower connection as well as the tower design itself, generated a total of 90. This is due to the main factor of the turbine being able to move with little structure within the tower. With this the PVC design will work, however it will not prove useful in the long term for testing purposes. The team will have to replace this with something that can prove more durable as well as reliable.

7.2.1.4 Slip Ring (Galling and Seizing)

Within the slip ring. This is main point of connection for the overall wiring of the turbine and control systems. This part is on a free-floating bearing with electrical wiring being ran through the central column of the slip ring. The main point of focus for the team is ensuring that both the wiring doesn’t overheat which would cause the wire to melt as well as causing the slip ring to stop free moving, with this different information in mind the team gave this a ranking of a 10.

The overall Occurrence of this phenomenon will be really low. The team will have to find the proper wiring size in order to help prevent the melting of the slip ring. The main way that the team would be able to notice this is with the loss of data collection within the PCC as well as the boost converter. The team has ranked this at a 3.

The overall detection for this method will be very easy, this is due to the main two reasons that the team will be able to tell. The first reason is within the yaw system, the team will have to move it by hand, and if the system does not move, the slip ring has seized. The second reason is within the data collection, if the teams' readings go to 0 or become super skewed, the slip ring has seized by the wiring melting together due to excessive heat.

With these different factors of the slip ring that were looked into, the team created a total of 240. This part is high-risk for the team due to the complexity that this part adds to the design.

7.2.2 Risk mitigation second semester

Within in this section, we will examine the factors mentioned above and will discuss possible mitigation steps that the team can take to ensure safety, as well as proper operation of the turbine.

7.2.2.1 Electrical Connections

The main way to correct the overheating issues within wiring is to obtain wiring that is better suited for different amps. The team can also avoid this problem by using a different core style of wiring as well as looking for ones that are self-insulated, and not exposed. One of the largest aspects of finding the proper way to reduce heat transfer across the wires is within the overall circuitry. It is important to make sure all the connections have not only a proper but also a common ground, this ground rail will provide a place for excess electrons to go and dissipate.

7.2.2.2 Pitching Connections

Within the current design for the pitching mechanism, the main fault is that the main part the controls the heim joint, can disconnect when pitching, causing the entire pitching mechanism to fail. With this the team will have to investigate a potential reprint which will connect ring to the pitching mechanism. The other option that the team can investigate is using a binding agent such as JB weld. This binding agent will be able to hold the connection ring in place allowing it to be held in place during operations.

7.2.2.3 Tower connection

The largest design flaw is within using a PVC pipe, due to the overall lack of strength within the PVC. The largest and most beneficial factor for creating a stronger connection, would be to machine a steel tower. With this, you can create a model for what the rest of the turbine will need to sit upon. The usage of a steel tower would also increase the overall factor of safety, which would make the final design stronger and more durable.

7.2.2.4 Slip Ring

The initial slip ring needed to be a 12-wire slip ring due to the number of wires needed for the overall control systems in the turbine. The team needs to find the highest gauge wiring the is possible for a 12-wire slip ring. This is ensuring that the wires do not overheat. If the wires were to overheat not only would the wires, then melt together, the team would also lose all portions of data collection.

7.3 Trouble shooting

Within all of these potential failures that have been listed above, the team has also come up with general trouble shooting practices for some of the different issues that could occur not only while testing, but also while examining/constructing the final turbine design.

7.3.1 Plastic fracture

If any of the following parts develop fractures, stop operation immediately and assess for hairline fractures across part. Chips will need to be sanded down past the occurrence of any hard edges. If hairline fractures are discovered across the part, replace the part.

When looking at the blades and hub prints, it is important to make sure that all parts are treated correctly. When placing the blades and hub, it is important to make sure you do not over tighten the blots, this will cause the prints to break and potentially shatter.

One of the other main components that will be subject to failure will be the Fin assembly. This failure will be caused due to excessive thrashing in wind testing. It is important to make sure the mounting bolts are secured but not over torqued causing excess pressure on the parts.

All the parts that are 3D printed will require the total part to be replaced, and this is due to the importance of the parts as well as the fragility of the 3D plastic being damaged.

7.3.2 Code Unresponsive

When not getting readouts from both the Point of Common coupling and Arduino digital readout, first check the wiring connections to all points with both the Arduino components, as well as the Point of common coupling. These will be your main sources of error.

If the problem is still unresolved, take off the nacelle and check the overall connections within the slip ring. Follow the wiring diagram to make sure all components are correctly clamped to each part. If all components are correctly clamped, using a voltmeter, run the motor at a smaller voltage and check all the wires to ensure all wires are intact and not melted.

7.3.3 Pitching Mechanism Binding

When moving the overall blade angles to the various stages and there is no movement within the pitching system. First you want to check the stepper motor to ensure it is disconnected and not locked in place. If the motor is disconnected and the pitching mechanism is still unresponsive, move the rotor as well as the shaft to ensure that they are free and not stuck within the bearings.

If the issue Is still unresolved, disconnect the heim joints and inspect for overall damage. If any damage is examined, these parts will need to be replaced to ensure the overall continuity of the system.

7.3.4 Improper AOA(Angle of Attack)

When adjusting the overall pitching mechanism and the blades do not adjust into the correct position. First you want to check the driving mechanism and make sure the overall alignment is in the correct order. Without the mechanism being in the correct position, the blades will be in the incorrect position and breaks the data collection as well as the overall pitching mechanism.

If the problem continues. The next step is to look at the overall heim joints, it is important to make sure that they are all equal lengths, otherwise the blades will be in overall distinct positions therefore throwing off the overall wind direction of the turbine and creating new airfoils and potentially harming the overall turbine design.

8 ER Proofs

The following section will indicate how the engineering requirements discussed in section 2.2 have been met by the group's design. These requirements are proved through both experimentation as well as computer simulation.

8.1 ER Proof #1 – Structural: Nacelle Connection

The first step to ensure structural competency for the nacelle connection was an FEA analysis. Seen below in Figure 9, the FEA indicates stresses up to 6.43 MPa. The force used in the analysis is based on the expected thrust forces that can be derived through Equation 1 along with the assumption of ideal axial induction (i.e., a = 1/3).

$$T = \frac{1}{2}\rho A V^2[4a(1-a)] \qquad Equation\ 1$$

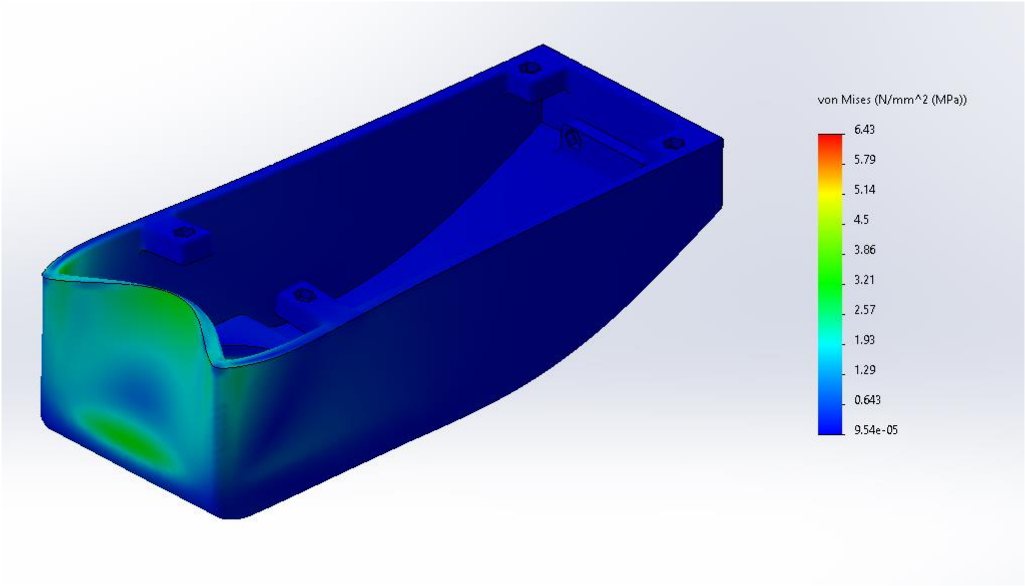


Figure 40: FEA Analysis of Nacelle Connection

Even though many sources claim that PLA's tensile strength is above the 6.43 MPa threshold seen above, the group still wanted to investigate the connection through physical means. Testing was performed by mounting a loading apparatus in place of the electrical housing. After each weight was added, the structure was observed for 30s and then rotated 180° four times. A total of 7 kg was applied without any part failures. With the operating apparatus, this resulted in 4.51 Nm of torque. This value is compared to estimated torques in Figure 10, indicating sufficient structural integrity to perform under the guidelines of the competition. The expected curve was developed through the use of Equation 1 as well as the geometry of the group's design. The group would have continued testing until failure, but the apparatus was lacking space and all the weights had been utilized, as shown in Figure 11.

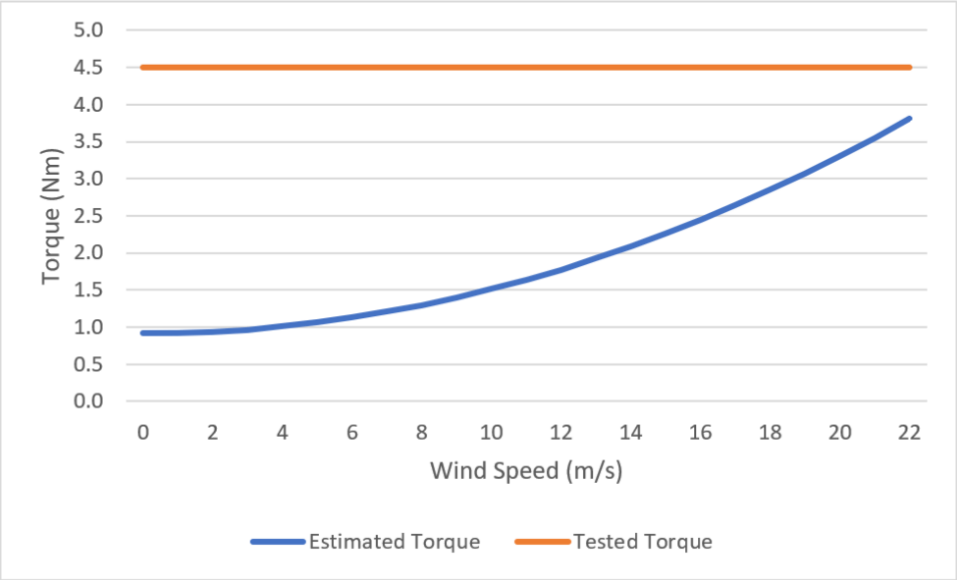


Figure 41: Tested vs Expected Torque Based on Wind Speed

Figure 42: Nacelle Connection Loading Apparatus

8.2 ER Proof #2 – Structural: Tower Stress

Another major source of stress will be the base and tower connection. After experimenting with several methodologies that would allow for 3D printing, it was determined that the part needed to be machined for safe testing. The FEA of this can be seen in Figure #43. The group did not do any explicit physical testing for this part, as the tensile strength of even the weakest of aluminum specimens are orders of magnitude higher than the stresses observed.

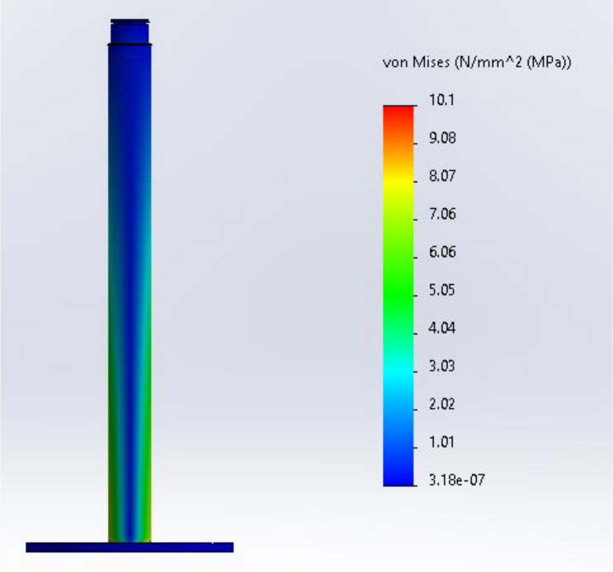


Figure #43: FEA Analysis of Tower

8.3 ER Proof #3 – Structural: Rotor

The movement of the rotor will produce centrifugal forces that will result in the largest stresses seen in the system. The team's analysis suggests the largest runaway rotational velocity will be on the order of 7500 rpm based on the 22 m/s wind speed maximum prescribed by the US Department of Energy. Figure # shows the runaway tip speed ratio arrived at through simulation.

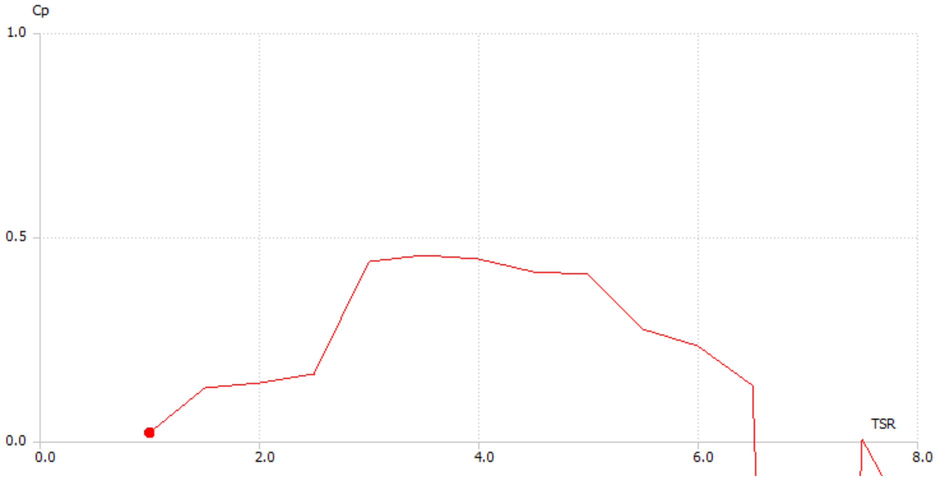


Figure #44: Runaway TSR at Maximum Conditions

Continuing from the obtainment of the runaway tip speed ratio (λ), the rotational velocity (Ω) can be derived as seen in Equation 2. Finally, Equation 3 allows the group to back into centrifugal forces experienced by the turbine utilizing the groups existing design. This will result in a maximum stress of nearly 14 MPa.

$$\lambda = \frac{\Omega R}{V} \qquad Equation\ 2$$

$$F = \frac{mv^2}{R} \qquad Equation\ 3$$

However, stress concentrations will display even higher values. Figure #45 is the FEA analysis of the rotor and suggest that values up to 35.8 MPa could be experienced. The presence of these concentrations will be the highest stresses seen by the group's design, therefore the group proceeded with experimentation to confirm the validity of the connection methodology utilized.

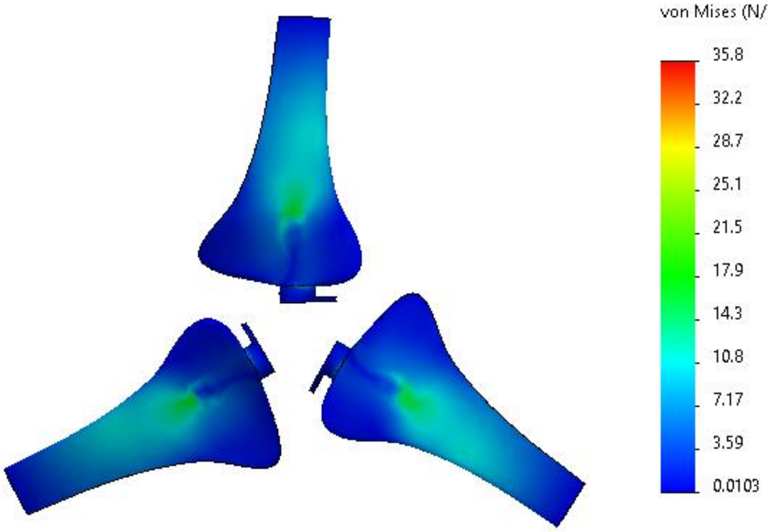


Figure #45: FEA Analysis of Turbine Rotor

The group borrowed dynamometer equipment supplied by the university's energy club depicted in Figure #46. However, the group was only capable of confirming performance up to 1400 rpm due to excessive vibration and issues with the apparatus. The turbine suffered no damaged or loosened bolts at the estimated 0.54 MPa of stress at this rpm, but the group hopes to modify the dynamometer setup to reach higher angular velocities without excess vibrations.

Figure #46: Dynamometer Testing Apparatus

8.4 ER Proof #4 – Efficiency: Starting Torque

Qblade analysis drove the design of the blades in regard to the starting torque. Figure #47 shows the expected torque production within a 3 m/s flow field at a starting pitch of 44°, where a torque value of nearly 0.02 Nm is shown.

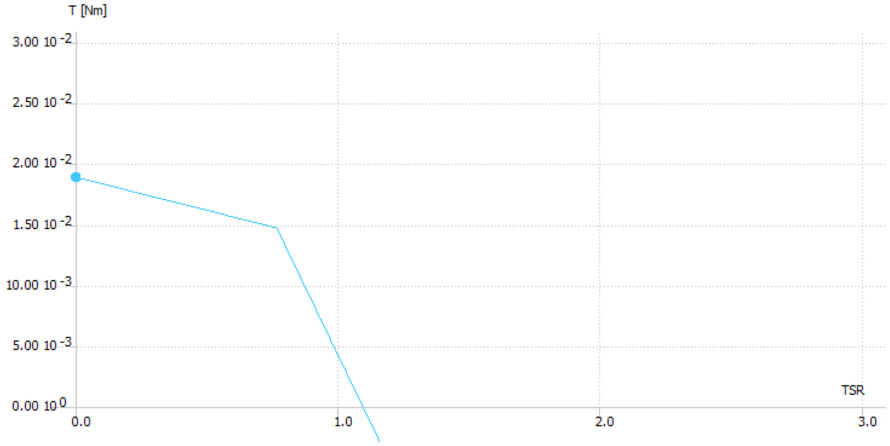
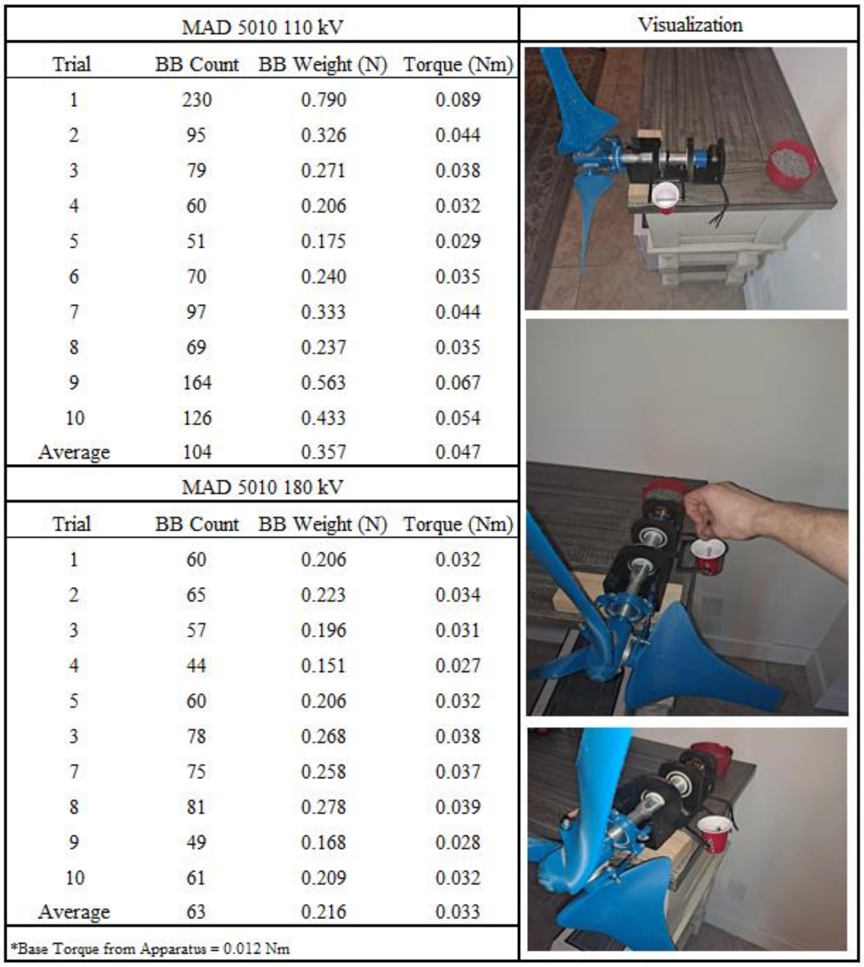


Figure 47: Torque vs Tip Speed Ratio at a 44° Pitch Within a 3 m/s Flow Field

It is important to find the assembly's required starting torque and comparing it to the expected aerodynamics at low wind speeds. The group has two motors under investigation, an older 110 kV motor a newer 180 kV motor. Using a small cup suspended by a lever arm, BBs were added until the turbine began to spin. This process is documented in Table 2.

Table 6: Assembly Startup Testing Apparatus and Results



MAD 5010 110 kV

Trial	BB Count	BB Weight (N)	Torque (Nm)
1	230	0.790	0.089
2	95	0.326	0.044
3	79	0.271	0.038
4	60	0.206	0.032
5	51	0.175	0.029
6	70	0.240	0.035
7	97	0.333	0.044
8	69	0.237	0.035
9	164	0.563	0.067
10	126	0.433	0.054
Average	104	0.357	0.047

MAD 5010 180 kV

Trial	BB Count	BB Weight (N)	Torque (Nm)
1	60	0.206	0.032
2	65	0.223	0.034
3	57	0.196	0.031
4	44	0.151	0.027
5	60	0.206	0.032
3	78	0.268	0.038
7	75	0.258	0.037
8	81	0.278	0.039
9	49	0.168	0.028
10	61	0.209	0.032
Average	63	0.216	0.033

*Base Torque from Apparatus = 0.012 Nm

Visualization

The investigation found that the 110 kV motor had a higher starting torque of 0.047 Nm when compared to the 0.033 Nm startup requirement of the newer 180 kV motor. This means that the design will need to be altered if the group desires to score points in startup testing for the competition.

8.5 ER Proof #5 – Efficiency: Yaw

The yawing test was performed by holding the fully assembled turbine above a vehicle with stalled blades. At 5, 10, 15, and 20 mph, reactiveness to yawing was measured when the turbine was situated at different angles. The crudeness of the testing procedure and presence of a crosswind made low wind speed testing results inconsistent. However, the yaw performed respectably at 15 mph and flawlessly at 20 mph. Further description of the yawing reactions can be found in Table 3. The yaw is also passively tested in the operating conditions ER proof.

Table 7: Yawing Testing Apparatus and Results

Wind Speed (mph)	Wind Speed (m/s)	Start Angle (°)	Performance				Visualization
			Unresponsive	Inconsistance Response	Volatile Response	Consistant Response	
5	2.24	90	✓				
		60	✓				
		30	✓				
10	4.47	90		✓			
		60	✓				
		30	✓				
15	6.71	90			✓		
		60			✓		
		30		✓			
20	8.94	90				✓	
		60				✓	
		30				✓	

8.6 ER Proof #6 – Efficiency: Brake

This process is performed with a loading apparatus and lever arm. After inducing torque on the shaft, the electronics and setup shown in Figure 9 resisted additional weights via use of the linear actuator until the holding torque of the brake was surpassed. There were several issues in regard to finding an exact value for the induced torque. The apparatus would rotate very slightly under the pressure of the apparatus and reduce the applied torque. This gave the impression that the brake was working, but instead was stopping less torque as the lever arm length decreased. However, the group converged on a holding torque of 2.64 Nm before this issue began to occur, which when compared to previous analyses would suggest sufficient braking power in tandem even without stalled blades as per Figure 10.

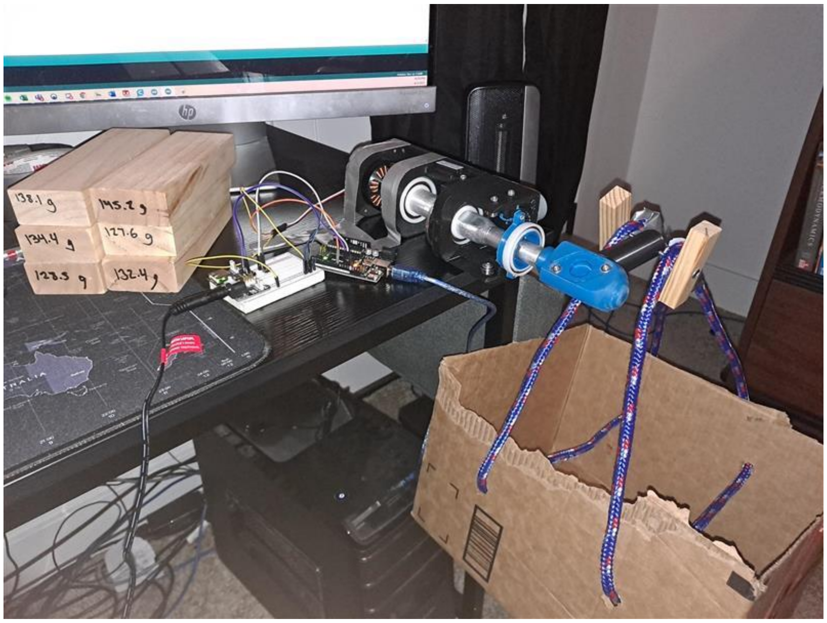


Figure 48: Brake Testing Apparatus

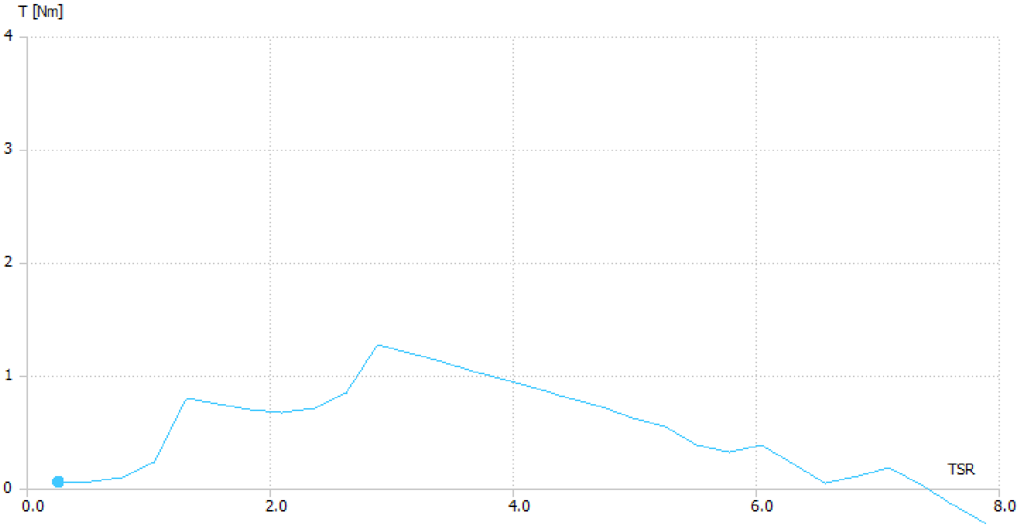


Figure #49: Torque vs Tip Speed Ratio at 22 m/s and Zero Pitch

8.7 ER Proof #7 – Efficiency: Pitching

Utilizing a 6V AC/DC adapter to supply the apparatus seen in Figure 8 with power, the max loading of the pitching mechanism was found as 3.3 N using an actuator that pushes and pulls the system. This maximum loading value may prove too low to operate at higher wind speeds. The process involved the use of large and normal sized Jenga blocks as weights. The group believes that special treatment of the PLA gears involved in the subassembly may improve the system’s performance. In tandem to this, the blade’s attachment orientation was altered so that the pitching would push to start and pull to stall, utilizing the natural forces that will be present on the turbine.

Figure #50: Pitching System Test Apparatus

8.8 ER Proof #8 – Efficiency: Operation Conditions

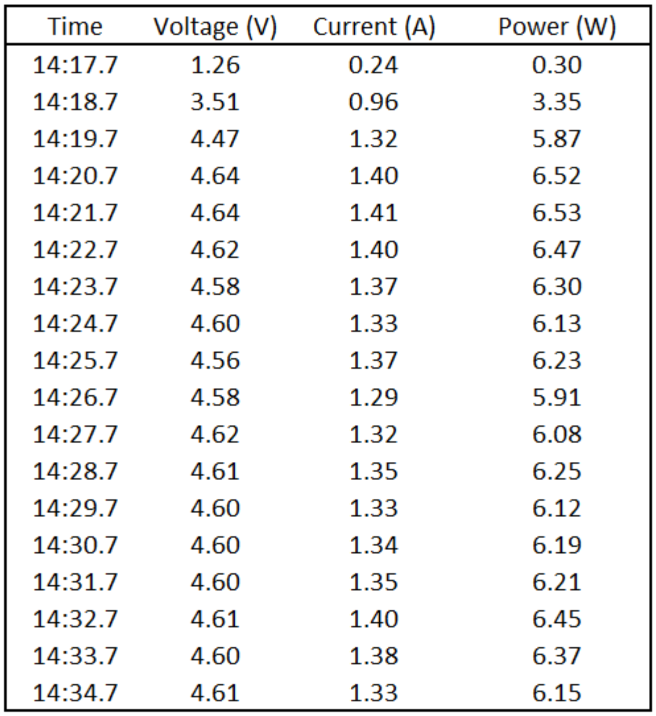
The operation conditions tested include the mechanical starting, operation, and stalling reference frames. The starting displayed subpar results, indicating issues with startup prior to wind speeds of 15 mph. However, the system proved to reach a high rotational velocity quickly once rotation began. The operating conditions seemed to perform well. However, with the test being strictly mechanical, the power production was not tracked. Therefore, the most efficient data that came from the operating testing was evidence of the yaw's efficiency which kept the axis of rotation parallel to the flow field even through several turns of the vehicle. Lastly, the stalling testing showed results above aerodynamic predictions. The rotor retained no movement up to 40 mph. However, as the testing had the turbine start in stalling, there is the possibility that going from operating into stalling conditions may prove less effective. Figure #51 shows the apparatus used to test the turbine at the aforementioned conditions.

Figure #51: Car Testing Apparatus

8.9 ER Proof #9 – Electrical: Power Output

The team requires the turbine to output a maximum of 48 VDC at operating conditions. In order to this, the kV rating of the motor, the three-phase rectifier, boost converter, and resistive load will all work in tandem. Although the group will work with the NAU 2021 CWC Electrical Team to supply this electric chain of components with a voltage supplied by the turbine in the coming weeks, early experiments were tested by supplying the generators with an artificial rotational velocity supplied by a handheld electric drill. Data from this experiment can be seen in Table #8. The recorded voltage is the value obtained after the boost converter.

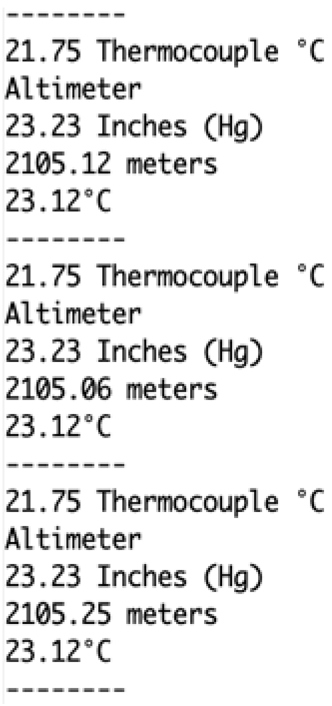
Table 8: Power Output from Electrical Components



Time	Voltage (V)	Current (A)	Power (W)
14:17.7	1.26	0.24	0.30
14:18.7	3.51	0.96	3.35
14:19.7	4.47	1.32	5.87
14:20.7	4.64	1.40	6.52
14:21.7	4.64	1.41	6.53
14:22.7	4.62	1.40	6.47
14:23.7	4.58	1.37	6.30
14:24.7	4.60	1.33	6.13
14:25.7	4.56	1.37	6.23
14:26.7	4.58	1.29	5.91
14:27.7	4.62	1.32	6.08
14:28.7	4.61	1.35	6.25
14:29.7	4.60	1.33	6.12
14:30.7	4.60	1.34	6.19
14:31.7	4.60	1.35	6.21
14:32.7	4.61	1.40	6.45
14:33.7	4.60	1.38	6.37
14:34.7	4.61	1.33	6.15

8.10 ER Proof #10 – Electrical: Data Acquisition

With the introduction of the online competition, the need to collect the group's own data has arisen. This is captured by Table 8 above, but there are several other atmospheric values that need to be represented if the group would like to remain competitive in terms of efficiency. The environmental data will come from various transducers that will read the barometric pressure, altitude, temperature, and wind speed. Data collected in several miniature experiments is displayed in Figure #. Note that wind speed is read by the PCC, meaning that wind measurements will be reported on the same sheet seen in Table 8. However, the drilling test did not involve a wind speed. Therefore, another test was run with the anemometer strapped to the top of the group's testing vehicle. The results showed a large amount of noise, as to be expected from the simulation of a flow field through vehicle testing. The solution to this will be a large amount of base data gathered in future testing to get as much data at each rated wind speed as possible. The wind speed data is shown in Table #9:



```
--------
21.75 Thermocouple °C
Altimeter
23.23 Inches (Hg)
2105.12 meters
23.12°C
--------
21.75 Thermocouple °C
Altimeter
23.23 Inches (Hg)
2105.06 meters
23.12°C
--------
21.75 Thermocouple °C
Altimeter
23.23 Inches (Hg)
2105.25 meters
23.12°C
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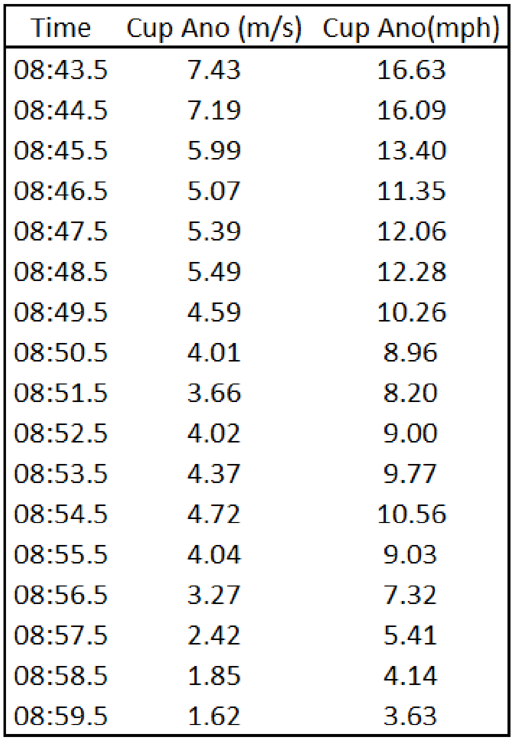
Figure #52: Atmospheric Data Readout

Table 9: Cup Anemometer Testing Results



Time	Cup Ano (m/s)	Cup Ano(mph)
08:43.5	7.43	16.63
08:44.5	7.19	16.09
08:45.5	5.99	13.40
08:46.5	5.07	11.35
08:47.5	5.39	12.06
08:48.5	5.49	12.28
08:49.5	4.59	10.26
08:50.5	4.01	8.96
08:51.5	3.66	8.20
08:52.5	4.02	9.00
08:53.5	4.37	9.77
08:54.5	4.72	10.56
08:55.5	4.04	9.03
08:56.5	3.27	7.32
08:57.5	2.42	5.41
08:58.5	1.85	4.14
08:59.5	1.62	3.63

9 LOOKING FORWARD

This section will include future work as well as future testing procedures needed for the contest deliverables. Future work will include both work that our team plans on doing to prepare for the contest as well as future work that incoming capstone teams can do to further optimize the design.

9.1 Future Testing Procedures

All capstone deliverables have been met however the team is still working to further optimize the design to ensure it is ready for the project development report due 5/23/2021 as well as the turbine design questions and answers due. In order to complete these the team will need to conduct various test. These tests are push button stop, loss of load, cut-in, power curve, and power control. These will be conducted on 5/7/2021 to ensure team stays on schedule.

The resources needed for these are a car (simulate wind tunnel) with mounting apparatus, wrench (fasten turbine to car), the turbine, a data acquisition system as well as an MCU.

It is also important that proper integration of components given to us via the electrical team is done prior to testing. This will include the rectifier, boost converter and the variable resistive load.

9.1.1 Testing Procedure 1: Push-Button Stop

This test is designed to test the safety of our turbine to ensure that it would meet regulations needed for grid connection.

9.1.1.1 Testing Procedure 1: Ensure the turbine stops on demand

This test will be run at wind speeds between 5 – 22 m/s in both yawed and steady continuous flow. The team will randomly press the stop button and observe if turbine shuts down via stalling then braking. This test will also see if turbine restarts again at any wind speed above 5 m/s. Shutdown is defined as dropping below 10% of the maximum 5-second bin average rpm achieved for rated conditions. The reason we are testing this is because we need to ensure maximum points for the safety task of the competition.

9.1.2 Testing Procedure 2: Loss of load

This test is designed to test the safety of our turbine to ensure that it would meet regulations needed for grid connection.

9.1.2.1 Testing Procedure 2: Ensure turbine stops when disconnected from a load.

This test will be run at wind speeds between 5 – 22 m/s in both yawed and steady continuous flow. The team will disconnect the turbine from the load and observe if turbine shuts down via stalling then braking. This test will also see if turbine restarts again at any wind speed above 5 m/s. Shutdown is defined as dropping below 10% of the maximum 5-second bin average rpm achieved for rated conditions. The reason we are testing this is because we need to ensure maximum points for the safety task of the competition.

9.1.3 Testing Procedure 3: Cut-in Wind Speed

The lowest wind speed at which a turbine produces power is called its cut-in wind speed. This characteristic can help compare turbines against each other and often times the lower the cut-in wind speed the better suited the turbine is for lower wind speed regimes [1]

9.1.3.1 Testing Procedure 2: Determine wind speed at which turbine starts producing power

The main variables being tested for cut-in wind are wind speeds and current. For this test wind speeds will be slowly increased from 2.5m/s to 5m/s. during this time the team will be monitoring the current to see if we are producing power. Producing power is defined as achieving a positive current average over a 5-second interval at steady conditions [1]. The reason for conducting this test is to ensure maximum possible points for the cut-in wind speed performance task of the competition.

9.1.4 Testing Procedure 3: Power Control

Rising wind speeds means greater mechanical and electrical loads therefore controlling both power and rotor speed is vital for a lasting and sustainable turbine.

9.1.4.1 Testing Procedure 2: Control Power to ensure it is operating at rated conditions

This test will be conducted at wind speed bins at both 12 m/s and 13 m/s. We will be monitoring rpm and power output. It is expected that we control power output at stay within the rated conditions for out turbine. The reason for conducting this test is to ensure maximum possible points for the control of rated power and rotor speed task.

9.1.5 Testing Procedure 3: Power Curve

Power curves can be a direct comparison of power performance between turbines and is often times used in industry as well as research. A power curve shows the electrical power output across varying wind speeds.

9.1.5.1 Testing Procedure 2: Develop a power curve and compare against simulation

This test will be conducted at integer wind speeds between 5 m/s and 11 m/s. Each integer wind speed will be tested for 60 seconds or less. The team will be monitoring the rpm as well as output power and storing them via the data acquisition system. Later a power curve will be developed and compared to simulation results. The reason for conducting this test is to ensure that we score the max amount of points for the power curve performance task of the competition. This integration will require that the variable resistive load is optimized in order to meet the mechanical load it receives.

9.2 Future Work

Once these tests are complete the team will be able to finish the final deliverables for the competition. The tests outlined above could easily be used to inform design changes for future teams. For instance, if we fail to properly integrate the stop button the design will not stop on demand. Future teams could then take this failure understand what went wrong and improve the design. Some major concerns currently for the design are root failure at the base of blades as well as our stepper motor not producing enough power to pitch the blades when operating at rated rpm. These could be fixed via stronger connection methodologies at the hub as well as using a stronger stepper motor that still fits within the (EH). Other future work for this design from an electro-mechanical perspective would be to develop a custom generator with lower start up torque. This would help the Aerodynamics team develop a blade that does not need max performance across such a wide wind speed range.

10 CONCLUSIONS

The team has produced a functioning turbine that shines in several areas. Particularly, the mechanical sophistication and efficiency of the pitching mechanism has proven superb in comparison to past teams. The utilization of a linear bearing to slide along the shaft, a modified swash plate to connect the rotating and non-rotating elements of the mechanism, the drive train allowing for symmetrical movement around the shaft, and the heim joints that allowed the connection to the blades took several months and research to develop. An area where the turbine may be lacking relative to previous projects includes the startup capabilities which failed to rotate the turbine at the desired wind speed of 3 m/s. The remainder of this section will go into detail on the strategies put forward by the team that were effective and ineffective in regard to the production of the final product.

10.1 Reflection

The most important aspect for the NAU 2021 CWC Turbine Team has been safety. The team is dealing with a device rotating at speeds up to 7500 rpm. Failure of any rotating part, even as small as a locking nut, could result in damage to nearby property or the on-site students. With the competition moving from a shielded wind tunnel to the top of a car on public roads, this importance has risen even since the start of the competition. These concerns lead to connection methodologies that reduced stress concentrations in the blades as well as connection methodologies that would long outlast failure in the plastic blades due to said stress concentrations. This in tandem with a double actuator based braking system resulted in a very safe design.

Economically, the team produced a turbine that can would be sold at $550. Pricing covers the material and labor costs but does not account for any desired profit. In comparison to this, there are many commercially available 400-600W turbines that are sold for under $300. This is half the cost of the team's turbine for roughly 10 times the amount of power production. Therefore, although the group is proud of the design fabricated, there are still areas for improvement. In terms of efficiency, the turbine operates on par with other turbines available on the market, reaching coefficients of power of roughly 44% at optimum conditions. This value is quite standard for horizontal axis wind turbines.

10.2 Post Mortem Analysis of Capstone

The group has matured a significant amount since the beginning of the project. The D4P courses previously taken by the students in the years leading up to the project have been instrumental to the develop of the future engineers, but the last year has taught lessons and induced a fight or flight response in almost all members of the group. The group was introduced to many new modes of design, such as through opensource software programs that aid in structural and efficiency estimations. Another area that the group delved into quickly is the world of kinematic mechanisms along with the names and functions of products available on the market. The design considerations of electronics as well as interfacing with an MCU is another topic that several members committed to memory. The experiences that each member had is a result of said member's assigned sub-team, academic workload, fiscal workload, implemented policies, initial planning, etc.. The Post Mortem analysis will delve into how these above factors aided or hindered the development of the project and the yearlong experience of designing, fabricating, and testing a micro-scale wind turbine

10.2.1 Contributors to Project Success

First and foremost, the group would like to address the hierarchy that was utilized starting late into the first semester and the entirety of the second semester. Individual team leads were identified to aid the administrative lead. This identification helped structure the groups into more formal sub-teams and guide the team. The introduction of the hierarchy also allowed for the team to cancel the full team weekly meetings, having only the leads meet to report on the status of the projects and receive updates from the client, and then relay those messages to the respective sub-steams in any desired manner. This significantly reduced time wasted by members spent listening to subsystem designs that said member was not involved in. This was especially prevalent in members who were splitting time between both the turbine and the siting project.

Another large contributor to the success of the team was the $4000 budget. Although the final cost estimation of the turbine, as seen in the BOM, is nearly $550, the additional budget allowed the team to channel their efforts into design improvements rather than get bottlenecked by premature purchasing mistakes over the lifetime of the project. The group also did well budgeting in the second semester, with certain individuals stepping up and keeping other members well informed of where the group stood financially.

From there, the group's willingness to alter design components for a more comprehensive overall design has proved crucial to the success of the project. From an early stage, the group decided to utilize 3D printing for prototypes. The group has gone through over $225 worth of plastic, but in doing so parts were optimized and the group was not locked into sub-par designs due to high machining costs. The group would highly recommend this strategy to not just future CWC teams, but any capstone team that involves fabrication. The step from theoretical project to real life machine is a large gap for undergraduates and the experience that came from designing countless iterations of certain parts has been invaluable.

The group also utilized time after official meetings to check up with each other on a professional and personal level. The group atmosphere was an integral part the success of the project. When working on the same project for as long as a capstone requires, to be surrounded by individuals who show one another respect and kindness is a great motivator to continue to work on the project diligently.

Apart from the good foundation the team was working with, there were also many subjects that the team needed to learn, internalize, and reproduce within a matter of weeks. For example, when the group began building the pitching mechanism there were no members with a solid idea on how to go about the design. It started by borrowing the idea utilized by last year's team, a swash plate that connected the blades to the nacelle. Swash plates are components that are typically used in helicopters to pitch the blades. From there, the group looked into connection methodologies that would allow an extra degree of freedom, as would be required to not jam into the blade. This introduced the group to heim joints. The group then began trying to assemble a driven mechanism, only to find that the dimensions of the swash plate were incredibly constraining. Research showed that use of a larger swash plate drastically increased the cost of the part. The group then moved forward by designing a swash plate that would hug a normal bearing. This would reduce the swash plate's number of degrees of freedom but proved inconsequential to the team's application. From there, the team investigated a way to drive the pitching system. Originally, the team wanted to use a crank-slider. However, after extensive discussion the group arrived at a design that utilized a gear train featuring miter, spur, and rack gears that were driven by a single stepper motor. Finally, to add structural integrity to the system, the swash plate was turned into a linear/rotational bearing hybrid that would act as support for the shaft but remain relatively frictionless. This iterative process does not properly encompass the amount of research that went into discovering the existence and implementation methods of these parts, or the amount of times the team messed up in between each step. This process was not exclusive to the pitching mechanism either. The passive fin took on three forms before completion, the nacelle connection took on two forms before completion, and the nacelle took on four forms before completion. More than anything, the project demonstrated the tenacity that is required of engineers when attempting to converge on an optimum design. Although some days were better than others, the group believes to have tackled each problem professionally and to the best ability of undergraduates experimenting in the world of design and fabrication.

10.2.2 Opportunities/Areas for Improvement

For every good aspect of the project, there were also issues that arose. The first and most prominent would be the organization of deliverables and workload. Due to the nature of the project in the midst of the pandemic, it was often difficult to have the members meet for extended periods of time to work with the turbine. This resulted in a lot of individual work, and sometimes resulted in disproportionate workloads. In future projects it is vital for the mental health of each individual to take on similar amounts of work. This can be solved with a more specific Gantt Chart. However, one of the reasons the original Gannt Chart used by the team which was purposefully left vague was due to the team's recognition of the learning curve associated with turbine design. If the group were to remake the Gannt Chart at this point in time and start from scratch, the Gantt Chart would be far more specific and effective in its original purpose.

Another major issue the team faced was in regard to interfacing with the school's financial administration. The first incident was seen in December of 2020, when the ordering process took nearly 3 months to complete, resulting in the group being put drastically behind. Secondly, there were several instances of the administration simply ordering the wrong items. The team resorted to asking for forgiveness rather than permission, purchasing the outsourced parts out of pocket and then requesting a refund for the parts. This strategy only worked due to the financial stability of several of the members. Future CWC or capstone teams may not be able to resort to this, especially considering the three-refund limit and transactions over a month old requiring special permission for approval. The best solution to this would be to be very vigilant of the administration and be sure to train the team's budget administrator extensively and make trivial purchases early in the process to assure that the members are aware of the process' procedures.

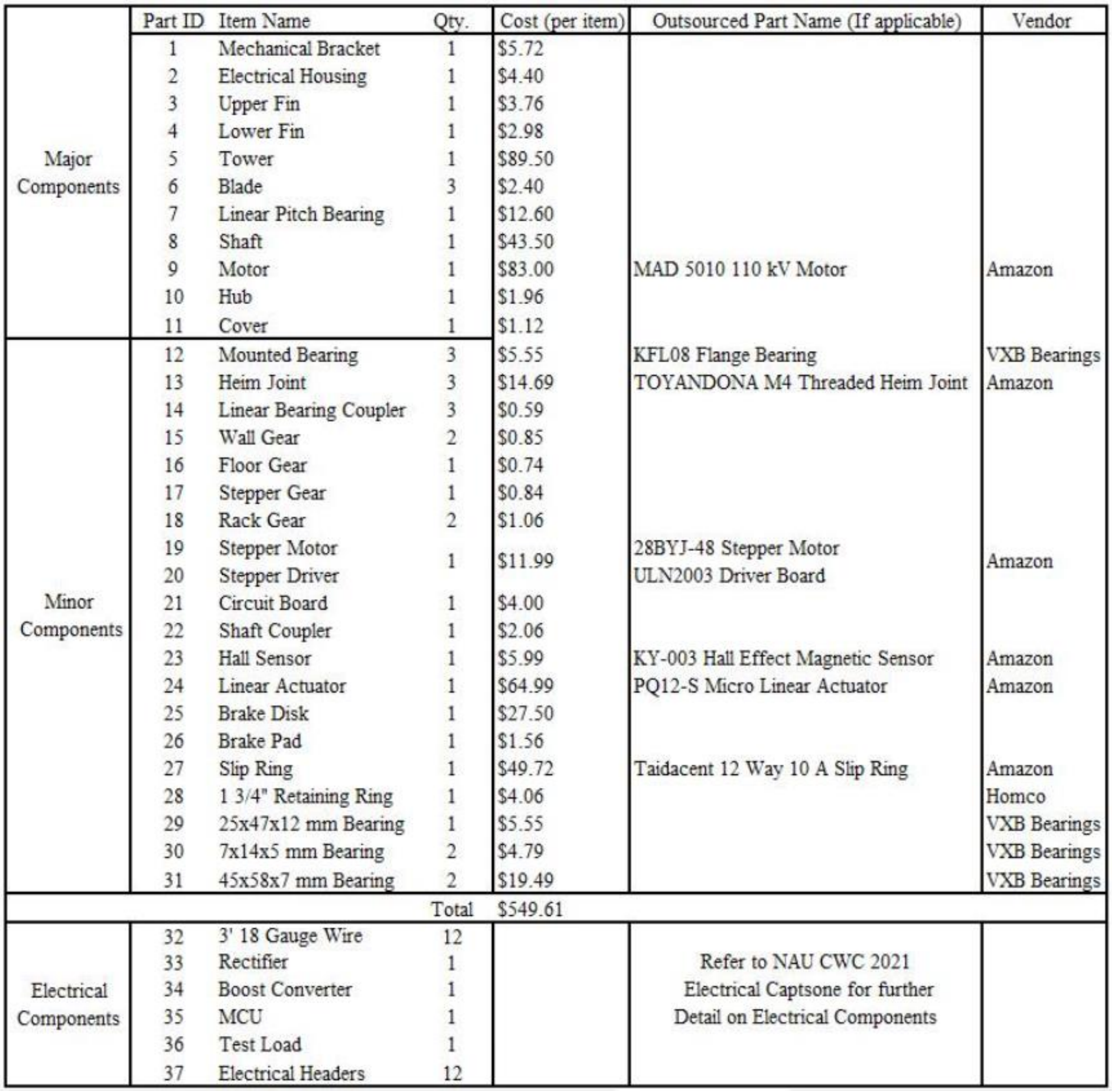
As previously mentioned, the group utilized a hierarchy that allowed for less wasted time of each member. While this point persists and, to the group's belief, outweighs the negative consequences, said consequences are still present; most prominently in the distribution of information. Since updates on the project were not commonly discussed in a mass setting, the members needed to read announcements released by the leads in order to stay updated with the project and each member's respective tasks for the coming week. Unfortunately, without the face-to-face interaction the information was sometimes improperly expressed or left unread by members. The group believes that starting with the hierarchy at the beginning of the project and emphasizing the role of the lead to update the members as well as the member's role of staying up to date will alleviate most of the problems. Members became accustomed to being updated verbally by meetings and when this mode of information expression was dissolved, the expected standard for both the leads and members were skewed and were not formed properly until much later in the project.

Although not the largest problem seen by the group, the mixing of the siting and turbine team proved problematic by the end of the semester. As leads were assigning work independently, certain members would sometimes receive an unreasonable workload. The group believes under the right conditions, the mixing of the two teams is a manageable endeavor. However, it needs to be recognized that members on both teams will face two separate learning curves of turbine design and wind farm design, coupled with dual workloads. The presence of multiteam members also needs to be considered by the leads when assigning work. Despite this recognition, the group would recommend keeping the groups separate to avoid conflicts.

One of the largest problems the group encountered is the interfacing with the electrical team. There are many design decisions that need to be a compromise between the available mechanical and electrical components. For example, the use of a 110 kV motor or a 180 kV motor will greatly effect both the electrical component train comprised of the 3-phase rectifier, boost converter, and variable load as well as the initial assumptions in the blade element momentum theory that is used to converge on a blade shape. The groups were in minimal contact throughout the first semester, but not nearly enough to properly discuss the design constraints that existed between the electrical and physical complications of the project. Even though this problem effected the group greatly, the solution is easily obtainable. Increased contact between the two teams in the first semester is key to the overall success of the project in total and

11 APPENDICES

11.1 Appendix A: BOM



	Part ID	Item Name	Qty.	Cost (per item)	Outsourced Part Name (If applicable)	Vendor
Major Components	1	Mechanical Bracket	1	$5.72		
	2	Electrical Housing	1	$4.40		
	3	Upper Fin	1	$3.76		
	4	Lower Fin	1	$2.98		
	5	Tower	1	$89.50		
	6	Blade	3	$2.40		
	7	Linear Pitch Bearing	1	$12.60		
	8	Shaft	1	$43.50		
	9	Motor	1	$83.00	MAD 5010 110 kV Motor	Amazon
	10	Hub	1	$1.96		
	11	Cover	1	$1.12		
Minor Components	12	Mounted Bearing	3	$5.55	KFL08 Flange Bearing	VXB Bearings
	13	Heim Joint	3	$14.69	TOYANDONA M4 Threaded Heim Joint	Amazon
	14	Linear Bearing Coupler	3	$0.59		
	15	Wall Gear	2	$0.85		
	16	Floor Gear	1	$0.74		
	17	Stepper Gear	1	$0.84		
	18	Rack Gear	2	$1.06		
	19	Stepper Motor	1	$11.99	28BYJ-48 Stepper Motor	Amazon
	20	Stepper Driver			ULN2003 Driver Board	
	21	Circuit Board	1	$4.00		
	22	Shaft Coupler	1	$2.06		
	23	Hall Sensor	1	$5.99	KY-003 Hall Effect Magnetic Sensor	Amazon
	24	Linear Actuator	1	$64.99	PQ12-S Micro Linear Actuator	Amazon
	25	Brake Disk	1	$27.50		
	26	Brake Pad	1	$1.56		
	27	Slip Ring	1	$49.72	Taidacent 12 Way 10 A Slip Ring	Amazon
	28	1 3/4" Retaining Ring	1	$4.06		Homco
	29	25x47x12 mm Bearing	1	$5.55		VXB Bearings
	30	7x14x5 mm Bearing	2	$4.79		VXB Bearings
	31	45x58x7 mm Bearing	2	$19.49		VXB Bearings
			Total	$549.61		
Electrical Components	32	3' 18 Gauge Wire	12		Refer to NAU CWC 2021 Electrical Captsone for further Detail on Electrical Components	
	33	Rectifier	1			
	34	Boost Converter	1			
	35	MCU	1			
	36	Test Load	1			
	37	Electrical Headers	12			

11.2 Appendix B: Full FMEA Both semesters

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
MAD5008 Motor	Fatigue (High Cycle Fatigue)	Motor breaking/ not spinning at desired RPM.	Over usage during testing phase.	84	Monitor motor, buy secondary replacement.
MAD5008 Motor	Buckling	Shaft along motor snapping	too much weight from shaft and other components to high of RPM	40	Examine the shaft, look for cracks as well as shaft changing in form.
MAD5008 Motor	Galling or Seizure	motor components seizing without proper oil.	spin plate locking in place.	120	Check the motor and replace if needed.
MAD5008 Motor	Combines creep and Fatigue.	crack in shaft	shaft can snap and not have good connection with shaft design.	36	add connection to shaft to minimize failure, have secondary motor on standby.
MAD5008 Motor	Combines creep and Fatigue.	crack in electrical components	Lose coils, loss of power through the motor.	63	Send motor back for recoil over, have secondary motor for replacement.
Blade design	Brittle Fracture	Snapping at base point	Plastic at high RPM	147	work on iterations to strengthen the blade, add potential fills in design.
Blade design	Deformation Wear	Blades elongating past the 19 cm set design.	Plastic becoming more brittle, blade becoming longer.	24	Measure the blades, examine the blades, and decide for different iterations of the blades.
Blade design	Stress Corrosion	Blades with 0% fill can have corrosion while spinning at high speeds.	Blades can break or cause separation/holes in the overall blade design.	192	Adjust the overall fill of the blades and decide which percentage of fill would be best.

Blade design	High-Cycle fatigue	Blades will be spinning at high speed until breaking.	Blades will potential be spinning upwards of 5000 Rpm. when testing for 10 min, the blades will spin a total of 5*10^4 rotations.	135	Examine the blades, replace the blades when the team notices any visible deformation to reduce chances for extreme failure.
Blade design	Stress raptures	the internal structures can fail.	With high speed and excessive forces on blades, the crystal structure can become compromised and adding extra spaces within the blade design.	84	Examine the blades, replace blades after several trials, also decide which blade design is best for the turbine design.
Linear Actuators	Force and/or temperature induced deformation	Tha actuators can snap when Appling the breaks to the turbine.	actuators are set in place, but they can be moved when force is applies.	144	have separate linear actuators. Team has high force and low force. Test to see which will work better with the final design of the turbine.
Linear Actuators	Impact deformation	high force can bend the actuators causing them to fail on retraction.	high force on the braking pad to stop the turbine can move the shaft of the actuators and break them.	72	look into creating a potential housing for the shaft to minimize deformation. Minimize the accusation distance to reduce torque fractures.
Brake pads	impact fatigue	High force and excessive wear to the brake pads	high force and excessive wear will shrink down the overall brake pads and reducing the overall coefficient of friction within the breaks.	270	Keep spare brake pads when the other pads reach that distance.
Brake pads	Adhesive wear	Brake pads can potentially fall off during testing and final design building.	This will decrease the overall friction if the adhesive holding the brake pads fail or become too warm.	200	Look for better break adhesives, keep spare brake pads for replacement if they fall off due to elevated

					temperatures or stress fatigues.
Linear Actuators	Combines creep and Fatigue.	Gearing within the actuator	The gearing within the linear actuator can break as well as become fatigued. The teeth of the gears can be worn down.	150	Keep testing the actuators for extension and time to fully correct. If the actuator is breaking (slowing down) replace the part.
Pitching system	Binding	Inability to pitch.	The mechanism could get caught on itself or bend in an unnatural manner.	64	Use of materials with a high modulus of elasticity to prevent any unaccounted-for movement.
Pitching system	Disconnection	Inability to pitch and loose parts on the rotor.	circular motion may unscrew the connections with little threading.	108	Tightly sealing locks with threads or adhesives
Pitching system	Brittle Fracture (Keystone)	A blade would lose the connection to the hub.	Intense angular velocities would cause the part to break.	270	Increasing the size of the region, introducing a chamber
Pitching system	Brittle Fracture (Keystone Member)	Inability to pitch and loose parts on the rotor.	Intense angular velocities would cause the part to break.	150	Careful programming and implementation of the actuator
Hub design	Force and/or temperature induced deformation	Forces on the baled and pull the hub design apart.	the overall force and lead to deformation in a plastic hub.	120	Test the first hub design with a 3d printed system to save money as well as test the pitching mechanism. Redesign with a Metalica hub for better structure.

Hub design	pitting corrosion	contact point for first design between hub and shaft is metal.	the shaft can rub up against the hub if it becomes lose causing the plastic to wear and break leaving a pit where the shaft was in contact with the hub.	72	Redesign the hub with a Metalica structure to ensure the safety of the hub.
Hub design	pitting corrosion	Contact points between the bearings for the pitching system and the hub design	the different forces in the blades, as well as the push and pull of not only the blades, but also the screw holding them in place and break the plastic of the 3D printed hub.	36	check the bearings, do not over torque the blades into the bearings. Redesign with metal structure to ensure the structure.
Hub design	Brittle Fracture	The points on the hub, connecting the hub to the pitch mechanism.	if the pitching mechanism pulls of pushes too hard on the connection points, the 3D plastic could potentially break, there for losing the pitch of the blades.	108	Monitor the stepper motor, as well, making sure the blades are not pitching to fast, this will save to connection points and increase the live to the overall hub design as well as the pitch.
Hub design	Surface fatigue	with the extra bolts attaching the hub to the shaft as well as the screws holding the blades on the bearings	with the extra holes, the structure of the hub design can become compromised, making it more likely to fail at the hub design, as well as the different points of the screws/bolts.	72	Strength the overall hub by filing more in for 3D printing, as well as replacing the overall design by using metal.
bearing choice	Galling and Seizure	the bearings can seize and stop the shaft, causing deformation in the shaft.	The seizure of the bearings can damage or even break the not only the shaft but also the motor.	112	The team will need to make sure the clearance between the shaft and bearings is enough to keep the shaft in place as well as to not damage the shaft

					and motor designs.
bearing choice	Surface fatigue wear	the ball brings will be affected without proper fittings.	the surface wear of the bearings will directly affect the speed of the shaft, which will negatively affect the turbines power output.	160	The bearings will have to be properly fitted for the shaft and turbine to be able to excel in the final design.
bearing choice	Force and/or temperature induced deformation	The bearing underneath the turbine could experience a greater force than rated for	This could cause the turbine to not work, as well as if the bearing is not rated for a proper load, the turbine will not spin with the direction of the wind.	96	The team will have to select a bearing with the overall rating of the force load. this bearing will have to supply the load as well as be able to turn with the direction of the wind.
Yaw bearing choice.	Galling and Seizure	Failure to change the direction of the turbine towards the direction of the wind.	The bearing moves the turbine, without this they turbine will fail one of the main tests within the competition.	135	The Bearing attached to the tower will be the main connection point. to ensure max performance, the team must select a bearing that is easy to move so the team can perform well during the final competition.
Yaw bearing choice.	High-cycle fatigue	With the shaft spinning at a high speed, the shaft an deform.	The shaft can deform and then shorten the overall length of the shaft, causing the rest of the turbine to fail.	40	The team will need to check the shaft. Also add bearings to help hold the shaft in place.

Shaft design	Force and/or temperature induced deformation	With the two-piece shaft, the force at the connection point can cause failure.	The shaft can come apart of. the overall Desing can come apart, causing the fly wheel to fall off and then the breaks will not work.	336	The team can overcome this by using a left-handed thread. as well as using different beading housings to strengthen the overall design.
Shaft design	Galling and Seizure	The shaft in the bearing can seize if it is not properly connected.	The shaft can seize, there for destroying the motor, as well as the bearing housings.	320	Check the different housing for the bearings with the shaft in mind as well as the clearance is correct with the shaft and the bearings.
Shaft design	impact wear	the shaft design will undergo a lot of different forces.	the different forces on the shaft can cause it to break, as well if the proper thread is not used, the shaft will come undone during the testing.	180	The team will need to conduct force analyze on the shaft design, as well as making sure the thread of the shaft is correct. the correct threads will ensure the overall sucess of the turbine.
Shaft design	impact deformation	the deformation between the connection points of the two shafts.	The forces of the connection as well as the different points with the bearing housings can add different impact points to the shaft design.	210	The team will have to conduct multiple force analyze on the shaft, find the overall potential deformation, and figure out where to place the bearings to reduce deformation.
Shaft design	Force and/or temperature deformation	The bolts holding the yaw to the nacelle.	the force of the bolts if tightened to much can break the connection points, causing the yaw to fall off.	80	The team will have to make sure the connection points are sturdy, as well as making sure the bolts are not over torqued.

Yaw design	Buckling	With a hollow design of the yaw, the weight with the force of the wind could cause the yaw to buckle in on itself.	the thickness of the walls, as well as the brittleness of 3D printing, the force can cause the middle of the Yaw to buckle in on itself.	24	Look at the yaw in solid works make sure the wall will be able to withstand the thrust force of the wind. If not create thicker walls of the yaw to make sure the final design does not fail
Yaw design	Joint Creep and Fatigue	The overall yaw system is too large to be printed in one 3D printer, the team will have to use 2 different prints for the yaw to be made.	with the two distinct parts, the team will have to make sure that the final yaw design is structurally sound.	49	The team will need to look for a larger printer if possible. If a larger printer cannot be found, the team will have to find a way to fit the two pieces together.
Yaw design	yielding	the yaw system could experience enough force from the wind for the yaw to break.	the overall forces on the yaw could potentially place to much force on the connection points from the nacelle that the yaw could break.	2	look at the connection points for the yaw, make sure the force of the wind and the different airfoil around the turbine will not exceed the for of the connections (Unlikely)
Yaw design	Brittle Fracture	With the combination of the yaw being in two pieces, as well as the connection points, could cause the yaw to break, and shatter.	the Yaw could break at the connection points for the bolts of the two pieces.	90	the team will need to examine the yaw at different critical points to look for any damage to the yaw.
Yaw design	Force and/or temperature deformation	Failure can cause electrical wiring to melt losing connection.	Wiring will melt together, can happen with extensive use and high current.	400	Look for lower gaged wiring to ensure better countify. Test motor at higher at

pitching connection	brittle fracture	connection ring in the swash plate can disconnect causing the swash plate to fail`	ring will disconnect, swash will stay intact.	180	Reprint part with stronger connections, even investigate printing the connection together/JB weld.
Tower connection	yielding	tower will yield and which could cause the different airfoils for the turbine, this would cause the turbine to be inefficient.	tower will begin to bend in whatever direction the main weight of the turbine is being pointed.	90	use stronger parts, investigate using steel tower vs PVC.
Slip ring	Galling and Seizing	the slip ring can seize and the wiring through it can get tangled. The slip ring also has outer bearings that can seize, and the turbine will fail to redirect with the change in airfoil.	the turbine will not be able to redirect when changing wind direction. The seizure of the slip ring can also loosen wiring connections, which will cause the turbine to not record data.	240	find a higher amp rating slips ring as well as test the final slip ring/connection point with car testing as all different speeds.