The Revolve:

Technical Design Report

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1. Introduction

The Revolve, designed by Zephyrus, is a portable wind turbine capable of powering small electronic devices off the grid. The purpose of this document is to outline the process by which Zephyrus developed the Revolve from concept to final prototype to ensure a safe and durable turbine. It is our hope that the design laid out in this report not only performs well at competition, but paves the way for the advancement of portable wind energy globally.

2. Design Objective

Campers, backpackers, and other outdoorsmen were viewed by the business team as having an unfulfilled need for portable energy, making them our target market. Research conducted by the business team identified the most important consumer needs for this market. These are shown below in Figure 1, along with the engineering metrics used by the design team to fulfill these needs. For further business details, refer to the Zephyrus Preliminary Business Assessment.

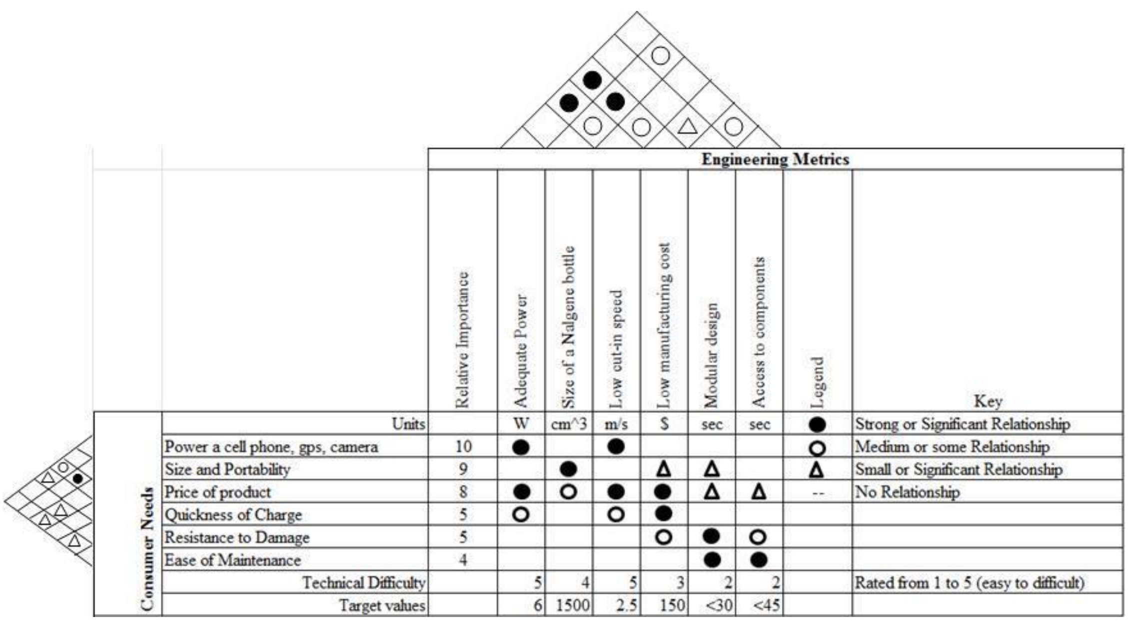


Figure 1: House of Quality (QFD).

Consideration of the House of Quality led to Table 1. Each business plan input has a corresponding design output which is the means by which the design team accomplished each objective.

Table 1: Outputs of the design team based on inputs from the business plan.

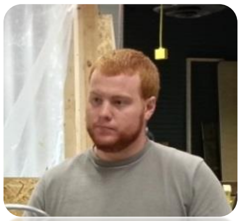
Business Plan Inputs	Design Outputs
Provide sufficient power to charge small electronic devices.	Designed alternator capable of supplying sufficient power.
Weight is less than 4 pounds.	Used lightweight aluminum 6061-T6 for supporting material and nylon ripstop fabric for blades.
Collapsed size is similar to a Nalgene water bottle.	Utilized vertical axis Savonius design with detachable blade arms. Fabric blades slide off arms. Tripod stand disassembles into small components.
Appearance is aesthetically pleasing.	Used dual blade Savonius design, anodized aluminum components to various colors, and used various blade fabric colors.

When compared to other small scale wind turbines the Revolve has several distinct advantages. Because of the focus on lightweight and collapsible components, the Revolve will be the best option for those wishing to charge their portable electronic devices as they trek through the great outdoors. Its modular design will allow for easy, inexpensive repair along with the ability to fulfill different customer desires. The Revolve is the first practical wind turbine designed specifically for consumers to use while camping, hiking, and backpacking, giving it a huge advantage.

3. Design Team

Zephyrus is a multi-disciplinary team of engineering students from the Colorado School of Mines in beautiful Golden, CO. The design team's knowledge in engineering theory combined with their diverse set of practical experiences helped to come up with the Revolve. These skills have been brought together with unprecedented team chemistry to produce an exceptional, cohesive design team.

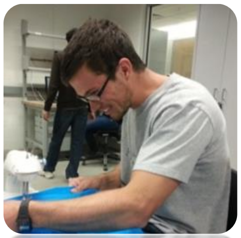
Cabe Bonner is the team's electrical engineer and led development of the power production circuitry. Cabe's experiences working for Cliffs Natural Resources with power systems analysis has served him well in accomplishing this.



Cabe Bonner

Jyoti Gandhi and Aaron Troyer, both mechanical engineering majors, led the design of the housing system and turbine testing. Jyoti has worked for GE Aviation in the past developing engine turbines while Aaron has professional experience designing and inspecting medical implants and instruments. The experience of both of these individuals has served them well in developing a lightweight and functional design.

Jyoti Gandhi



Aaron Troyer

Kate Rooney is in charge of the support structure of the turbine. Kate is another mechanical engineering major and has worked overseas with Bosch, a German manufacturer of car brakes. Her experience has given her a great understanding of the design process and was a valuable asset in making the support structure portable.

Kate Rooney

Kevin Tan focused our CAD efforts due to his many years of experience in SolidWorks, which have developed his modeling and computer simulations skills. He was responsible for modeling parts in SolidWorks, producing engineering drawings, and running computer analyses. He was crucial in evaluating various aesthetic features of the turbine, producing scale representations of proposed designs, and analyzing design options.

Kevin Tan

Leading the entire design project was Jeremy Webb. Jeremy's experience working for NREL and his understanding of wind power gave him the tools to become an expert in all aspects of the project. His skill, dedication, and superior project management abilities made him well-suited to oversee all aspects of the design and ensuring the project is on track.

Jeremy Webb

Quinn Weber became the team's expert machinist and was in charge of assembling the turbine. He has studied small scale power generation and its application to residential life, which gave him great insight into the overall design features needed. As an avid outdoorsman who represents our target market well, Quinn played a key role in ensuring our design satisfied customer needs.

Quinn Weber

4. Design Overview

The Revolve is divided into four subsystems shown in Figure 3 below. Fully assembled, it stands 4 feet tall with a rotor diameter of 17 inches. Collapsed, the Revolve fits in a small bag 12 inches tall and 5 inches wide, similar to a Nalgene water bottle. It weighs approximately 3.5 pounds and disassembles into 14 pieces, shown in Figure 2. With an experienced user, assembly takes less than 120 seconds.

Figure 2: Disassembled Revolve wind turbine.

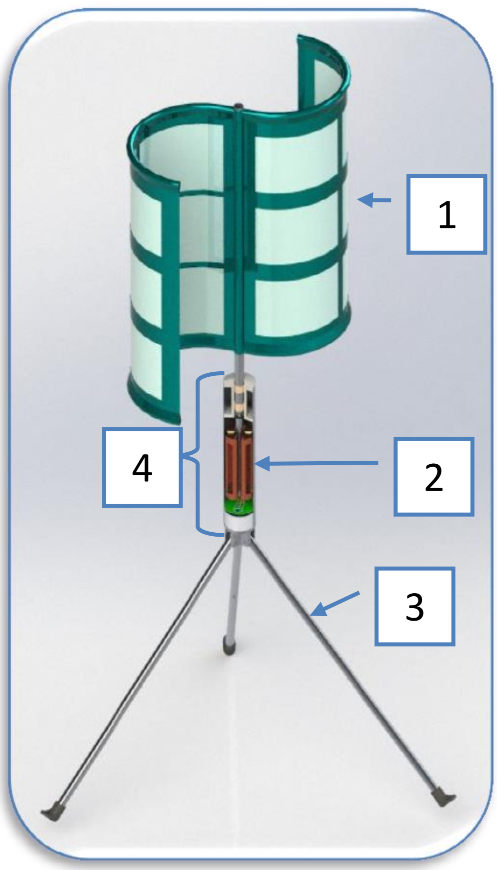


Figure 3: Breakdown of different subsystems of the Revolve wind turbine.

1. **Blades**
   - Semi- circular shape to capture maximum wind
   - 3 flaps on each blade to reduce backstroke drag
   - Lightweight, hollow aluminum arms
   - Durable 30D nylon ripstop fabric
   - Two blade design for ease of manufacturing
   - Smooth rotation due to low-friction bushings
2. **Generator**
   - Three phase brushless with permanent magnet
   - Six copper coils with 400 windings each
   - Fully enclosed in housing system for all weather use
   - Optimized for use in low wind speeds
3. **Support Structure**
   - Lightweight, hollow aluminum legs
   - Adjustable height and angle for use in any terrain
   - Ability to stake in ground for improved stability
4. **Housing System**
   - Protects weather sensitive components including bushings, generator, and circuit board
   - Lightweight aluminum shaft
   - Injection molded internal mounts
   - Location of USB power plug

5. Modeling and Testing

To reach the final design of the Revolve, several stages of modeling and testing were performed. With the results of each modeling effort, necessary refinements and adjustments were made in order to produce a high performing wind turbine. Below is a summary of the path taken to develop each component used in the final Revolve design. These components include the blades, support structure, housing system, bushings, materials, generator, and electronics.

5.1. Blades

Zephyrus initially evaluated ten different blade design ideas in a weighted decision matrix to determine the one best suited to satisfy consumer needs. The winning design was a tri-arm vertical axis Savonius turbine with slats shown in Figure 4. The key feature of the Slatted Savonius is its dynamic blade movement; the slats close on the front side to collect wind energy and open on the backside to allow wind to pass through. A prototype was constructed using $\frac{1}{8}$ " thick acrylic sheets for the slatted blades, shown in Figure 5. This prototype consisted of a steel ball bearing to support the central shaft and used the generator and 4.5:1 gearbox provided by the Collegiate Wind Competition.

Figure 4: CAD model of Slatted Savonius.

Figure 5: Prototype model of Slatted Savonius.

In order to prove the functionality of this design, the prototype was tested in a wind tunnel under incrementally increasing wind speeds ranging from 0-8 m/s in 1 m/s increments. After 8 m/s was reached, wind speed was decremented by 1 m/s back to 0 m/s. Blade revolutions were counted manually for two intervals of twenty seconds at each wind speed and averaged to get revolutions per minute. This rpm was plotted against wind speed and is shown in Figure 6.

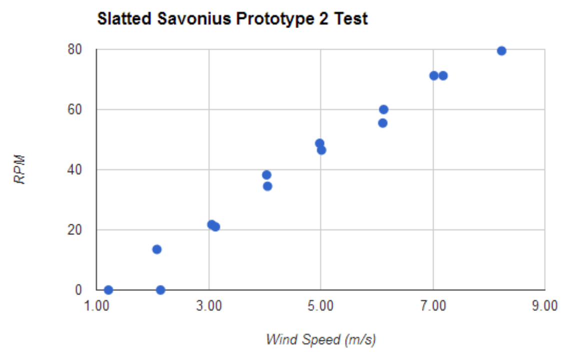


Figure 6: RPM versus wind speed for preliminary wind tunnel test of Slatted Savonius.

The results of this test showed the Slatted Savonius rotated at 80 rpm at a wind speed of 8 m/s. This was encouraging, but numerous faults were also discovered. It was found that using a single ball bearing did not sufficiently support the central shaft and the heavy acrylic slats introduced a rotational imbalance. This was due to the sudden change in angular momentum as the slats rotated. In addition, the gearbox used had a ratio too small to produce sufficient voltage. The maximum voltage seen was 50 mV AC. It was concluded that multiple bearings, lighter blades, and a higher gearbox ratio were necessary to improve performance.

Incorporating these results, the fabric Window Savonius was developed and is shown in Figure 7. This design maintains the same key design feature of the Slatted Savonius, opening and closing blade components, but reduces weight and therefore imbalance. The refinements to the bearings and the gearbox are described in sections 5.2 and 5.6 respectively.

Figure 7: Model of fabric Window Savonius.

It was initially thought that three blades would provide better overall balance, but after re-evaluation it was determined that two would be more appropriate and the reduction in weight and manufacturing complexity was an added advantage. These considerations were incorporated into our final design, the Revolve.

Several different designs of the window fabric were tested to optimize the sizes and attachment methods of both the flaps and the pattern of the holes behind them. Each design was tested using the wind provided by a Holmes high performance tower fan. Flaps with various dimensions were sewn onto the Savonius fabric frame in different configurations, shown in Figure 7. The flap design selected was the one which sealed the window opening the best. The holes on the back side of the Savonius were also tested to determine which size and configuration kept the front flaps from penetrating through, but also allowed the most air to blow through on the back side. The final design is shown in Figure 13. It consists of a flap with two unattached, adjacent edges that are hemmed. The other two edges are sewn onto the main fabric structure. The hole on the back side has a single vertical fabric strip to help maintain the structural integrity of the fabric and prevent the middle of the flap from blowing through.

5.2. Bushing Selection

The Slatted Savonius wind tunnel test revealed that one steel ball bearing could not support the central shaft vertically as mentioned earlier. This, in addition to cost considerations led to the selection of two low-friction bushings in the Revolve. Nylon PTFE bushings were selected and calculations were performed to ensure they would not fail under expected loading, shown in Appendix B: Bushing Calculations.

5.3. Support Structure

A tripod stand was chosen because it is adjustable, collapsible, lightweight, and durable. The support attaches to the bottom of the generator housing with two button pins, allowing the option to attach a variety of other support structures. Each leg is attached with pin joints, allowing for adjustability in uneven terrain. The three legs are made out of hollow aluminum tubes with elastic through the middle, similar to tent poles. The bottom of each leg is fitted with an end cap designed with stake holes for added stability.

Calculations were completed to find the most effective height and shaft diameter to support the Revolve under 66 ft/s (20 m/s) winds. Based on this analysis, legs with an outer diameter of 0.50 inches and an inner diameter of 0.43 inches were chosen. With these dimensions, the legs were able to maintain a low weight and keep the turbine 20 inches off the ground. Overall the whole tripod support weighs only 0.4 pounds and collapses to half of its deployed size.

5.4. Housing System

The objectives of the housing system were to securely hold the generator, circuit board, and bushings. A hollow aluminum shaft with outer diameter 1.875 in, wall thickness 0.035 in, and length of 10 in was selected to allow enough space for each component while minimizing cost. In order to securely fasten the components inside, a mounting system was machined out of solid aluminum. This system has an end cap to seal off the inside and individual casings for the generator and bushings that are aligned with two long screws. In order to reduce the weight and machining time further, the casings were recreated with 3D printing out of ABS plastic. For mass production, these casing components will be injection molded. This system has proven effective at supporting all necessary components.

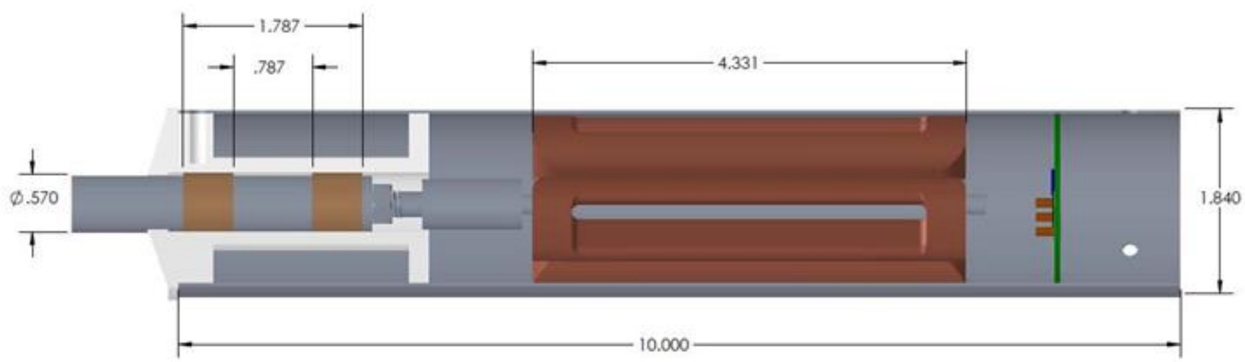


Figure 8: Housing system specifications.

5.5. Materials

The fabric material for the blades was chosen to be 30D nylon ripstop, commonly used in hot air balloons and tents, for its durability and weather resistant properties. Ripstop fabrics are woven with thick reinforcing threads, preventing tears from propagating.

Drawn Aluminum 6061-T6 was decided as the material for all structural components of the turbine because it is lightweight, durable, and weather resistant. The blade support arms, the center shaft, the housing shaft, and the legs are all made out of 6061-T6 aluminum. Other desirable properties include a high strength to weight ratio and recyclability. Since the central shaft of the blades is subjected to the highest loads, analysis was completed to ensure 6061-T6 material properties are sufficient to support the expected loads. These calculations are found in Appendix C: Central Shaft Calculations.

5.6. Generator

During the Slatted Savonius wind tunnel test, it was seen that a gearbox with a ratio of nearly 100:1 would be needed to produce 5V with the Electrifly Ammo 28-56-1530 kV brushless motor. The high torque required to spin this gearbox led to an unsatisfactory cut-in speed. Because of this, it was decided to design our own three phase generator to eliminate the need for a gearbox. This custom generator consists of a high strength permanent magnet that is attached to the rotating axis of the turbine and coils of copper wire that are fixed to the inside of the housing unit. It was determined that 6 coils of 400 winding would generate the required 5V at a low blade speed of 30 rpm, which corresponds to roughly 13 ft/s (4 m/s) winds based on the Slatted Savonius test. We expect the Revolve to perform even better than this, and a cut-in speed of less than 13 ft/s is satisfactory.

5.7. Electronics

In order to design our own 3 phase rectifier, we started with a single phase rectifier and tested it using a function generator to make sure the circuit performed as expected. This was extended to make the 3 phase rectifying circuit in Figure 9. Diodes rated to 20V and 3A were used to rectify the AC output and a 47nF capacitor was used to smooth out the waveform. The open circuit line-to-line voltage of the generator was compared to the rectified output voltage to ensure there were no substantial losses. A voltage regulator was included to limit the output to 5V, and a USB port was integrated to allow for a common charging platform for mobile devices.

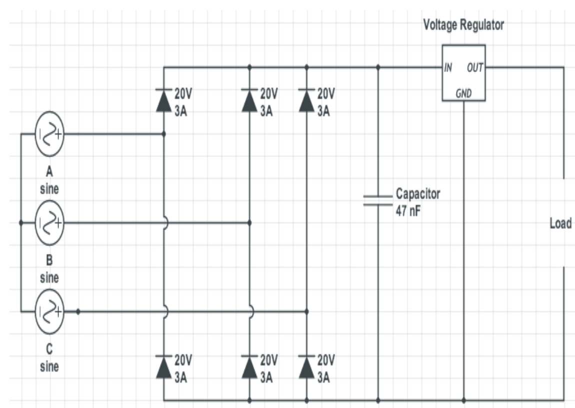


Figure 9: Three phase rectifiying circuit.

6. Finite Element Analysis

Finite Element Analysis (FEA) in SolidWorks was used to acquire theoretical testing results. These results provided an overall Factor of Safety (FOS) for the blades. Initial parameters and conditions were determined by considering the operational forces based on standard Savonius drag coefficients. This is a conservative simplification because the drag forces in a standard Savonius will be higher than in the window design. Each arm on the concave side was subjected to a force of 9.68 N while each convex arm was subjected to a force of 4.62 N. This difference was due to the different drag coefficients on either side. The lower portion of the central shaft was fully fixed, preventing axial, radial, and translational movement. This setup is shown in Figure 10. Using these parameters, several useful types of FEA were done. The most important was the (FOS) analysis in Figure 11, which shows a minimum FOS of 2.19. This signifies our turbine blades are designed to withstand twice the expected operational loads.

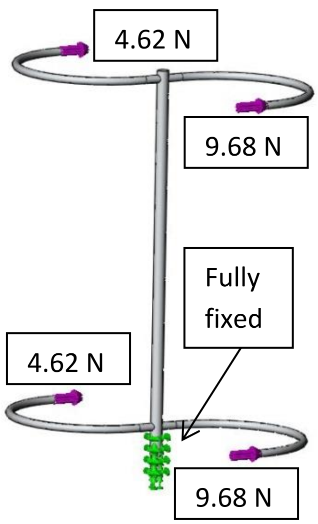


Figure 10: Fixture and loads orientation for FEA analysis.

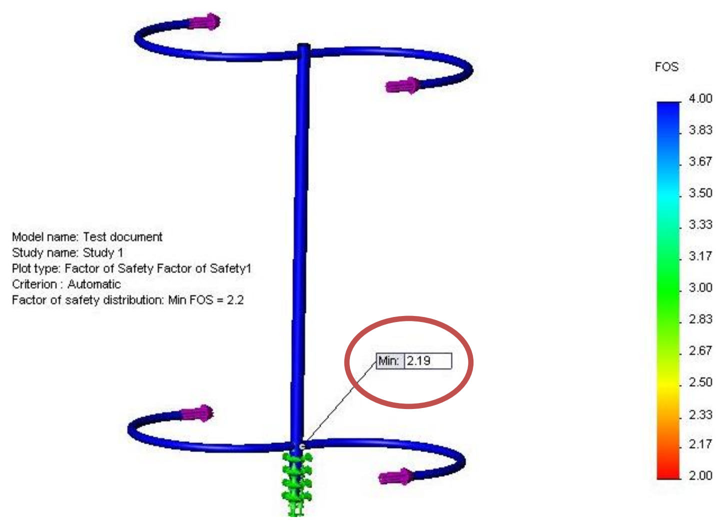


Figure 11: Factor of safety analysis using SolidWorks.

Other analyses conducted include von Mises stress and displacement. The highest von Mises stress was 125.33 MPa which is well below the yield strength σ_y=276 MPa. In a displacement analysis, it was determined the maximum displacement occurred in the top arms, and was approximately 1.383 cm (0.544 in) in the direction of the applied force. Both of these values fall within our acceptable range.

7. Safety Analysis

The Revolve turbine has been designed with customer safety as a top priority. The design consists primarily of nylon ripstop fabric and 6061-T6 aluminum. The nylon fabric blades deform when impacted by a solid object and the arms are constructed with no sharp edges, making the Revolve safe for human contact. To prove this concept, a human hand was modeled with low density foam and a concentrated wind source was aimed at the turbine blades. After maximum blade speed was reached, the foam hand was moved into the spinning turbine both from the top and from the side. No physical deformation of the foam limb was visible providing us enough confidence to repeat the test with human subjects. Human hand testing also supported the foam hand test conclusion; the rotation of the blades was halted and reported pain level was minimal.

The window blades of the Revolve also provide a built in safety feature. At very high wind speeds the flaps will blow through the windows in the fabric altering the turbine's aerodynamics which limits the maximum rotational speed. Each blade arm also has a capped end to eliminate potential sharp edges. On the inside of the housing shaft, a layer of electric insulation is applied over the entire length. Since the aluminum shaft is electrically conductive, this insulation will prevent electric current from traveling through any aluminum components that the user interacts with.

8. The Revolve Versus Testing Model

This design review has been focused on the Revolve, the turbine designed by Zephyrus to be marketed and sold to consumers. This is different than the turbine to be tested at the Collegiate Wind Competition. The Revolve uses a custom built generator without a gearbox while the testing model uses the Electrifly Ammo 28-56-1530 kV brushless motor with a gearbox and transformer to produce power. In addition, the competition model implements an electronic emergency braking system for when no load is attached or a stop button is pressed. However, based on safety testing this braking system was not included in the Revolve because of the safety features already incorporated.

9. Engineering Specifications

Table 2: Engineering specifications for the Revolve.

Turbine	
Type	Vertical axis Savonius with 2 window blades
Total turbine mass	3.5 lbs
Deployed size	4 ft height x 1.5 ft swept diameter (1.22 m x 45 cm)
Collapsed size	1 ft height x in width (30.5 cm x 12.7 cm)
Blades	
Swept area	986 in^2 (6360 cm^2)
Blade arm diameter	8.5 in (21.5 cm)
Blade height	18 in (45 cm)
Blade material	30D nylon ripstop fabric
Blade characteristics	Collapsible
Electronics	
Generator	Direct drive, brushless, permanent magnet
Housing diameter	1.77 in (4.5 cm)
Housing length	9.84 in (25 cm)
Coil height	4.33 in (11 cm)
Coil properties	400 windings per coil in a 3 phase configuration
Voltage	5V at 30 rpm
Rectifier	6 diodes rated at 20V and 3A, 5V voltage regulator, 47nF capacitor
Housing shaft material	6061-T6 aluminum
Support	
Bushing	2 Nylon PTFE low friction bushings
Length/OD/ID/spacing	0.5 in/0.625 in/0.57 in/0.79 in (1.3cm/1.6 cm/1.4 cm/2 cm)
Legs	Adjustable tripod with 0.5 in (1.3 cm) OD hollow shaft, plastic end caps with stake holes
Shaft material	6061-T6 aluminum
Design Limits	
Rated wind speed	65.6 ft/s (20 m/s)
Rated power output	7.38 ft-lbf/s (10 W)
Environmental Parameters	
Operating temperature range	-4 °F to 122 °F (-20 °C to +50 °C)

10. Bill of Materials

Table 3: Bill of materials for the Revolve.

Part Name	QTY	Material/Description
Blades		
Fabric blade	1	30D nylon ripstop fabric
Arm	4	13.6 in length aluminum tube 0.375 in x 0.035 in
Central support shaft	2	9 in length aluminum tube 0.5 in x 0.035 in
Metal insert	6	1 in length aluminum solid shaft 0.305 in OD
Center Housing		
Shaft	1	10 in aluminum tube 1.875 in x 0.058 in x 1.759 in
Bushing	2	Nylon PTFE 0.5 in length, 0.57 in ID, and 0.625 in OD
Bushing housing	1	Injection molded thermoplastic polymer
Permanent magnet	1	Neodymium 0.5 in OD
Spool of wire	1	Copper, 30 AWG (for generator)
Spool of wire	1	Copper, 20 AWG (for wiring)
Circuit board	1	Protoboard
Diode	6	Silicon, rated at 20V and 3A
Capacitor	1	Polyester film, 47 nF
5V voltage regulator	1	Integrated circuit
Support Structure		
Tripod mount	1	3 in length aluminum solid shaft 2 in OD
Pin	3	0.9 in length stainless steel 0.15 in OD
Leg	6	10 in length aluminum tube 0.5 in x 0.035 in x 0.43 in
Cap with stake hole	3	Rubber

11. Engineering Diagrams

The key subsystems which are unique to this design are shown in the drawings below in Figure 12 and 13.

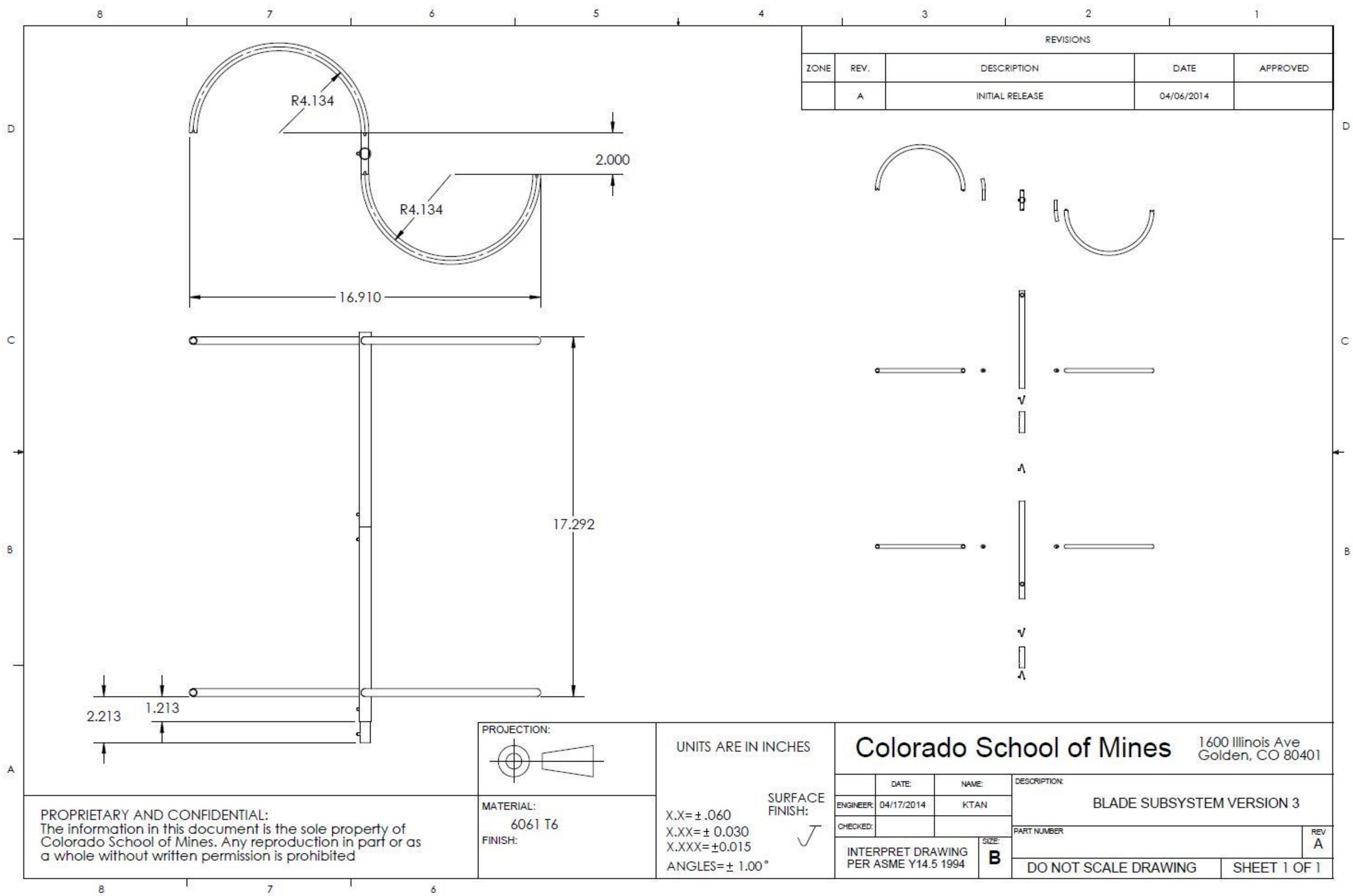


Figure 12: Dimensions of blade support structure.

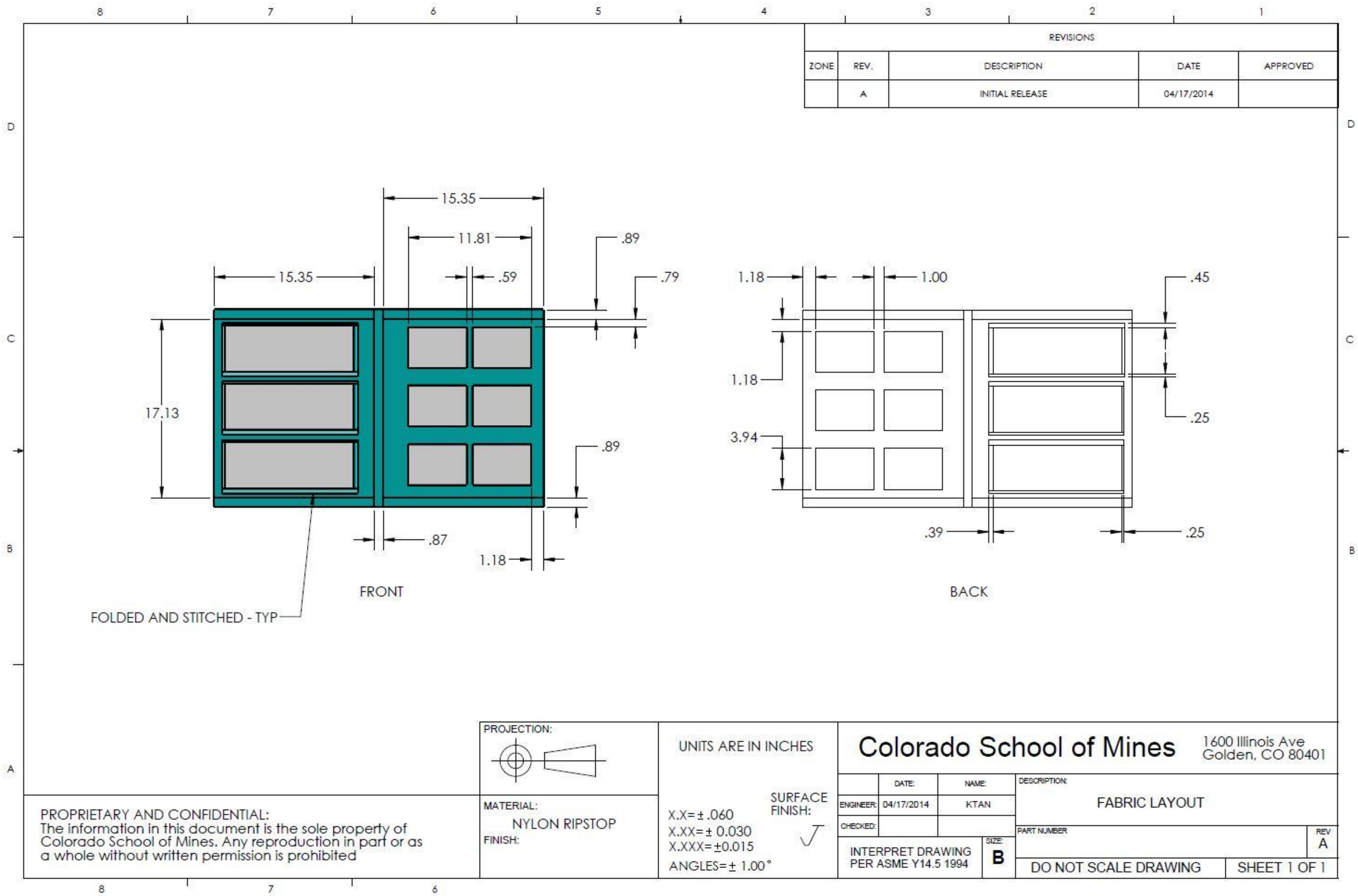


Figure 13: Dimensions of fabric window blades.

Appendix A: Wind Loading Calculations

The following calculations show steps taken in order to determine the wind load expected to be seen by the Revolve. To simplify the loading conditions, a vertically distributed force acting at the center of each blade was applied shown in Figure 14.

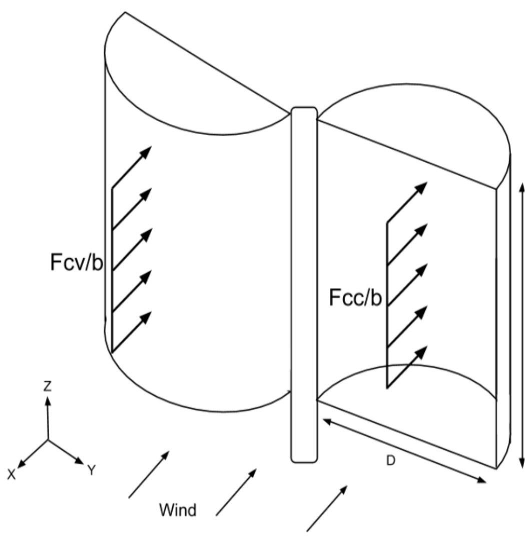


Figure 14: Wind loading on two-arm Savonius.

Assumptions

- Maximum loading occurs at a wind speed of 20 m/s
- No torsional loadings on shaft because resistance to turning is minimized by bushings
- The maximum loading will occur when the two arms of the turbine are perpendicular to the wind because at this point both arms will have the largest cross-sectional area perpendicular to the wind
- Air is at standard temperature and pressure
- A standard Savonius is used because it assumes higher loadings than actually present
- Only directions perpendicular to the axis of rotation (z axis) will be considered.

Force Calculations

The design conditions of the Revolve took the max wind speed to be $v = 20\frac{m}{s}$, with a standard air density of $\rho = 1.2\frac{kg}{m^3}$. From Fundamentals of Fluid Mechanics by Munson et al, the coefficients of drag for the concave side and convex side were found to be $C_{cc} = 2.3$ and $C_{cv} = 1.1$, respectively. The projected area of each blade is $A_{cc} = A_{cv} = 21.5cm * 45cm = 0.09675m^2$. The force of drag on the concave side is $F_{d,cc} = \frac{1}{2}\rho v^2 C_{cc} A_{cc}$ and on the convex side is $F_{d,cv=}\frac{1}{2}\rho v^2 C_{cv} A_{cv}$. Substituting in known values, $F_{d,cc} = 53.41\ N$ and $F_{d,cv} = 25.54\ N$.

Appendix B: Bushing Calculations

The total force of drag experienced by the turbine is the sum of the drag force on the concave side and the convex side, $F_{d,tot} = F_{d,cc} + F_{d,cv} = 53.41\ N + 25.54\ N = 78.95\ N$. To determine the force exerted on each bushing, the conditions of static equilibrium were applied to the loading conditions shown in Figure 15, $\Sigma M_{b1} = F_{b2}(a) - F_{d,tot}(\frac{1}{2}b + c + a) = 0$.

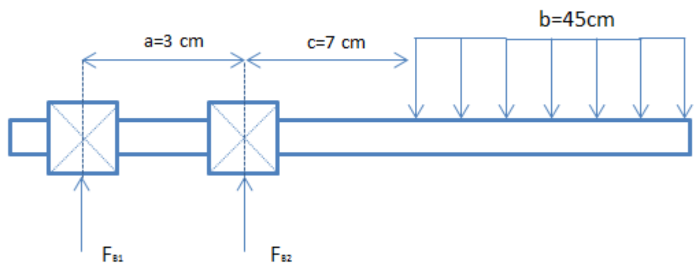


Figure 15: Loading conditions for bushing calculations.

Distance a was assumed to be 3 cm center-to-center in order to save space while still providing sufficient stability to the central shaft. Substituting known numbers into this equation gives $F_{b2} = 855.3\ N$. The force on the other bushing was then found to be $F_{b1} = -776\ N$. Since F_{b2} is larger, it was used to verify the selected bushings. F_{b2} is distributed along the inner contact area of the bushing, $A_{is} = (ID)(L) = (0.01448\ m)(0.013\ m) = 1.839\ cm^2$. Knowing the rating of the bearings to be 400 MPa, the applied stress on the bearings was found by $\sigma = \frac{F_{b2}}{A_{is}} = 4.651$ MPa. The factor of safety on our bushings is 86.0, indicating sufficient bushing selection.

Appendix C: Central Shaft Calculations

A mechanics of materials analysis was performed to determine the required thickness of the central shaft of the blades. The results showed that a shaft thickness of only 40 μm was necessary under the wind loading conditions described in Appendix A: Wind Loading Calculations. Since this value was so small, an impact analysis was conducted to ensure the shaft would not sustain permanent deformation when a 35 kg backpack was dropped on it from a height of 1.15 m. It is assumed that the pack is dropped onto the center of the shaft laid on the ground.

Impact Calculations

The force due to impact is greater than the force due to static loading. The equation to determine this force is $F_i = W\left(1 + \sqrt{1 + \frac{2\eta h}{\delta_{st}}}\right)$, where W is the weight of the impacting body, h is the height it was dropped from, δ_{st} is the static deflection and η is a correction factor obtained using $\eta = \frac{1}{1+\frac{m_{impacted}}{3m_{impacting}}}$. However, since it is desired that the shaft mass be no more than 0.25 kg, the correction factor will be 0.998 or smaller. A value of 0.998 will therefore be used. For a simply supported beam, the static deflection of the shaft can be calculated using $\delta_{st} = \frac{Wb^3}{48EI}$. The stress from impact is $\sigma_i = \frac{F_i}{A}$. Taking this stress to be the yield stress of the aluminum, the elastic modulus to be 69.8 GPa, and introducing a safety factor of 2.0 gives, $\sigma_i = \frac{WS_f}{A}\left(1 + \sqrt{1 + \frac{2\eta h}{\delta_{st}}}\right)$. Substituting everything in and solving for r_i using Mathematica yields

$$r_i = 0.5\sqrt{3.8415\left(-2.2628 * 10^{-7} + r_o^2 - 2\sqrt{3.6893(-2.2628 * 10^{-7} + r_o^2)^2 - 3.683(-4.720 * 10^{-7} r_o^2 + r_o^4)}\right)}$$

The plot in Figure 16 shows a relationship between the inner and outer radius of the shaft required in order to resist permanent deformation from the impact loadings described above. Based on this analysis, the final central shaft dimension for the Revolve was chosen as 0.5 in OD with a thickness of 0.035 in.

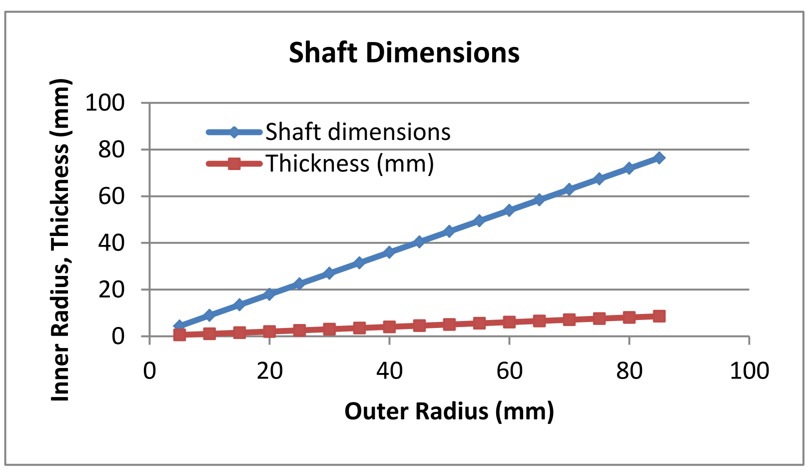


Figure 16: Shaft impact analysis results