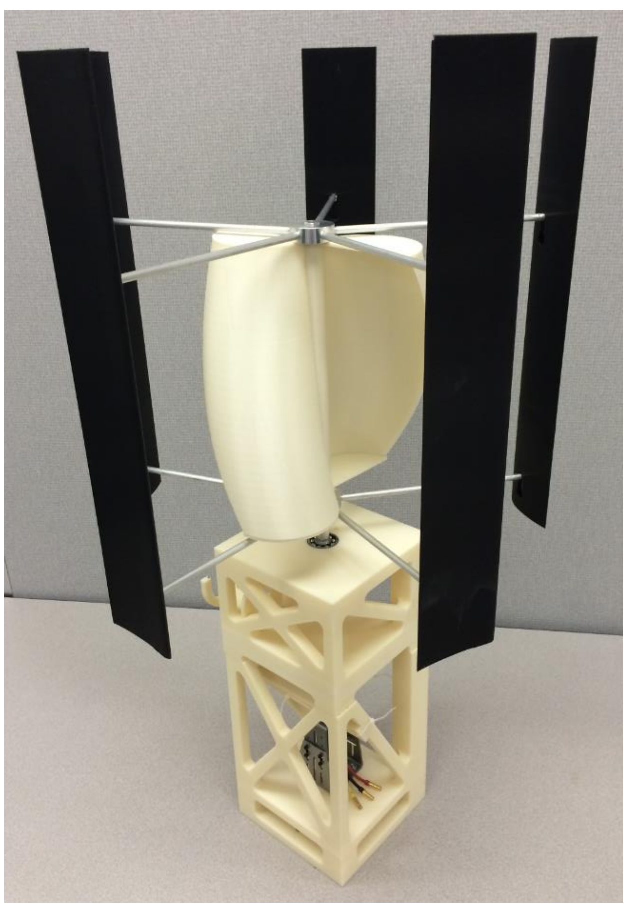
WIND TURBINE DESIGN REPORT

Wildcat Wind Power – Kansas State University

18 April 2014



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Introduction

The turbine designed for the 2014 Collegiate Wind Competition was designed not only to be functional, but also marketable. Our design incorporates a design that is very different than the bulk of turbines currently in the market and targets a market that has a large opportunity, but currently has little competition. Our blade design differs from the market standard because we used a vertical axis orientation, which is omnidirectional and has a larger aesthetic appeal. Also, it was decided that the manufacturing process would utilize 3-D printing for turbine blades and many other components. The largest benefits of 3-D printing are that it has a fixed capital cost and is customizable. There were many challenges associated with our design; however, after testing and several iterations, a final design was chosen and is detailed below.

Mechanical Design

Design Motivations

Throughout the design process, our team decided we wanted to design this turbine in such a way that, if damaged or redesigned, we could easily swap out parts. Not only was this characteristic especially useful for us as designers, but we figured that a real world turbine that is easy to assemble/disassemble would also be easy to repair. In the event of a blade getting broken or a part being worn, the ability to disassemble and reassemble the turbine in a matter of minutes would be especially useful and appreciated by maintenance workers. We believe that this motivation is evident in our design.

Turbine Orientation

The first issue tackled by the mechanical design team was blade orientation. Generally speaking, wind turbines utilize a horizontal axis system, known as HAWTs. Currently, significant research is being done on the use of vertical axis wind turbines, VAWTs. In particular, our team had three members who had done previous research (in the form of literature reviews) on VAWTs. With that in mind, after much deliberating and discussion about industry standards, we decided to move forward with VAWTs based on many issues including, but not limited to the following: simpler blade design, member background knowledge, and larger swept area. Orthographic views of the turbine can be seen in Appendix A.

Turbine Rotor Design and Construction

We utilized a blade profile similar to a NACA 7412 profile as shown in Figure 1. A lot of time was spent on the website airfoiltools.com where we looked at lift and drag charts for many different airfoils. We decided to manufacture two sets of blades and test them to see which one performed best. The two airfoils chosen were the NACA 7412 and a thinner NACA 6409. They were chosen because of their low drag coefficients with still relatively high coefficients of lift. Testing determined the NACA 7412 performed best, presumably because if had a higher lift coefficient than the NACA 6409.

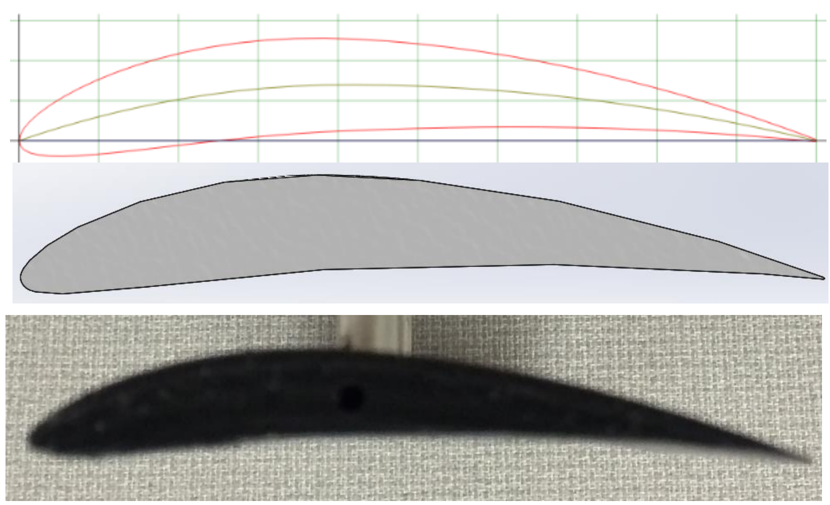


Figure 1. NACA 7412 Airfoil Used on Our Turbine
Top: Profile from airfoiltools.com
Middle: Profile of SolidWorks Model
Bottom: Profile of 3-D Printed Turbine Blade

The blades were modeled in SolidWorks and sent to Rapid PSI in Wichita, Kansas to be 3-D printed out of ABS plastic. The 3-D printer was able to print the inside volume of the blades in a honeycomb pattern resulting in a density of approximately 30 percent of the plastic's nominal density. The "sparse fill" printing was chosen to reduce the weight of the blade and decrease the moment of inertia of the rotor. The outer shell of the blade, which is an eighth of an inch thick, is solid plastic for strength and also creates a smooth aerodynamic surface for the airflow to attach to. The length of the blades was chosen to be 45 cm, the maximum possible while still fitting into the competition-allotted 45 cm cube for the rotor.

To connect the blades to the transmission shaft, we utilized a slip-lock attachment system. The system consisted of holes and slots in the blades attached to aluminum connecting rods with circular plugs as shown below in Figures 2 and 3.

Figure 2. Connecting Rod with Pinned Plug

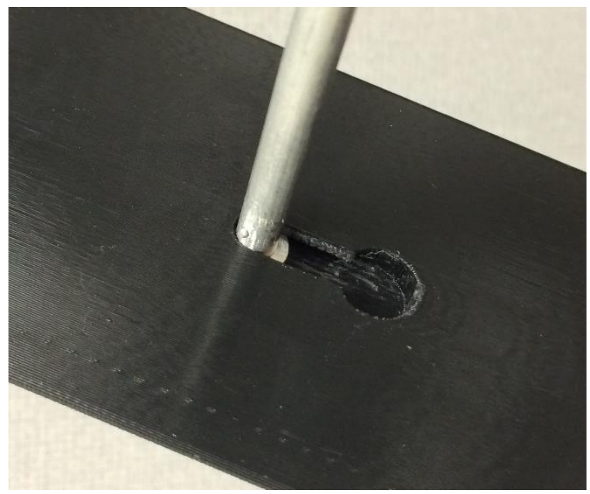


Figure 3. Slip-Lock Connection between Turbine Blade and Connecting Rod

The connection is similar to the chain lock on most hotel doors. The only issue we encountered with the slip-lock design was clearance in the parts. Specifically, some experimentation was needed before a proper clearance was decided on. The slots on the blades were applied directly to the 3-D model and were 3-D printed right into the blades. The aluminum rods with the plugs pinned to the end were manufactured in the Kansas State Mechanical Engineering Machine Shop. Aluminum was chosen for the connecting rods because of its light weight with the goal of minimizing the rotors moment of inertia. The length of the rods was chosen to maximize the swept area of the rotor while still fitting with in the competition-allotted 45 cm cube.

To attach the connecting rods to the transmission shaft we had the Kansas State Mechanical Engineering Machine Shop manufacture hub collars to our specs. The hub collars, as shown below, were designed with five female threaded holes with equal spacing on the collars' circumferential face. The connecting rods were then threaded to match the female threads in the hub collar. To prevent the collars' vertical movement along the shaft, a set screw was placed in each collar. To prevent the collars rotation around the shaft, we designed the center hole of the lower hub to be circular with a square cutaway that fits the shafts square edges as shown in Figures 4 and 5. Also shown in the Figures, the top hub has a square center hole that again fits the shafts square top. The hub collars were also designed to be made out of aluminum, again to reduce the turbines moment of inertia.

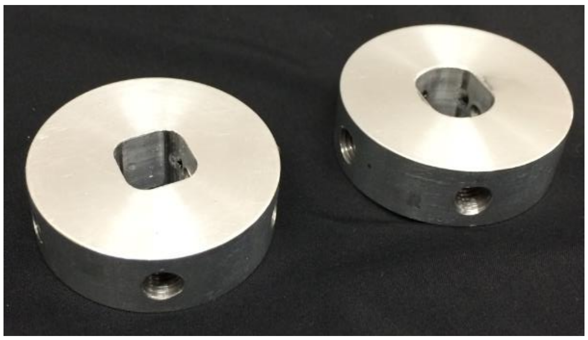


Figure 4. Isometric View of Hub Collars

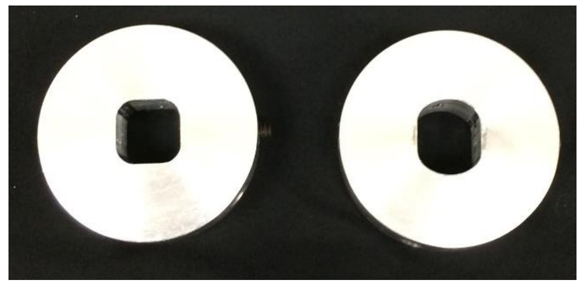


Figure 5. Top View of Hub Collars

The transmission shaft was also manufactured by the Kansas State Mechanical Engineering Machine Shop and was designed to serve many functions. Sections of the shaft which the hub collars are in contact with are squared to transmit the torque produced by the rotor. The notches in the shaft were designed to either hold the hub collars in place or to set the rotor's weight on the bearings. Figure 6 shows an engineering drawing of the shaft.

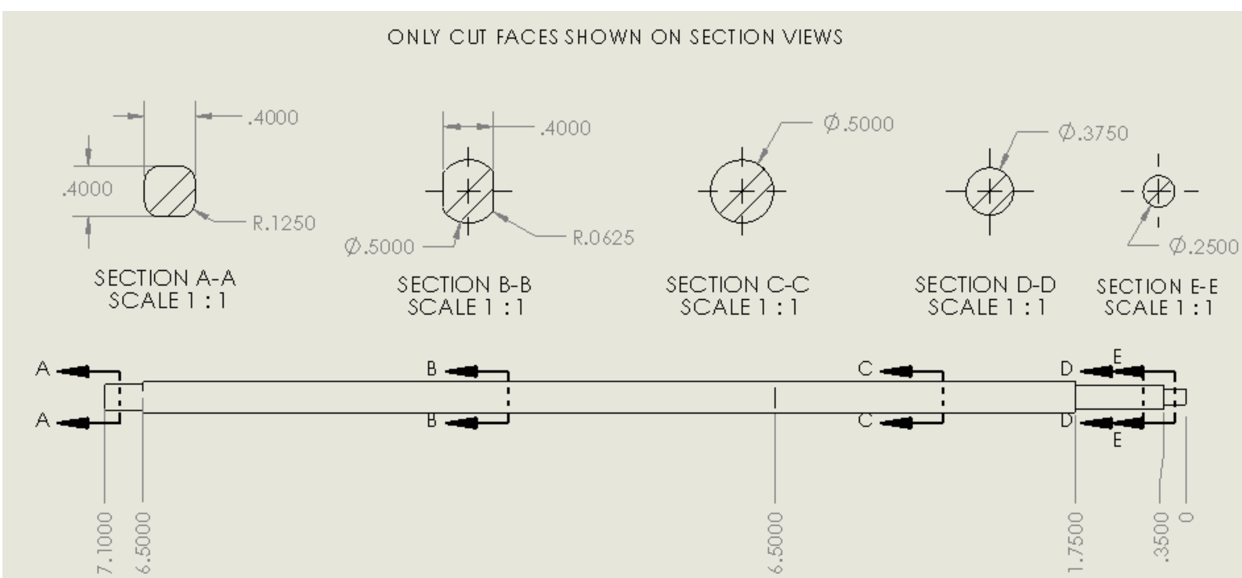


Figure 6. Engineering Drawing of Transmission Shaft

Once again, the transmission shaft was manufactured out of aluminum to minimize its moment of inertia. The length of the shaft was chosen so that the rotor blades sit high enough above structure that the structure would not inhibit airflow.

Savonius Interior

During our testing, one issue we faced consistently was a very high cut-in speed. This is a common issue in VAWTs and one we had initially hoped to avoid. Unfortunately, during our testing, it became clear we were not going to be the exception in this case. However, a design that one member of our team had seen in the past detailed an H-Rotor Hybrid system utilizing a Savonius-like interior which functioned to assist in start-up. Thus, we decided to manufacture a Savonius cup insert for the center of our turbine which can be seen below in Figure 7. Because Savonius designs utilize drag instead of lift to operate, they have a much lower cut-in speed than Darrieus or H-Rotor VAWTs, though they generally have trouble operating at higher wind speeds. Our team feels this Savonius interior fills a niche role that would otherwise require higher wind speed at start-up. This hybrid takes advantage of the Savonius effectiveness at low wind speeds as well as the H-Rotors effectiveness as higher wind speeds.

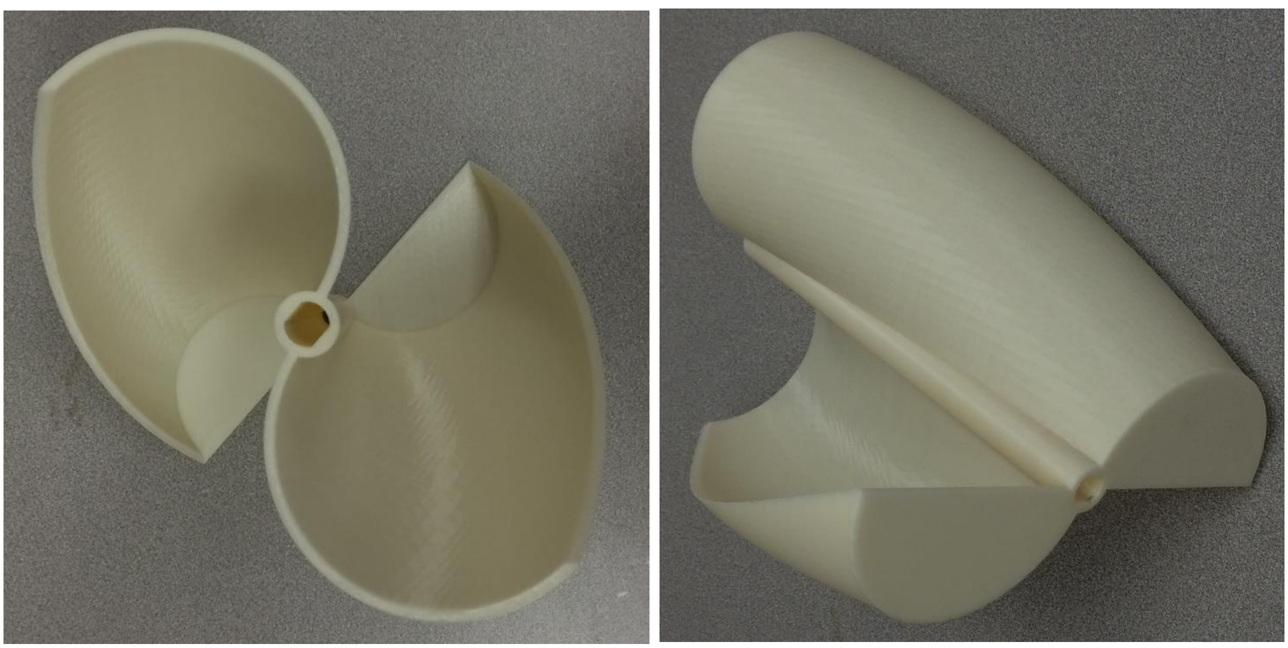


Figure 7. 3-D Printed Savonius Insert

Similar to the blades, the Savonius insert was also modeled in SolidWorks and then 3-D printed out of ABS plastic. This time the printing was done by the 3-D printer owned by the Kansas State Mechanical Engineering Department. The insert was designed with square holes similar to the hub collars to fix its rotational movement thereby transmitting the torque to the shaft. To fix the vertical movement, the insert was designed to fit snuggly between the hub collars.

Structure Design

The design of our structure was an iterative process. Many days were spent with the team huddled around a computer with SolidWorks adjusting dimensions as needed to make everything fit appropriately. The final design can be seen below. The discontinuity halfway up the structure was caused by a 3-D printer malfunction, fortunately, the discontinuity did not significantly affect the structural integrity or the assembly of the turbine. The final iteration of the structure can be seen below in Figure 8.

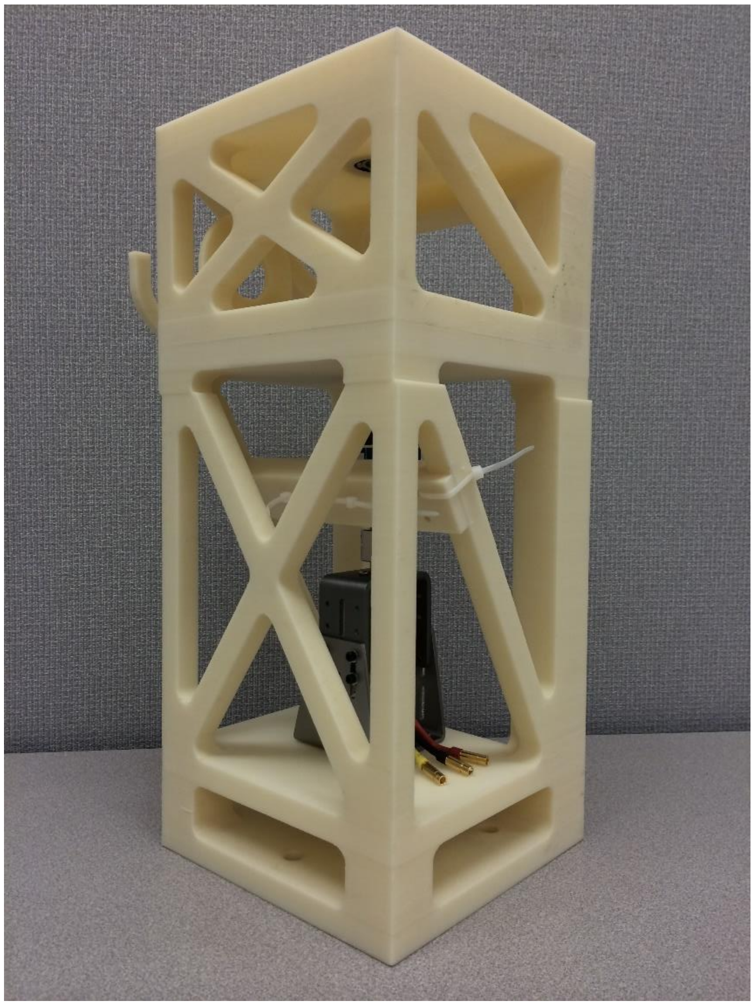


Figure 8. Final Iteration of Turbine Structure

The first feature of the structure we designed involved supporting the moment created by the wind on the rotor. To do this we used two bearings set three inches apart and press fit into the structure. The top bearing serves the secondary purpose of supporting the rotor's weight. The area between the bottom bearing and the lowest shelf houses the generator and the gearboxes. The lower gap was needed because the generator leads need somewhere to go in certain configurations, in this case through the lower "floor" and into the bottom area of the structure.

In our initial design (not pictured in this report), our structure wobbled significantly as the turbine spun at high speeds. To make sure that the structure was stable, we consulted a friend in the Civil Engineering program at Kansas State who is specializing in structural design. Specifically, with his guidance, we were able to design a truss system which forced much of the load to the back of the structure and away from the areas more prone to wobbling. Also, we were able to still keep much of the area open such that we are able to get our hands to key components inside the turbine without worrying about timely dis-/reassembly. Implementing this, along with the two bearing points of contact, minimized the wobble in the turbine and effectively removed the problem.

Like the Savonius insert, the structure was also 3-D printed out of ABS plastic using the 3-D printer owned by the Kansas State Mechanical Engineering Department. Due to size constraints of the 3-D printer, we were forced to print the structure in two pieces and fix them together using pegs and industrial glue. The two parts of the structure can be seen below in Figure 9.

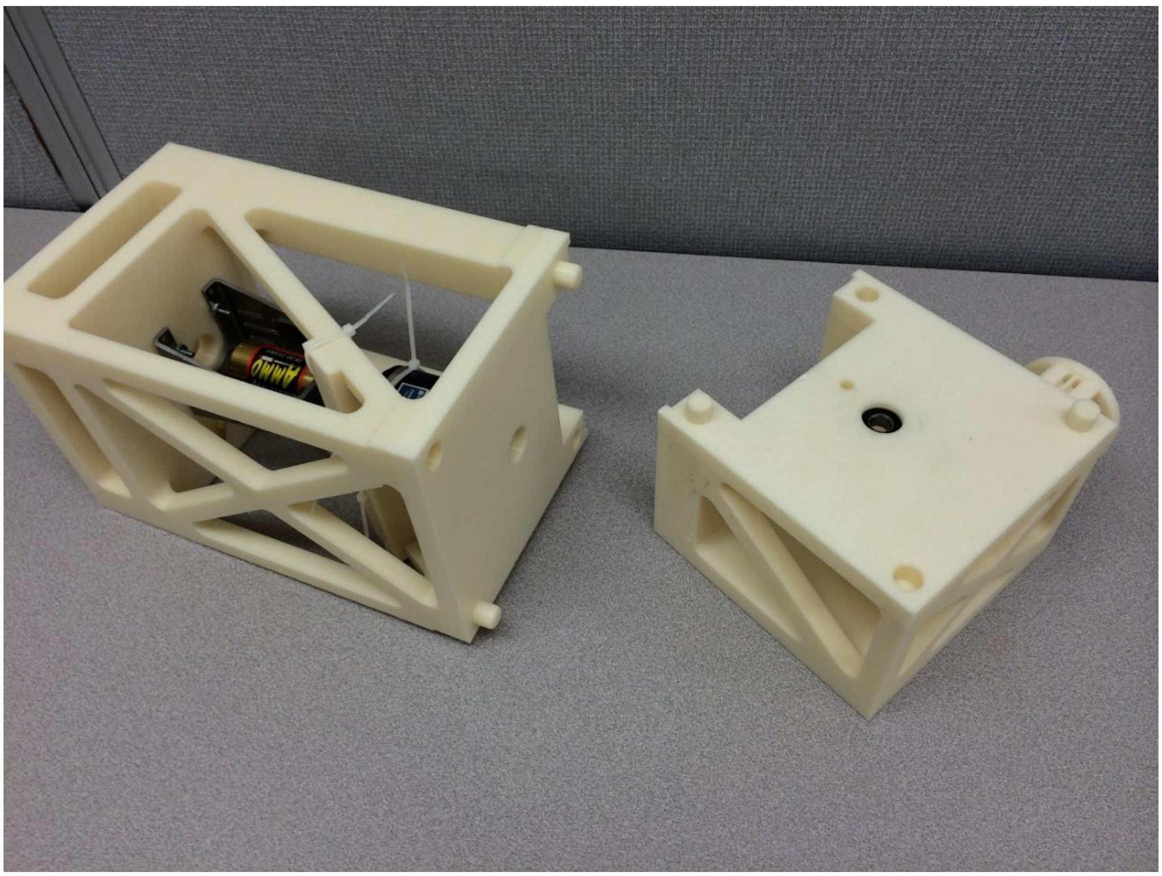


Figure 9. Both Pieces of the Final Structure

Sparse, honeycomb, filling was used to print the inside of the structure similar to what was done with the turbine blades. Unlike the turbine blades, the motivation for the sparse fill was not to cut weight, but to cut manufacture time and cost. If the large structure were printed to be solid plastic, it would take much longer to print and would use a lot more plastic effectively driving up the time and material cost.

Material/Manufacturing

Our team was very fortunate to have significant access to a variety of 3-D printing resources which allowed for quick prototyping of many of our individual components. In particular, we were able to manufacture precision turbine blades quickly, consistently, and in bulk. We utilized a variety of printing resources including one of the 3-D printers owned by the K-State Mechanical Engineering Department as well as two companies: DEPCO in Pittsburg, Pennsylvania and Rapid PDI as mentioned before. This technology also allowed us to quickly manufacture our base structure and effectively track changes. When a change needed to be made, it could be made in our 3-D software (primarily SolidWorks) and we could send that file directly to the printer. This technology is, by no means, perfect and we hit speed bumps along the way, but it also allowed us to do many things we would have otherwise been unable to do.

All the aluminum parts were made of 6061 Aluminum. This material gave us the best weight/strength ratio for our purposes and is a relatively easy material to work with.

Gearbox Selection

To get the RPMs we need to the generator, a gearbox was a must. ElectriFly, the same company that produced the generator, also offers a gearbox that was made specifically for their generators. This gearbox is adjustable to four different settings, the largest of which is 4.55:1. Figure 10 below shows the ElectriFly gearbox attached to the ElectriFly generator.

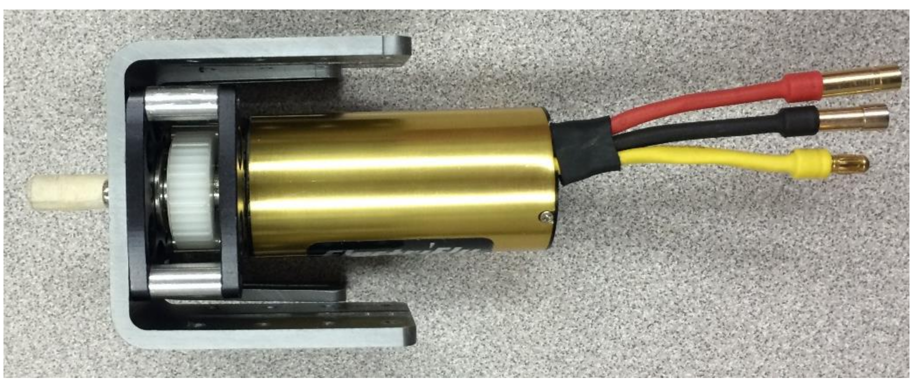


Figure 10. ElectriFly Gearbox Attached to ElectriFly Generator

After testing, we determined that a larger ratio was needed. We decided to purchase other gearboxes that could be coupled to the ElectriFly gearbox to create larger gear ratios and could still be adjustable. We purchased gearboxes with the gear ratios of 13:1 and 5.29:1 from Standard Drive Products shown in Figure 11. The ratios with these gearboxes coupled with the ElectriFly gearbox gave us a wide range of ratio options that can be seen Table1. Another factor in picking the 13:1 and the 5.29:1 ratios was the time crunch to get the turbine done in time for the competition. Only a few different gearbox options were in stock, limiting our options. At the time of this report, testing had shown the 13:1 option worked the best for our application.

ElectriFly Gearbox Alone	SDI Gearboxes Alone	13:1 and ElectriFly Gearboxes Together	5.29 : 1 and ElectriFly Gearboxes Together
2.86 : 1	13 : 1	37.14 : 1	15.11 : 1
3.57 : 1	5.29 : 1	46.43 : 1	18.89 : 1
3.64 : 1		47.27 : 1	19.24 : 1
4.55 : 1		50.09 : 1	24.05 : 1

Table 1. Possible Gear Ratio Combinations

A shaft coupler is used to connect the transmission shaft to the low side of the gearbox and another shaft coupler connects the high side of the gearbox to the generator as shown in Figure 11.

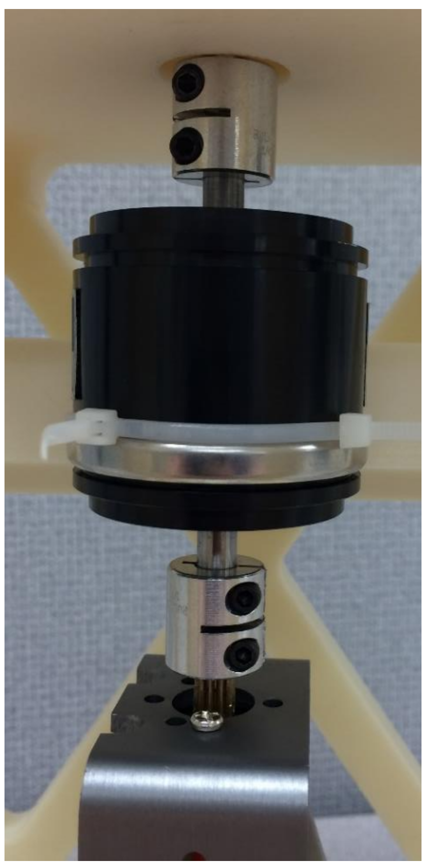


Figure 11. Gearbox Purchased From Standard Drive Products

To prevent the gearbox from rotating about its radial axis, a brace was 3-D printed by the Kansas State University 3-D printer. The part can be seen below in Figure 12.

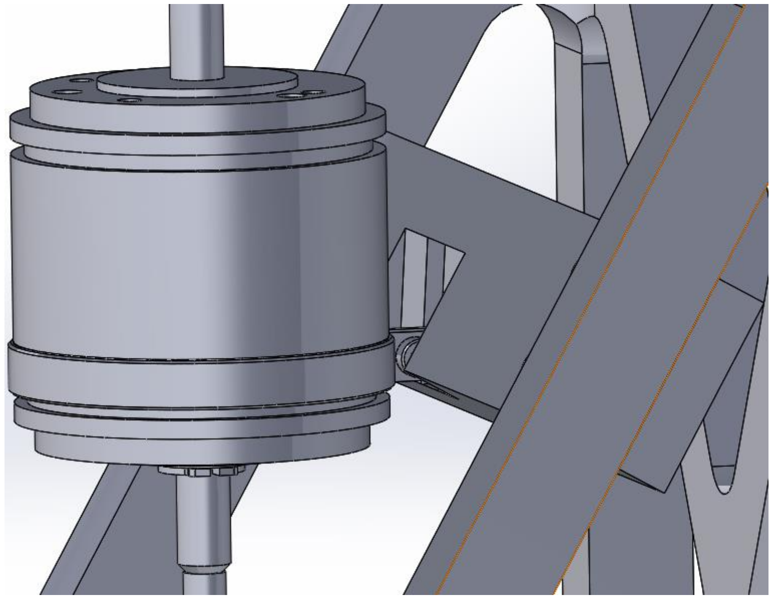


Figure 12. SolidWorks Model of Brace Used to Prevent Gearbox Rotation

Testing

Testing of our designs was completed using a variety of different methods. A concern was that the turbine blades would fail under the bearing stress placed on them by the centrifugal force and the connecting rods. With the use of SoildWorks, an FEA analysis was conducted that showed the blades would have no problem bearing the stress of rotating at high RPMs. Once the turbine blades and connecting rods were manufactured, we conducted a physical test to verify the FEA results. The physical test was conducted by placing the rod in the blade and having two people pull in opposite directions. The use of a spring force gage showed the two people were able to pull with a force of 80 pounds and the joint did not fail. Knowing the weight of each turbine blade, hand calculations were completed and determined that at 300 rpm the force on each rod-blade joint is only 8 pounds; therefore we can say with confidence the turbine blades will not fail at the connecting rod joint under reasonable conditions.

Initial flow tests of the turbine were completed using a large 48 inch shop fan. This method had a few problems, including turbulent, inconsistent flow and an inability to determine air speed. Fortunately, the Engineering & Wind Erosion Research Unit located in Manhattan, Kansas generously let us test our turbine in their wind tunnel that they use for soil erosion studies. We were unable to acquire an accurate power curve from these tests because our turbine blocked the airflow from the wind tunnels pitot tube which measures air speed. Also the wind tunnel can produce a maximum wind speed of approximately 11 m/s and we were unable to test our turbine at the higher wind speeds.

Mechanical Team Overview

The mechanical team consisted of seven seniors in mechanical engineering and one sophomore in biological systems engineering, each with different backgrounds and skills that were helpful in the design of this turbine. All design decisions were made as a team and each member was involved every step of the way. That being said, each individual had personal strengths motivating them to work on more focused sections of the design. Below is a short overview of each team member's main contribution.

Aaron Akin –	Aaron came to the team during the second semester and helped with the mechanical side of the design and often helped communicate between the mechanical and electrical teams.
Stuart Disberger –	Stuart focused most of his energy on the business plan part of this competition. His interest in business has led him to complete the requirements and receive a business minor from Kansas State Engineering.
Bret Gross –	Bret spent much of his time working on a mechanical brake before it was known that the electrical break would be enough to stop the turbine. Bret did great work designing the short-shoe-external drum break he learned about in his Machine Design II course at Kansas State University. Unfortunately his design did not make it on the final turbine.
Joe Kuhn –	Joe handled much of the task delegation and was our go-to-guy when anything needed to be modeled in SolidWorks. Joe has taught a modeling/drafting course at Kansas State University for the past three years.
Jordan Robl –	Jordan's efforts were focused mostly on the gearboxes. Using the knowledge gained from a Machine Design II course at Kansas State University, he was able to communicate with gearbox distributors about specific gearbox needs and options to acquire the best possible product for our application.
Aaron Thomsen –	Aaron took the lead when it came to testing our designs. He scheduled times and tested each iteration of the turbine. He was also the main contact and was in constant communication with all of the different manufacturers and suppliers that were utilized by our team.
Lane Yoder –	Lane was the team's aerodynamics expert. He designed the turbine blades using the knowledge he picked up from the Aerodynamics course he took at Kansas State University.
Cody Yost –	Cody has a background in manufacturing. He helped Joe 3-D model and made sure that the drawings and SolidWorks files had all the dimensions and tolerances that manufacturers needed. Cody has interned with manufacturing and construction companies the past three summers.

Unique Features

This turbine has many unique features including its orientation, the hybrid design of the rotor, and the manufacturing techniques used.

Generally, when a person thinks of a wind turbine, the image in their head is of a horizontal axis turbine. What sets this turbine apart is its vertical orientation and rotor design. Feedback received from the Manhattan, Kansas community indicated that a vertical axis turbine is more aesthetically appealing and many called it “a work of art”. Adding to the aesthetic appeal and functionality of our turbine is the Savonius cup insert. The Savonius insert increases the turbines effectiveness at low wind speeds as discussed previously. Aesthetically, the changing appearance of the Savonius insert contrasts nicely with the uniform pattern of the turbine blades. Aesthetics may be an important factor for anyone considering purchasing a wind turbine whether they are a home owner putting a turbine on their roof or city officials deciding whether or not to use turbines to power street lights.

Important to mention is the fact that vertical axis wind turbines are omnidirectional, meaning they work regardless of what direction the wind is blowing about its circumference. Horizontal axis turbines can struggle adjusting to changes in wind direction while vertical axis turbines thrive in these conditions. They can also be better at handling turbulent winds if they are designed properly.

Lastly, the manufacturing techniques used to create this turbine are unique. 3-D printing allows our team to be extremely flexible and adapt to each customer’s specific demands. The 3-D printing also allows these demands to be met quickly because we just have to spend a few minutes making changes in SolidWorks where another team might have to manufacture new molds or develop new manufacturing techniques.

Electrical Design

The electrical design first focused on creating a list of design criteria and then how to maximize points earned. Below is a list of design criteria that were considered.

Design Criteria

- Power Curve Verification
- Cut in Wind Speed Task
- Control at Maximum Power
- Durability and Safety

Following that, a block diagram of the circuit was constructed. The circuit proposed was built and tested, and then revised. The final iteration's block diagram can be found in Figure 13. The section labeled Electrical Components gives a detailed description of each component.

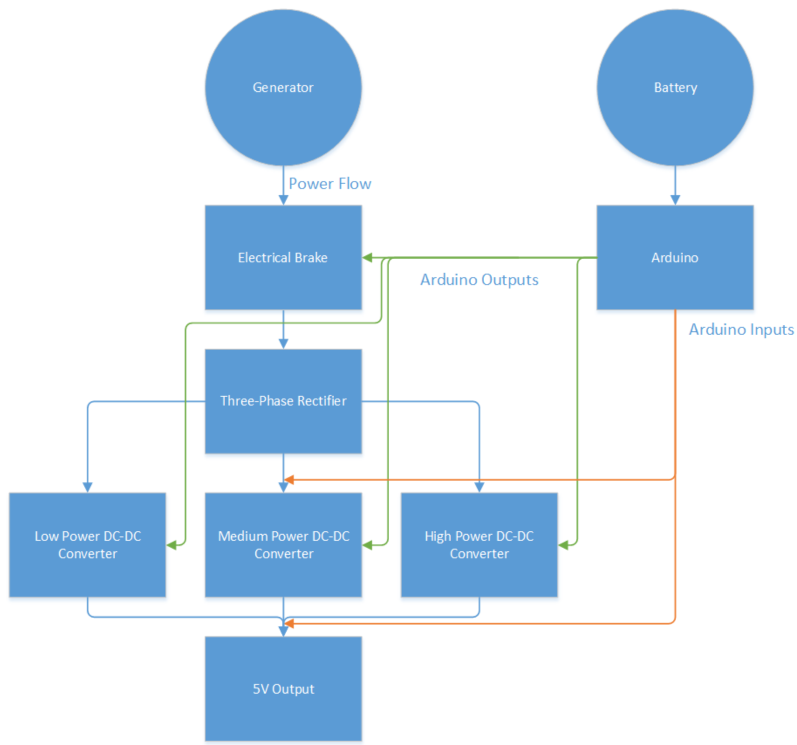


Figure 13. Block Diagram of the Electrical Circuit

The electrical components for the turbine are very similar to the components that would appear on a turbine that is marketed by the business plan team. The first difference is that the output would be 12V and used to charge a battery and the other is that the brake could be triggered based on wind speed.

In order to maximize points earned for these criteria the team made sure our solutions were cost effective, energy efficient and had a large factor of safety.

Microcontroller

The microcontroller monitors and automates many of the processes in the circuitry of the design. The microcontroller chosen was an Arduino Uno and will be operated on its board for simplicity. In addition, it will help with quick debugging during design and at the competition. The Arduino will specifically monitor the output of the rectified DC and use this to toggle the various boost modules. It will also monitor for loss of load via the speed detection circuit and use this to initiate the electrical brake. The Arduino will also monitor the speed detection circuit to determine if brake pulsing needs to occur to keep the turbine rotor at a safe speed. If the judges choose to initialize the brake process through a button press, the Arduino will also monitor the button and begin the braking process accordingly.

Electrical Brake

After many braking ideas, the most efficient and simple brake is the electrical back EMF brake. This is performed by tying the leads of the generator together and allowing it to slow itself down. However, the lack of a common ground in the circuit made this difficult and required the ground of the phases to be tied to the Arduino ground through a large resistor to prevent any dangerous currents going through the Arduino. This brake is sufficient for a 10% rated speed stop within ten seconds.

Rectifier

The first portion of the circuitry after the generator is the three phase rectifier. We chose to use an IXYS FUS-45-0045B three phase bridge rectifier. This rectifier provides us with a steady DC output with an appropriately sized capacitor and has a voltage drop of approximately 0.55V. This is ideal in our low voltage, low power scenario. It can handle up to 45V and 45A, which is a higher load than we will reasonably encounter. This will be mounted via thermal paste to an aluminum panel on the wind turbine housing for maximum heat dissipation. The Arduino will be monitoring the output of the rectifier voltage level to assess when to activate individual DC-DC converter modules for optimal efficiency. This will be covered further in the DC-DC converters section.

Speed Detector

The speed detection circuit was built to estimate the approximate speed of the rotor and brake the turbine if it was found to be operating at an unsafe speed. This will allow the Arduino to make safety judgments and brake the turbine when needed without additional human support. Along the same lines, the speed detector circuit will also be used to detect a no load situation at which the turbine is found to be operating at a speed above normal. Once this is detected, the Arduino will signal for a full shutdown to 10% of the rated speed of the rotor or less.

DC-DC Converters

The second section of the circuitry will involve use of DC-DC converter evaluation boards. The evaluation boards were chosen due to their simplicity and preassembly with required passive elements. Another benefit of using the purchased boards was for their high efficiency and small footprint. The high efficiency of the boards allows for a lower cut-in voltage. The design will incorporate three DC-DC converters and the Arduino will toggle each chip on in its voltage range. Following the boost, the circuit will pass the power onto the competition power supply for judging. Table 2 gives more information on the specifications of the converters used.

DC-DC Converter Specifications			
	Lower Power	Medium Power	High Power
Model Number	TPS61202EVM-179	LTC3115-1	LM25116EVAL
Voltage Rating	0.3-5.5V	2.7 – 7V	7 - 28V
Current Rating	1.5A	2A	7A

Table 2

Modeling and Testing

The modeling and testing procedure used for the circuitry was threefold. All of the circuits were first simulated or thoroughly researched. After it was determined that they were adequate, they were fabricated or purchased. The next step was to test them on the test bench. For instance, all of the DC-DC converters were powered by a DC power supply and tested over a wide range of voltages and loads. Finally, the circuitry was connected to the generator and performance was tested. The different testing stages were used to determine if the components met the design requirements and would be used in the final design.

Electrical Team Overview

The electrical team consisted of three students in electrical engineering all with power backgrounds. All design decisions were thoroughly researched and their advantages and disadvantages were considered. Below is a short overview of each team member's main contribution.

Will Duren – Will contributed most to the design of the DC-DC converter. After designing a DC-DC converter in class, he determined it would be better to purchase the DC-DC converters. He created a list of specifications and purchased DC-DC converters based off of those specifications.

Martin Mixon – Martin utilized the skills he learned in Electronics Lab and Wind and Solar Design to characterize the generator and help with circuit assembly. Martin also helped design a frequency counter, which tracks the speed of the generator.

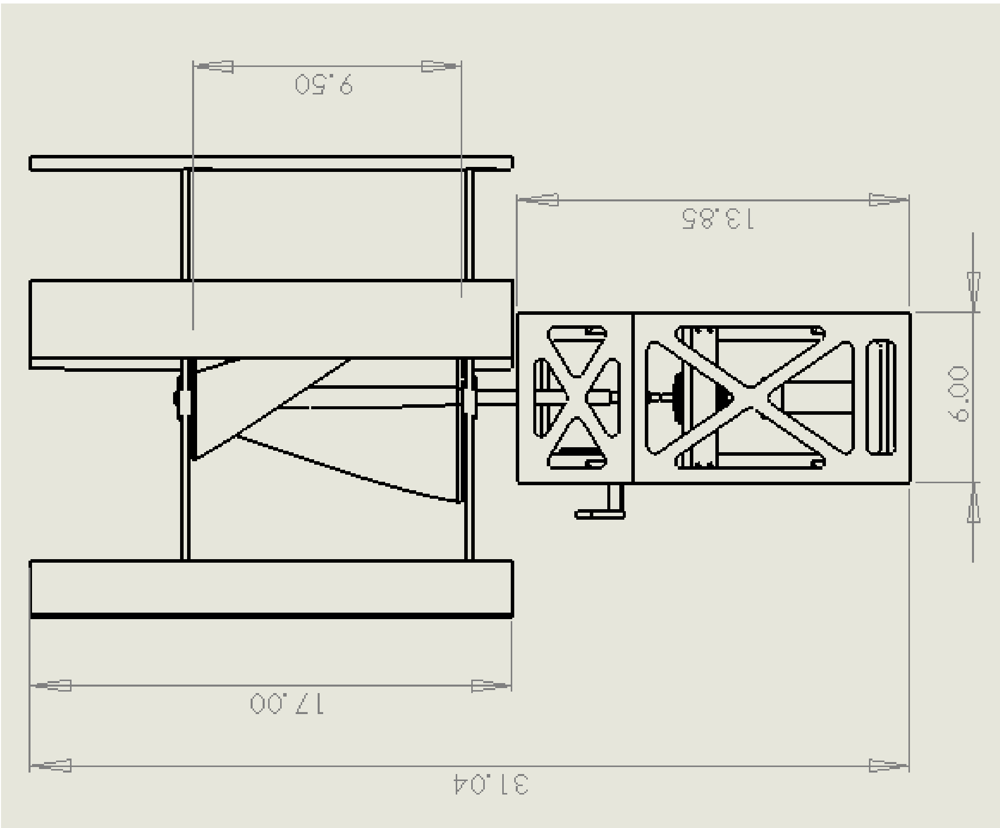
Shae Pelkowski – Shae has a strong programming background and programmed the Arduino to control the turbine's electrical components, and safety shutdown procedures. He also designed the electrical brake and found a three-phase passive rectifier to meet specifications.

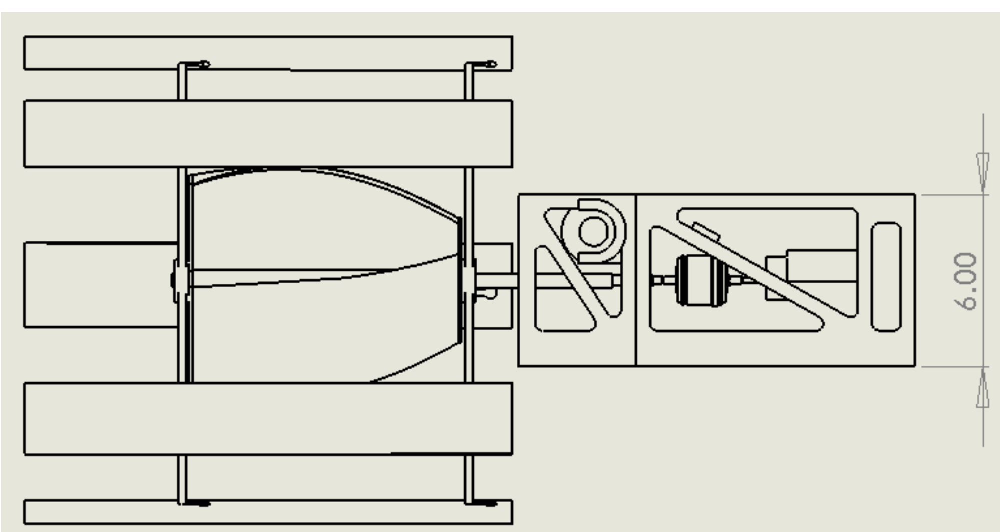
Conclusion

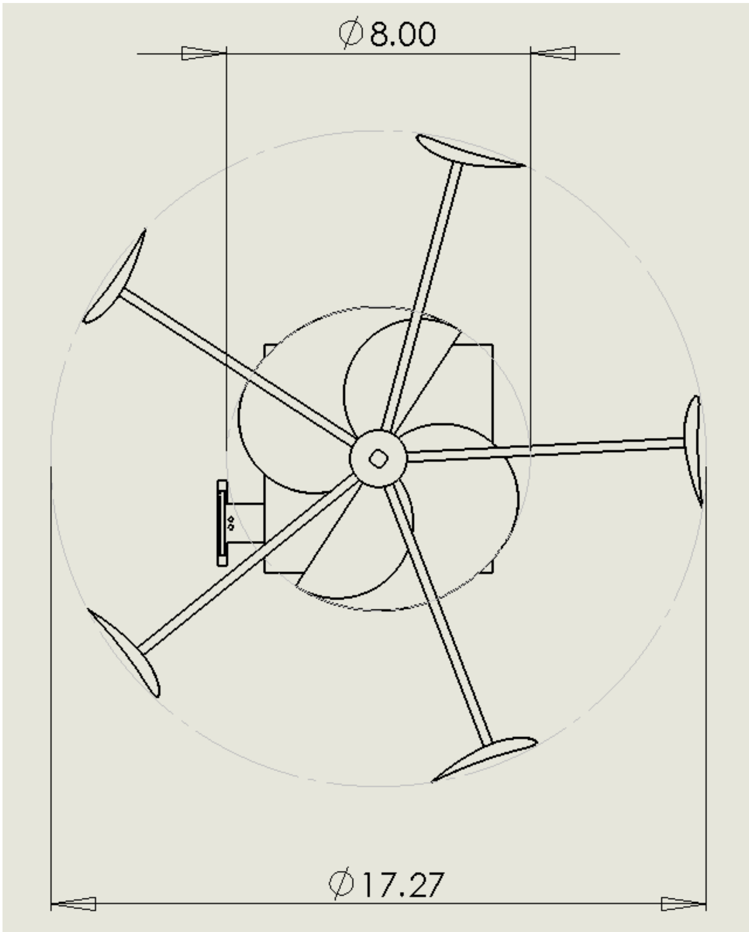
The result of our final design, a picture of our final turbine design, can be found on the title page. The team was able to create a lightweight, portable, and aesthetically pleasing wind turbine. While performance had to be sacrificed, it was crucial for our design that we stick to our design in order to make it marketable. We believe that there are still many modifications that can be made to the turbine that can make it perform better and hope to add those to the turbine in the 2015-2016 competition.

Appendix A – Overall Dimensions of Turbine

*Note: Units are in inches







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