WRITTEN REPORT

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Table of Contents

1 **INTRODUCTION……………………………………………………………………2**
1.1 Executive Summary………………………………………………………………2
1.2 Overview…………………………………………………………………………2
1.3 Design Consideration…………………………………………………………3-4
2 **ELECTRICAL AND SOFTWARE DESIGN……………………………………5**
2.1 Electrical and Control Subsystems………………………………………………5
2.1.1 Voltage Input Measurement Circuit…………………………………5
2.1.2 Management System………………………………………………6
2.1.3 PCC Implementation………………………………………………6
2.1.4 *Emergency* Braking System………………………………………6
2.1.5 Buck-Boost Converter Analysis……………………………………7
2.1.6 Low Pass LC Filter…………………………………………………8
2.1.7 Generation Curves………………………………………………9-10
2.2 Software Design……………………………………………………………10
2.2.1 Flowchart………………………………………………………………11
2.2.2 Code Function…………………………………………………………11
3 **MECHANICAL DESIGN………………………………………………………12**
3.1 Blade Design…………………………………………………………………12
3.1.1 Design Constraint……………………………………………………12
3.1.2 Selected Airfoil………………………………………………………12
3.1.3 Blade Design Process…………………………………………………12
3.1.4 Performance and Energy Analysis……………………………13-14
3.1.5 Structure Load Analysis……………………………………………14-15
3.1.6 Blade manufacturing…………………………………………………16
3.2 Hub Design……………………………………………………………………16
3.2.1 Hub Design and manufacturing Process…………………………16
3.2.2 Rotor assembly………………………………………………………17
3.3 Tail Design……………………………………………………………………17
3.3.1 Tail Design Process……………………………………………………17
3.3.2 Tail Manufacturing……………………………………………………18
3.3.3 Tail Analysis……………………………………………………………18

Chapter 1: Introduction

1.1 Executive Summary

At the CWC 2017-2018, Juracán Energy Team presented the vulnerabilities of the electrical grid of Puerto Rico in the aftermath of a catastrophic hurricane Maria event of 2017. Most of the energy generation is based on fossil fuels, and the generation and use of power at distant places therefore when the hurricane event hit the island an imminent energy crisis ensued. The team presented their 2MW turbine design with the capacity to hold 67 m/s winds and the purpose of aiding the distribution system to provide power critical infrastructure such as hospitals, supermarkets and water distribution pumps. This system would effectively aid immediately after a catastrophic event hit since its design was made to survive and outlast such scenarios. Using this same objective, the team for the CWC 2018- 2019 decided to focus on remote locations that received the worst and longest lasting effect of the hurricane event.

Remote locations such as inland towns and rural communities experience great hardships due the lack of access to power, water, food and data. These locations depended entirely on bridges, electrical lines and subterranean pump systems to obtain their basic resources. Once the hurricane hit all prior mentioned elements, these remote locations were cut off. People would instantly lose communication, electricity, water and their freedom all at once. This devastating circumstance could prove deadly to some of the most vulnerable elements of the community such as the diabetic patients which depend on their insulin to remain at low temperatures in order to be administered properly, The proposed solutions for these locations in the event of a new catastrophe a micro grid system was designed using a smaller and more accessible turbine as either a supporting energy unit or main energy output system.

The micro wind turbine would be a 400W, 12V turbine inspired by the Auto Maxx "DB-400 WINDMILL". This wind turbine will be implemented in unison with other available clean energy resources of the community such as solar panels. The purpose of the micro grid is to provide an electrical generation with different energy sources while having a control system. With this, the basic electrical resources will be provided to a centralized location of the locked-out region. This centralized location could be a house or block were the affected civilians can go to. The main use of the energy would be for lighting, a small economic fridge or for communication equipment like radios, or to charge their batteries. The wind turbine will be placed in a nearby location were the wind conditions would be available. The turbine is designed to be a light turbine with few mechanical components and the possibility of being dismounted and stored in a safe place in case of the event like hurricane Maria and re deployment after the event passes.

1.1.1 Overview

For this competition the turbine design was changed to improve its performance. The turbine is a direct drive with a passive yaw control, and a three-blade whose design was modified to be more effective. The aerodynamics were based on the characteristics of the electrical generator, it is a change from last year, since the generator was selected based on the aerodynamics power output. As for the base is a rotational, that adjusts to the wind flow with the help of the yaw control, which is an addition to the previous design. On the electrical system, the entire control system was tested several times, to make a more effective system electronics like a LC filter which will help to the power curve were added, additionally was worked on the protection the electronics devices like the voltage sensors, this sensors has a maximum input of 25V to protect them as a voltage divider was added. The control system can shut down when a load is removed or when the push button is pressed. As for the overall durability of the turbine its design for high speed as part of the purpose of turbine potential use. The turbine in generation has been tested using a fan that can blow up to 8 m/s.

1.1.2 Design considerations

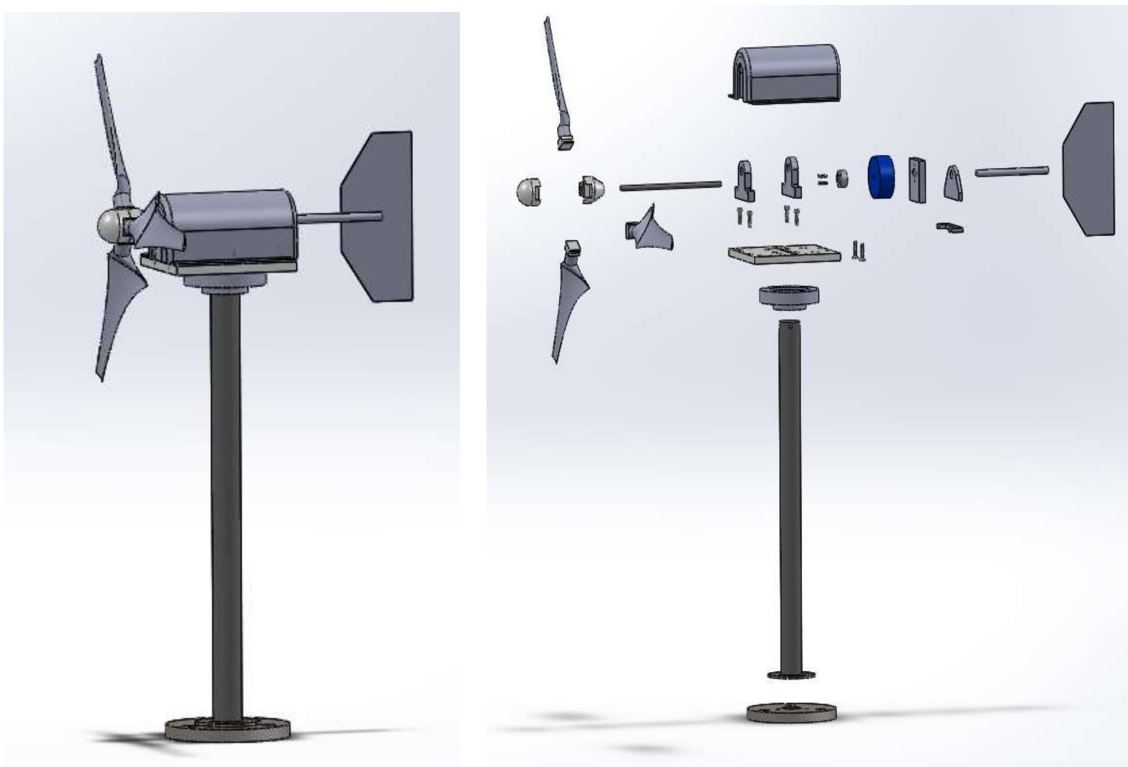
The main purpose of the turbines design is to be an energy source on a microgrid which will be operating on a remote community, since its primarily objective is to operate after an catastrophic event such as a hurricane. Its design must be easy to deploy and light weight since it is intended to be a system that can be removed before the catastrophe and deployed after into service or be re located elsewhere if necessary. Once deployed, the system must be durable and of low maintenance since it will be producing energy without frequent technical overview. As for control design it must shut it down to prevent any further damaged if is over generating or something else is wrong with turbine.

With this purpose in mind a trade study was made for the classification of the wind turbine system. Horizontal Axis Wind Turbines were favored and were the main elements of choice for this trade study due to its superior Betz limit in comparison with a vertical axis system. The higher Betz limit is crucial for the design in order to maximize energy intake thus the options presented for the trade study are all horizontal axis systems.

Problem Statement	Choose a H.A.W.T. classification	Weight	Baseline UpWind and Pasive Yaw	Up wind With active Yaw	Down Wind
Criteria	Ease of manufacturing and assembly	4	Datum	-1	1
	Silent (low level of vibrations)	2		0	-1
	Durability	5		0	-1
	Ease if operation	3		-1	0
	Self start	5		0	0
	Work well in diferent wind conditions	5		0	-1
	Generate power at low wind	4		0	0
	Geneate stable power	4		0	0
	Shut down	5		0	0
	Follow wind direction	4		1	0
	compact	3		0	0
	Low economic cost	3		-1	1
	Control	3		0	0
	Total:	50	0	-6	-5

Table: Trade study for H.A.W.T. classification

In this trade study, the horizontal axis wind turbine classification was evaluated. The three options presented were as follows: an up-wind system with an active (control system) yaw, a downwind system (which has no need for a yaw control) and the base line that is an up-wind system with a passive yaw. The chosen classification was the baseline since it presented a model that is both simple and makes best use if the wind. The downwind system was a possible alternative, but it’s needed to make up for a tower shadow and for an appreciably aerodynamic nacelle made more difficult the durability of the system and mitigating vibrations and noise as analyzed by the team [wind energy explained reference page [6]. Once this trade study was fulfilled the general design was implemented with the design objectives in mind, see figure 1.



(a) (b)

Fig. 1: (a) Turbine model (b) exploded view

The wind turbine design considerations that support the objectives are a direct drive system, slim nacelle, and the general durable and replaceable nature of its components. The direct drive was chosen in order to reduce weight in the system and additional maintenance complications such as gear degradation. The slim nacelle was designed to protect the main components and to permit an easier transition of the air from the rotor to the tail. It is noticeable that the nacelle is smaller than the base plate, the base plate is wider to encompass a future mechanical break that is intended to be part of the next iteration of the project for future experimentation. Lastly most of the exposed components of the design, such as blades, nacelle, hub and tail fin are both durable and made easy to replace which is one of the parameters designed for the turbine. Since it is expected for the turbine to work on extended periods without maintenance it is designed so that the system's broken, or corroded components can be easily replaced for new parts while the reclaimed parts are restored and placed to use elsewhere.

On the electrical design it was consider controlling the output voltage to not exceed the 40V maximum output. It was taken on consideration too, the safety of the electronics devices, since if one sensor gets damaged the system will not operate to its perfection. For the microcontroller a capacitor bank was made by using the specification on the rules to not exceed the maximum energy value. As for the generation multiple key point were considered like the torque, output voltage, rpm ratio, dimension, etc.

Chapter 2: Electrical and Software Design

2.1 Electrical and Control Subsystems

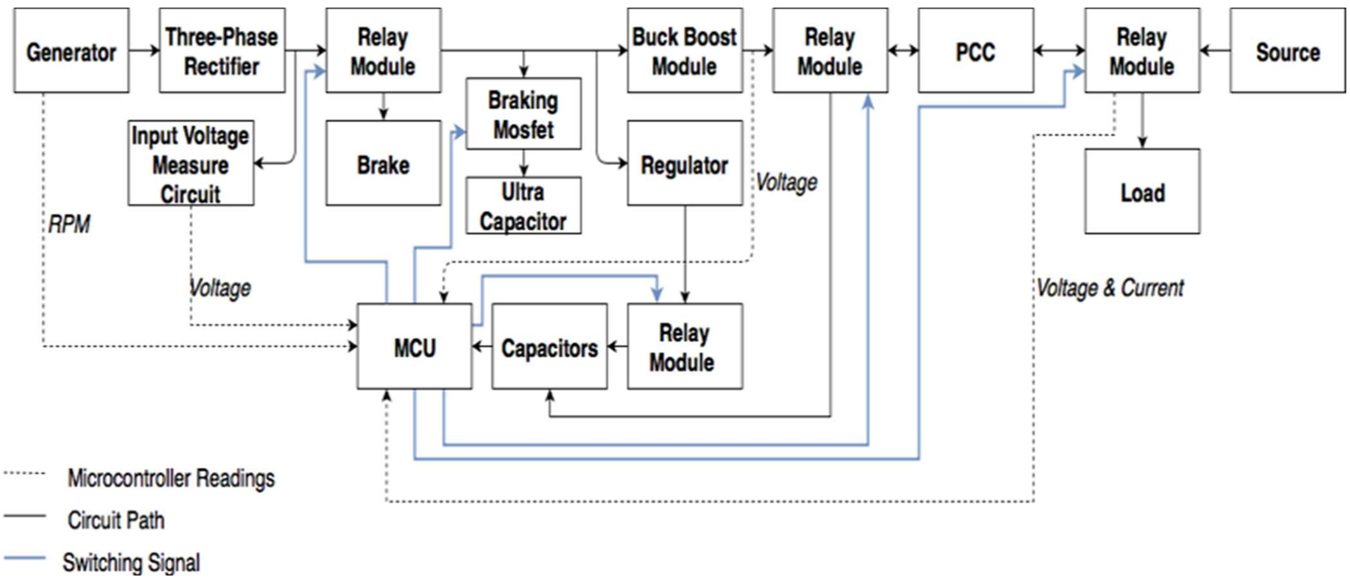


Fig. 2: Electrical System Block Diagram

The complete system can be divided in the following general subsystems: generation, rectification, DC-DC conversion, and braking. MATLAB/Simulink/Simscape was used during the design process. A microcontroller was used to generate control signals based on measurements performed by sensors available in different parts in the system. Details of all the components is presented below.

2.1.1 Voltage Input Measurement Circuit

The voltage input measurement circuit is connected directly to the DC output of a three-phase rectifier to read the generated voltage of the turbine. It is assumed that the power generated from the generator is converted into DC power through diode bridge rectifier circuit with unity power factor and the load current is continuous [1]. This input voltage is very important for the control system since it is used by the microcontroller for decision making. The circuit is composed of two resistor, a voltage sensor, and a voltage follower op amp. The resistor was used to prevent current loss and create a one to ten ratio. Since with the past turbine there was a problem with voltage sensor capacity, this was added to increase the voltage measuring range, while keeping to sensor and microcontroller.

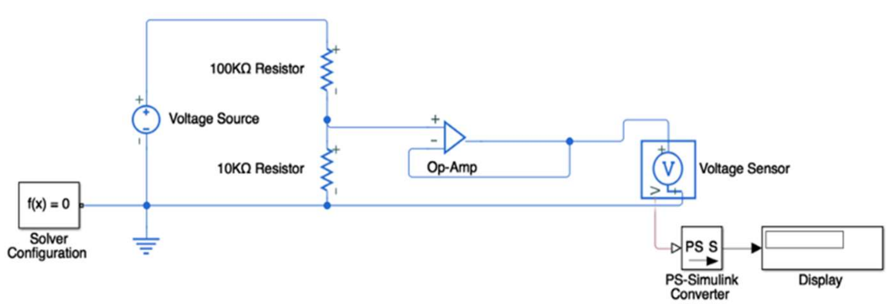


Fig. 3: Voltage Input Measurement Circuit

MATLAB/Simulink was used to test the circuit (see Figure 3). The voltage in the 10KΩ resistor can also be calculated using the following equation, where the variable are: V_{R2} = voltage on the resistor parallel to the voltage sensor, V_S = voltage source, R = Resistor.

$$V_{R2} = V_s * \frac{R_1}{R_1+R_2} \quad (1)$$

2.1.2 Management System

To ensure a proper operation of the wind turbine, an Arduino microcontroller had to be implemented to the system alongside a variety of sensors. This device will constantly monitor the input voltage the data is received from the voltage sensor. By reading the respective parameter the microcontroller can determine the state of the turbine and what change it is needed to have a proper functionality of the system. As safety is the number one priority the microcontroller must always operate. To ensure this, a capacitor bank was placed in parallel to the microcontroller providing a proper microcontroller operation while the control system state change. The capacitor bank is composed of five 10V/2200μf capacitors with a total storage capability to be less than 1 Joule. The storage capability of the capacitor can be calculated using the following equation, where the variable definitions are: E = energy (Joules), C = charge, V = voltage.

$$E = \frac{1}{2}CV^2 \quad (2)$$

2.1.3 PCC Implementation

To keep the microcontroller power up all time, a set of two-state relay module hl-54s were used to manage the point of common coupling (PCC) depending of the generation conditions. When the generation is low or the system is in brake mode, the PCC will be using an external power supply of 5V to maintain the microcontroller power up. On the other hand, when the turbine is generating properly, the PCC will be supplying power to the microcontroller and the load as well.

2.1.*4 Emergency* Braking System

According to the Bureau of Labor Statistics in 2016, 5,190 fatal work injuries were reported in the United States; a 7% increase of the previous year [2]. As safety is of utmost importance to turbine designers and manufacturers, the turbine must shut down rapidly and have a fail-safe shutdown capability as well. To achieve these capabilities, a braking state was implemented in the control system. This state disconnects the microcontroller and the load from the generation. In addition, the PCC is switched as an input to power up the microcontroller. The generation is routed to a 16V 58F BMOD0058 model ultra-capacitor using a power MOSFET for a couple of seconds and then is routed directly to ground. The ultra-capacitor demands a lot of current causing the turbine to slow down, then it sent directly to ground, and a large amount of current is returned into the generator causing an electrical torque that counter acts the generator mechanical torque which achieves system equilibrium.

The braking state can be activated by disconnecting the load to prevent an over speed in the system due to an over voltage generation can be produced by the load given the lack of resistance in the circuit that cause a lower torque on the generator. The system will automatically return to normal operation when a load is connected again or by an emergency button in the system that can shut down the turbine at any time. Figure 4 shows the diagram for the ultra-capacitor brake connection.

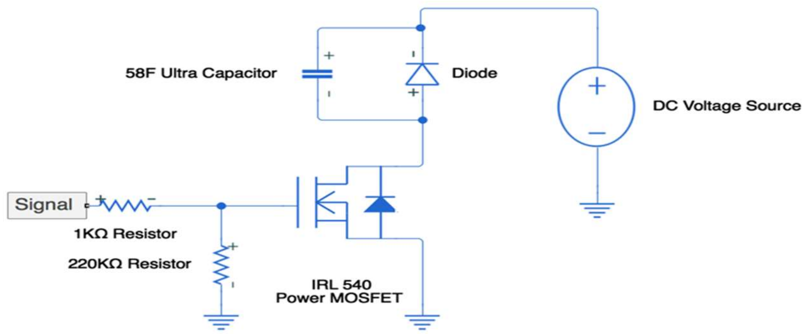


Fig. 4: Pulse Brake Circuit Diagram.

2.1.5 Buck-Boost Converter Analysis

The Buck-Boost converter helps to maintain fixed DC output voltage with maximized output power by controlling the gate pulses of the converter, which in-turn controlled by duty ratio of the PWM control [3]. The converter used has a voltage input from 4V to 36V and a voltage output from 0.8V to 30V. To test the efficiency of the buck-boost converter an electronic load model and a fixed 5V power supply were used. The electronic load was directly connected to the output of the converter. During the tests the converters efficiency was evaluated with two different output voltages. First the converter was set to an output of 5V with different input voltages as well as different constant current loads (input voltage ranges from 5V to 30V and the constant current draw load from 0.010A to 1A). Then the output of the buck boost converter was change to 12V and tested using the same process. Figure 5 shows the setup use to test the efficiency of the buck-boost converter.

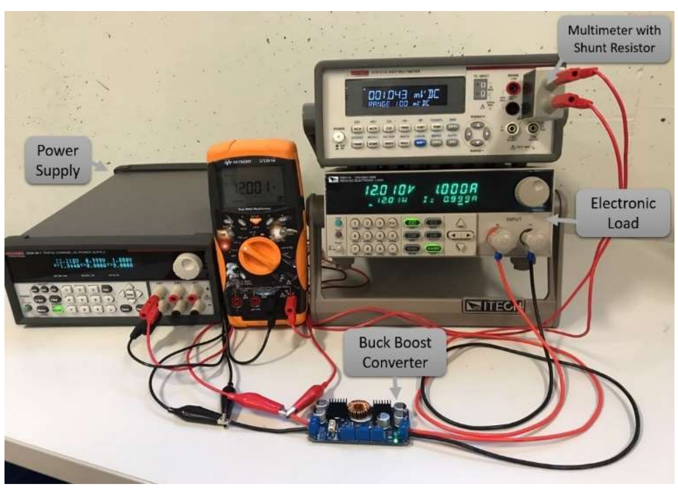


Fig. 5: Buck-Boost Converter Test Setup.

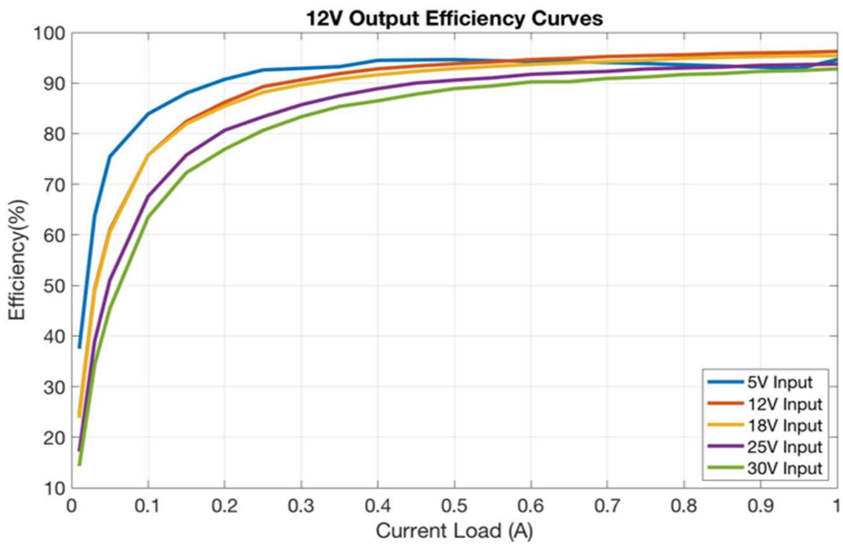


Fig. 6: 12V Output Efficiency Curves.

2.1.6 Low Pass LC Filter

A low pass LC filter was used to reduce the high frequency noise above 100Hz that the power electronics produce. A second order Butterworth low pass LC filter with a 100Hz cut-off frequency was implemented. Inductors can be used in combination with capacitors, which complete the function of the inductors, to form the LC filters that can separate the required signals from unwanted ones. The propose filter design contains three 1000mh inductors connected in parallel to achieve a 333mh. On the other hand, the capacitor is used to remove the high frequency signals that pass through it. The system contains a 7.6mf capacitor bank composes of two 3,300mf and one 1,000mf capacitors connected in parallel.

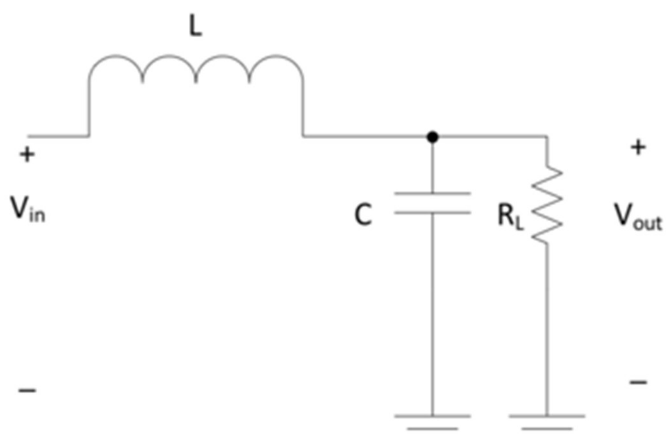


Fig. 7. LC Filter Diagram.

During the testing process we connected the LC filter in between the output of the buck boost converter and the load. An oscilloscope was used to measure both the input and the output of the filter.

The wind turbine was connected to the three-phase rectifier which supply's DC voltage to the buck boost converter. Also, an electronic load was connected to the output of the LC filter set to a constant current load.

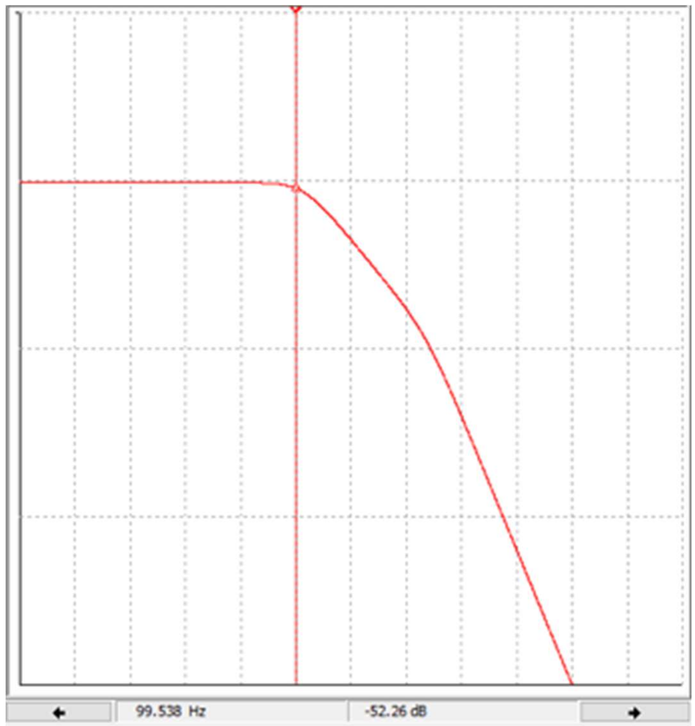


Fig. 8. LC Filter Response.

Figure 8 shows the frequency response of the Low pass LC filter. This graph displays the frequency at the x-axis and the gain in the y-axis. This filter was designed to have a cut off frequency of 100Hz. In this graph we can see that at 99.54Hz the gain starts to decrease drastically as expected.

2.1.7 Generation Curves

After determining the more efficient voltage output for the buck-boost converter. The generator was connected to the three-phase rectifier of the control system to determine the generation curves. An rpm sensor was attached directly to the shaft to measure the speed of the generator. During this test, the control system was evaluated with five different constant current loads by using the electronic load. The generator was rotated at different speeds in the range of 0rpm to 900rpm.

Figure 9 shows the power output of the control system varying the speeds with different loads. The system is powered by a TURNIGY 5208 Gimbal Motor use as a generator, which is capable of generate voltage at lower speeds.

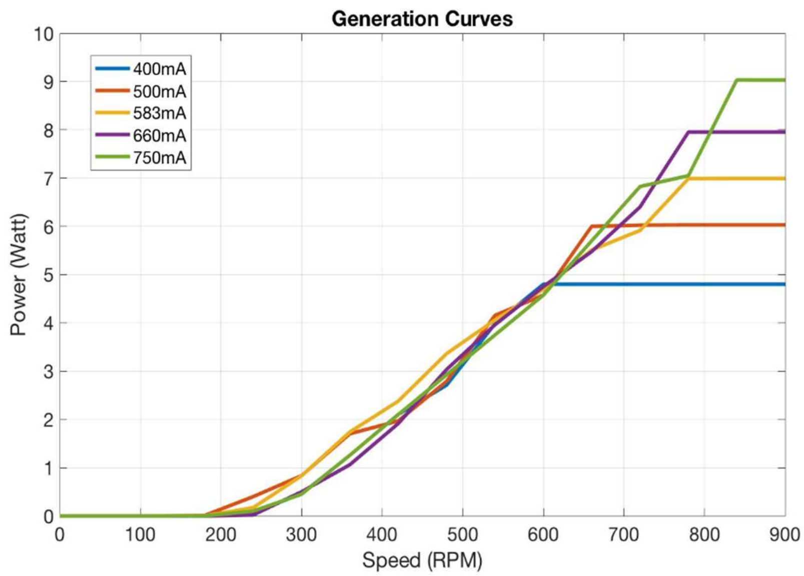


Fig. 9. Generation Curves.

2.2 Software Design

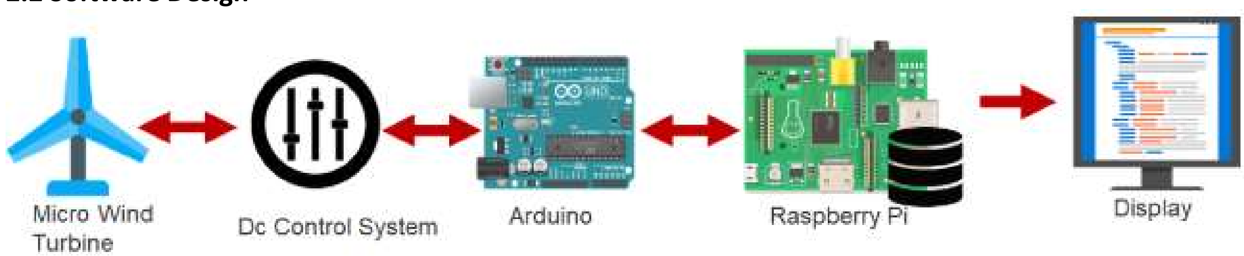
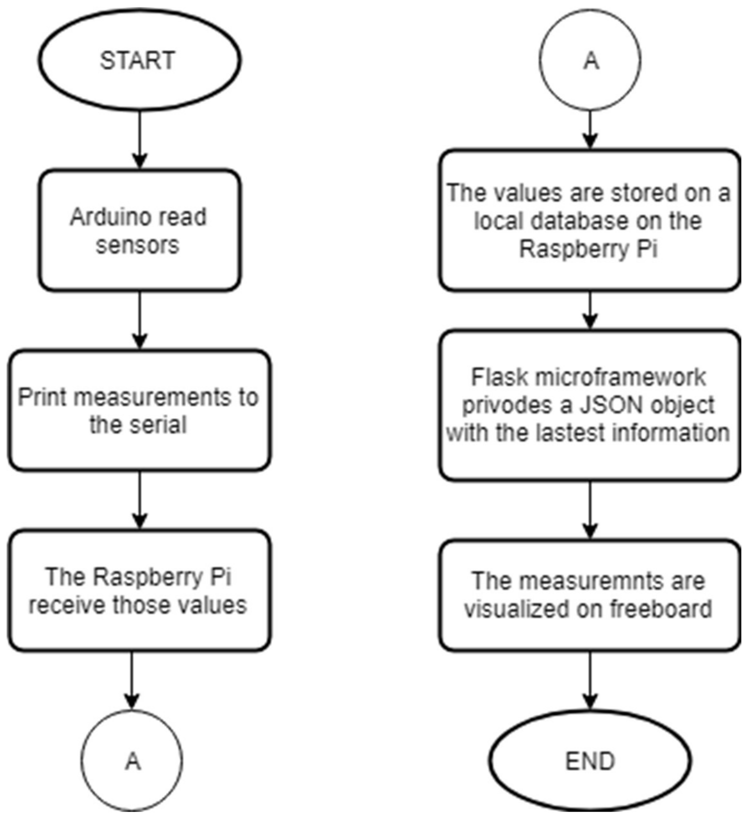


Fig. 10. Structural Diagram of the system

A similar project highlights the importance for a monitoring system such as the visualization of the energy consumption [4]. Micro turbines have become more common as energy sources due to its easy installation process and power generation efficiency [5]. In Fig 10. we can observe the overall structural diagram of the monitoring software designed by the computer team. The monitoring software was created to provide a way to monitor the overall behavior of the micro wind turbine and was developed to assist the team to identify if the micro turbine is operating as it should. The monitoring software monitors the micro turbine through the control system connected to it. This can be achieved by connecting a microcontroller externally to the control system, that is able to read the measurements of the DC control system. The readings are sent to a single board computer via USB, a single board computer, that acts as the command center. It then stores the read values in a local database, to permit later data analysis and benchmarking of changes to micro turbine. From the acquired data we can visualize it and display it.

2.2.1 Flowchart



The implemented system starts by the Arduino reading the sensors of the DC Control System. The Arduino performs the corresponding calculation to get the measurement from the signal of each sensor. Finally, the Arduino prints the results to the serial port where the Raspberry Pi can read them.

2.2.2 Code Function

The Raspberry Pi executes a script written in Python to read the serial monitor of the Arduino and store the measurements in a local database. A second script was also written which will provide an API written in the web microframework that will provide a JSON object with the latest information read from the database, as well as maximum key values. To visualize those values, an open source web application named Freeboard is used as a dashboard. This dashboard uses the local API to provide visuals and different types of graphs of key data points and will be automatically refreshed a few times every second.

Chapter 3: Mechanical Design

3.1 Blade Design

3.1.1 Design Constrains

The design of the blades was performed taking into consideration various parameters. The blades' length and diameter of the hub were designed to comply with competition rules. The dimensions of the rotor along with the specifications of the generator and wind speed for rated power dictate the tip speed ratio of the design. Durability and 3D printer capabilities were taken into consideration since thin airfoils produce durability problems and printing deformations. Foils of this type were not taken into consideration.

3.1.2 Selected Airfoil

The blade utilizes two airfoils, the S1223, and a circular foil that functions as the root of the blade. [6] The S1223, is selected because of its ability to produce high lift at low Reynolds number. The calculated Reynolds for this design is 53,333 Re. Taking this number into consideration, the S1223 airfoil was selected by looking for airfoils with a maximum lift to drag ratio at 50,000 Reynolds. This airfoil has a Max Thickness 12.1% at 19.8% chord. [6] Since the blades will be 3D Printed this larger thickness benefits the overall structure of the blade.

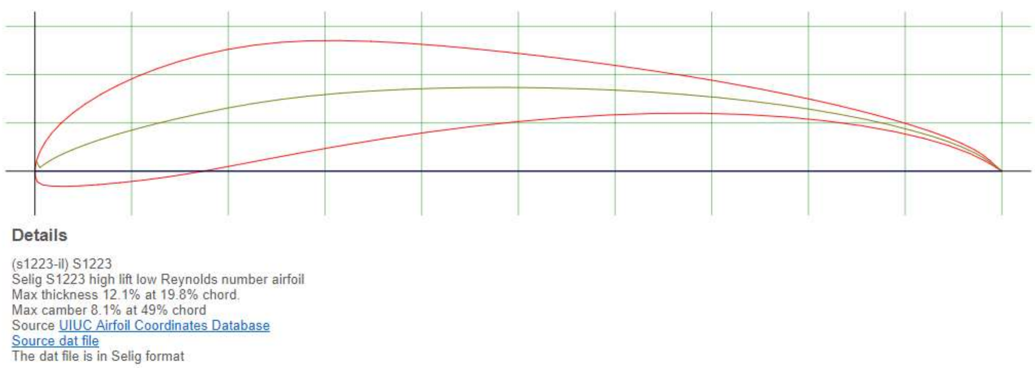


Fig. 11. S1223 Airfoil used for blade design. [6]

3.1.3 Blade Design Process

The blade design and aerodynamic simulations were done using QBlade, an open source software. Analyzing the S1223 airfoil, in QBlade, the ideal attack angle and lift coefficient were found at maximum lift-to-drag ratio. This yielded, for the current blade, a lift coefficient of $C_L = 1.169$ and an angle of attack $\alpha = 1.0°$. Having found these parameters, the blades can be designed in QBlade. In Figure 12 below one can see the lift-to-drag ratio analysis plotted against angle of attack.

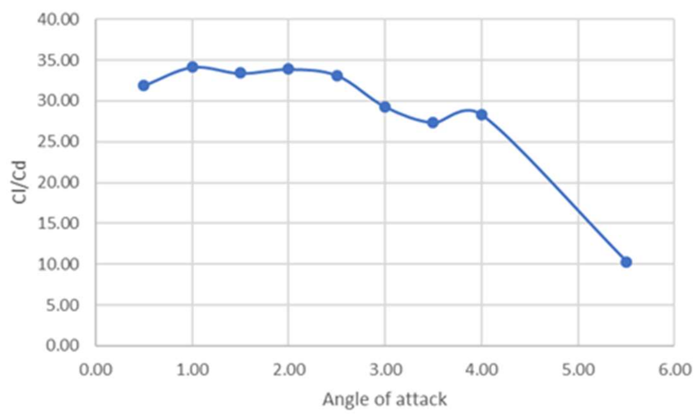


Fig. 12. Lift-to-drag ratio analysis plotted against angle of attack.

Based on QBlade's format for blade designing the blades had to be divided in sections, the number of sections was set to 15. The idea is to implement a methodology that changes the profile of the foil by section based on generator, blade length and rotor radius until the blade is formed. Using the Manwell and McGowan Wind Energy Explained as reference, an Excel sheet was developed to calculate the blades' chord and twist angles by section. This methodology is called the 'Betz optimum rotor'. [7] One of the first parameters to be calculated is the tip speed ratio. Using the tip speed ratio equation $\lambda = \Omega R/U$, the tip speed ratio was calculated to be 4.19.

Table 1: Blade description as seen in QBlade.

Section	Pos (m)	Chord (m)	Twist	Foil
1	0	0.02	0	Circular Foil
3	0.029	0.085	30.4	S1223
5	0.057	0.056	13.31	S1223
7	0.086	0.04	7.23	S1223
9	0.114	0.031	4.09	S1223
11	0.143	0.025	2.16	S1223
13	0.171	0.021	0.9	S1223
15	0.2	0.018	0	S1223

3.1.4 Performance and energy analysis

Once the blade design has been completed, it is subjected to various theoretical tests in QBlade to determine its performance. The focus of these studies is to evaluate the power coefficient of the blade at the calculated tip speed ratio and the theoretical power curves of the rotor at different wind speeds. The power coefficient is the first test after designing the blade, this study is done setting the wind speed at 10 m/s and evaluates the coefficient of power plotted against a range of tip speed ratios from 1 up to 10 in increments of 1. This study found the maximum coefficient of power to occur at a tip speed ratio of 4 which matches with the calculated tip speed ratio of 4.19 used in the design of the blade. Figure 13 below shows this behavior.

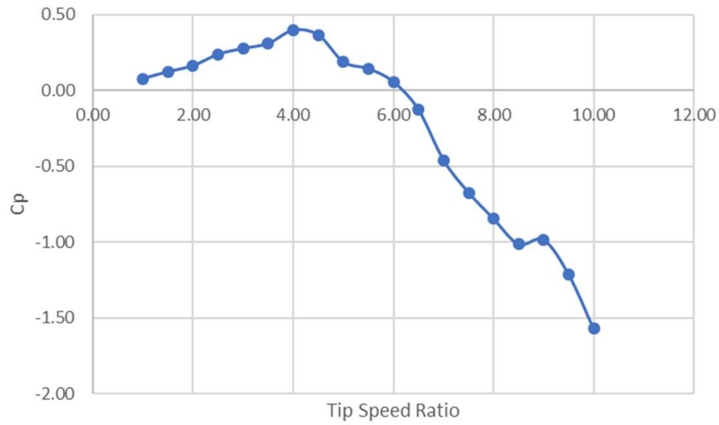


Fig. 13. Coefficient of power plotted against tip speed ratio.

The theoretical power curves evaluate the power transformation the designed rotor is capable of. It was decided that to achieve this goal, a starting point could be evaluating the past competition turbine's experimental and theoretical data. With this information it was found that the current system had an 80% efficiency, meaning that 20% of the energy was loss. What this means is that by quantifying these losses, the theoretical data could accurately predict the behavior of the rotor. For this competition's design, the theoretical studies calculated a cut-in speed of 5 m/s and a rated power occurring at 10 m/s.

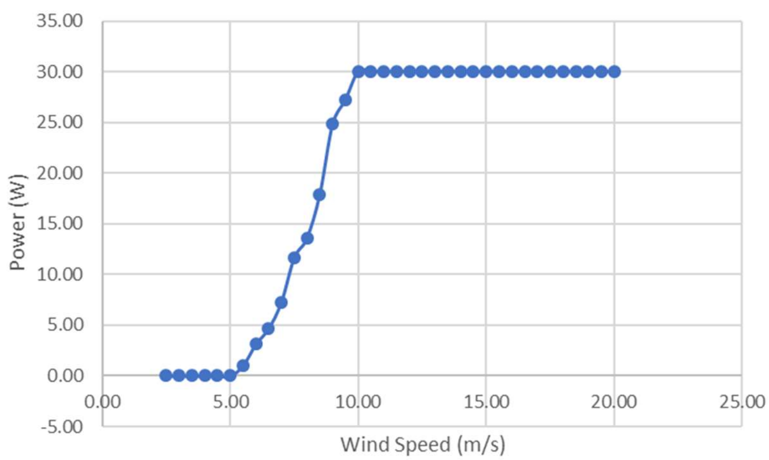


Fig 14. Power curve plotted against wind speed. Shows the theoretical cut-in speed and rated power.

3.1.5 Structure Load Analysis

Wind turbine blades are subjected to various loads during operation. The flow of the wind applies a direct force on the blades while the rotation produces centrifugal forces. To validate the design of the S1223 blades and obtain information of the structural integrity at its operating limits a finite element analysis within SolidWorks was necessary. These analyses were performed on an assembly of the rotor with an earlier version of the blades which strongly resemble the current set of blades in a modeled wind tunnel bearing the dimensions provided in the Collegiate Wind Competition 2019 rules and requirements manual [8]. The material utilized for these analyses was Polylactic Acid with an Elastic Modulus of 350 MPa, Shear Modulus of 240 MPa, and a Density of 1300 kg/m^3. A centrifugal force analysis for this rotor assembly was performed in which a rotational speed of 3,500 RPM was chosen as it is higher than the maximum anticipated rotor speed determined in QBlade of 2,500 RPM. The results of this analysis can be seen in below where the highest stress points where located around the roots of the blades.

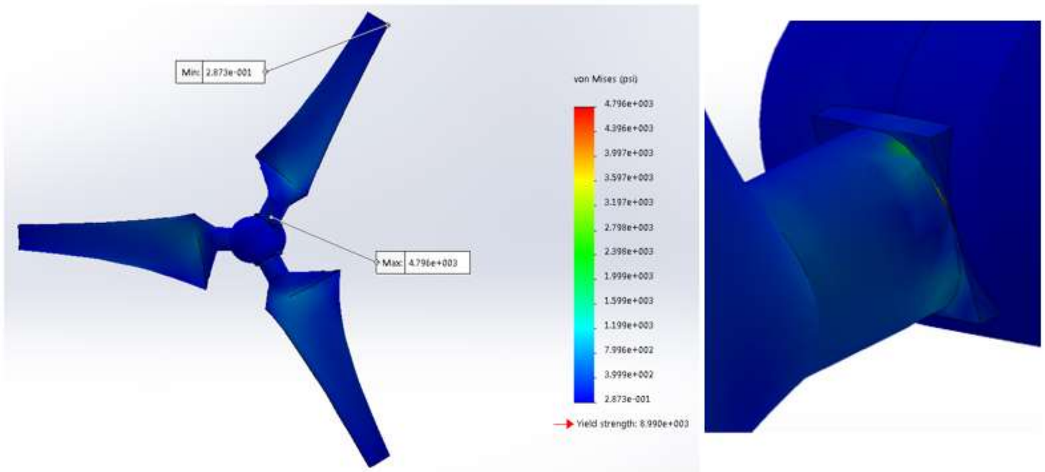


Fig. 15. Centrifugal Force Analysis Results.

The same rotor assembly was then placed within a modeled wind tunnel at wind speeds of 20 m/s in which the forces due to wind pressure were recorded. A blade element momentum analysis was also carried out to determine the magnitude of the forces applied by the wind at a speed of 20 m/s upon the blades from which a thrust force of 1.52 N was found. These forces were then added to the ones obtained from the centrifugal analysis and a new simulation was performed. The results of this analysis can be seen in Figure 16 in which the maximum stress points were again located at the roots of the blades. From this simulation a minimum factor of safety of two was also obtained which indicates that the rotor assembly and blades could withstand winds at speeds over 20 m/s.

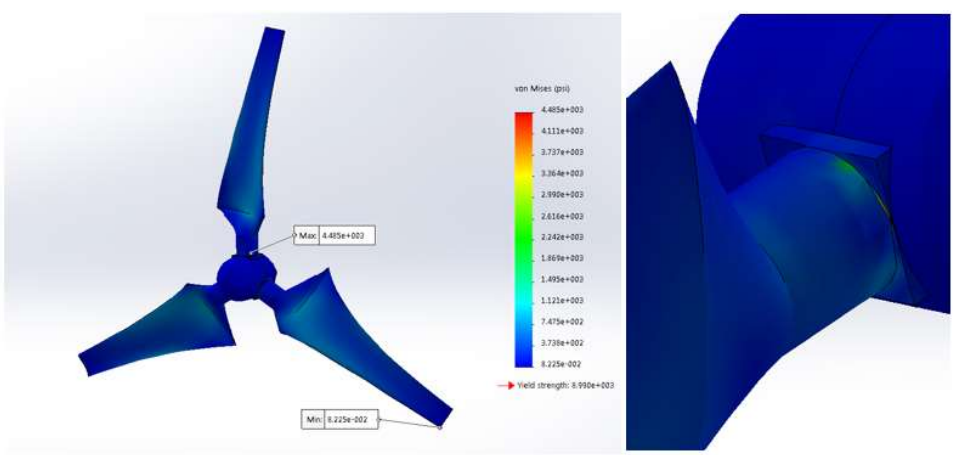


Fig. 16. Centrifugal Force and Wind Force Analysis Results.

3.1.6 Blade manufacturing

Blades were manufactured in a PRUSA MK3S 3D Printer using Polylactic Acid (PLA) filament. These were positioned on its leading edge with the purpose of having the layers parallel to the length of the blade with the added benefit of needing less support material as seen in Fig. 17 below. This was done in order to produce blades with the best structural properties possible with less wasted material on the support structures. Consecutively, a resin coating was applied in other to improve airflow along the surface and further improve their structural strength. Once applied, the resin coating is sanded with progressively finer grit sand paper to remove imperfections and achieve the smoothest surface possible. One of the priorities during this process is to keep the weight of each blade similar in order to maintain balance on the rotor.

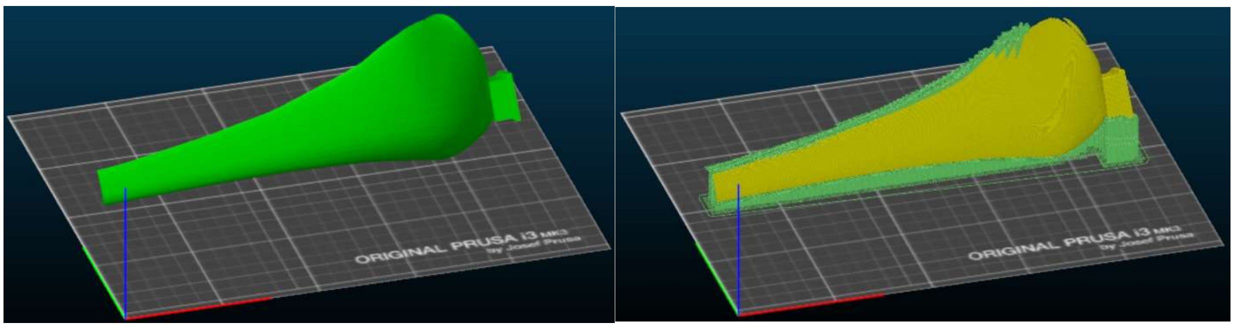


Fig. 17. Blade positioning in Slic3r Prusa Edition.

3.2 Hub Design

3.2.1 Hub Design and manufacturing Process

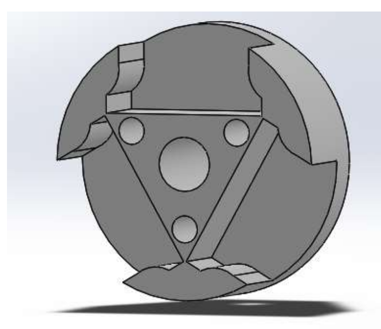


Fig. 18. internal hub features.

The hub system for the CWC 2018-2019 was based on the system used for the 2017-2018 competition and redesigned for an upwind turbine system. The designs were made in SolidWorks and featured two hub elements which hold the blades captive, one is the nose hub section which makes first contact with the wind and the other is the rear hub section which has slots for the shaft, screws and a cutter pin. Figure 18 presents the internal design that is present on both hub elements. This internal design is made in a way that the blade's roots fall into the slots as fit as possible and are solidly mated together. Lastly, the hub system was manufactured using 3D printed PLA due to its rigidness and strength.

3.2.2 Rotor assembly

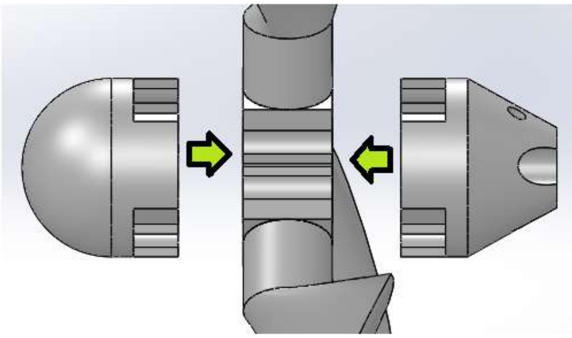


Fig. 19. hub mating arrangement

To illustrate the assembly structure, Fig. 19 presents a side view of the arrangement of the rotor mating. The three blades are presented on the middle of Fig. 19, on the left is the nose hub section and on the right of the blades is the hub rear component. These two components together are responsible for the rotor's solidity. Once all components of the rotor are connected one to the other, screws are inserted on the rear hub slots that pass to the nose hub section to make the mate tight and leave all parts of the rotor solidly mated. This effective mate converts all rotor components into one single rotor peace which is placed into the shaft and mated using a cutter pin.

3.3 Tail Design

3.3.1 Tail Design Process

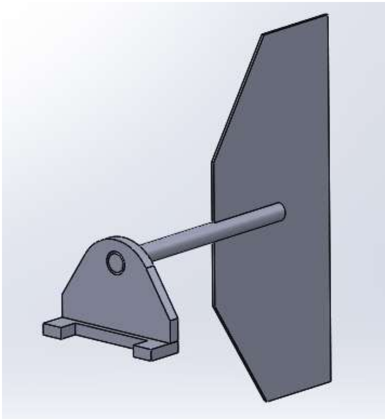


Fig. 20. Passive yaw system tail system.

The tail was designed to be a component of easy iteration since we chose to go for an experimental approach to view different sizes and possible shapes for the system. The tail's fin is designed using a sweep area of 32% as a first iteration due to the lack of tail boom length this incrementation will provide much needed air contact for quick directional response. [9]

3.3.2 Tail Manufacturing

The base tail system was machined using a CNC mill and was made from aluminum while the fin was made of a thin sheet of stainless steel and was given form using a plasma cutter. Stainless steel was chosen for its strength and since the sheet is very thin it does not weight much making it an ideal material for the task.

3.3.3 Tail Analysis

The main form of evaluation of the passive yaw system was through direct experimentation. The equipment used to evaluate the yaw system due to the lack of a wind tunnel was through an industrial fan with a radius of 111.76cm. The industrial fan was placed at 355.6cm of distance from the turbine, this was done to make the wind as defined as possible before entering in contact with the blades. The average wind speed produced by the fan was 7.215 m/s and once it reached the turbine its speed was 2.72 m/s on average. Once the preparations for the tests were ready and evaluated, three main tests were made: the first one was placing the turbine at an angle of 90^0 in the wind's direction, the second one placing it at 180^0 (facing backwards to the wind) and lastly the last test was spinning the turbine. As a first iteration the fin with the 32% of sweep area was tested without the nacelle. In this first iteration the turbine re-oriented itself to the wind in 5.77 seconds in the first test, 11.64 seconds in the second test and 4.33 seconds on the third test. A possible explanation of why the third test presented shorter timing response than the other could be since the tail is in motion, while for the other tests it must surpass its own inertia and break static friction to set itself in motion. In conclusion, the tests are presenting the team with valuable data and the best trait of the system is that is made for easy assembly and disassembly of many of its exposed components which promotes comparisons between fins and other components that may affect the turbines orientation.

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