Executive Summary: Design of a Small-Scale Wind Turbine to Improve Drinking Water in Garacad, Somalia

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This document presents the design of a small-scale wind turbine to improve drinking water in Garacad, Somalia. Access to safe water is a problem that 40% of the 783 million people living in Sub-Saharan Africa face every day [1]. More specifically, the population in Somalia has the lowest accessibility to clean water of any recognized country in the world. With a population of over 9 million people, 70% are drinking dirty water [2]. Because of the Somalis' lack of access to clean water, outbreaks of waterborne diseases such as Acute Watery Diarrhea (AWD), polio, and cholera are common [3]. In order to help improve the quality of drinking water in Garacad, our team has designed a small-scale wind turbine that can power a UV-LED light for water purification. The UV-LED, shown in Figure 1, is able to be powered by our wind turbine and can run on just 1 watt of power while destroying 99.99% of harmful microorganisms in the water [4]. By using a UV-LED that is wind powered, the people living in Garacad would be able to drink water that is much cleaner.

Figure 1. Water container that uses a UV-LED light attached to the inside of the lid [5,6]. The UV-LED light takes just 60 seconds to disinfect a container of water.

The prototype needs for our small-scale wind turbine include power, durability, aesthetics, and ease of manufacturing. The need for power was the primary goal that needed to be satisfied by our wind turbine, because without power we cannot run the UV-LED light. Our turbine also had to be durable to withstand high wind speeds, aesthetically pleasing, and able to be easily manufactured so that Somalians can fix their turbines in the event of external damage. Along with our customer needs were the accompanying metrics: withstand wind speed, time to manufacture, power generated, and cost. Each of these metrics were able to be related to at least one customer need which allowed us to see the interrelationships between the various customer needs.

The following sections of the summary include concept generation, screening, and selection, sequence of prototypes, and performance of our final design. These sections will explain how we came up with our concepts, the process we took through each prototype, and how our final design performed in the beta testing.

Concept Generation, Screening, and Selection

To generate concepts for our small-scale wind turbine, we used the 6-3-5 method. Our team was given three sheets of paper, one designated for each of the three main subsystems: turbine blades, transmission, and support. For five minutes, each team member generated three concepts for one of the main subsystems. The papers were then rotated between team members, and the process was repeated for six rotations. As a result, 18 total concepts were generated for each main subsystem.

From the 18 total concepts generated, we were able to focus on six final concepts that we could use. In order to narrow down our six possible concepts for the three subsystems, three screening matrices were used. Each screening matrix consisted of six feasible concepts and a reference concept as the column heading, and the prototype metrics as row labels. For each metric, the concepts were compared to the reference concept and given a rating. A concept was given a "+" rating if the concept performed better than the reference concept for that metric. However, if the concept performed worse than the reference concept, it was given a "-" rating. Lastly, if the concept performed similar to the reference concept, it was given a "0" rating.

Upon summing up the pluses and minuses in the screening matrices, we were able to rank the concepts for each of the three main subsystems. From these rankings, our team could see which concepts essentially scored better or worse than others. The concepts that did not rank in the top three were removed and no longer considered for our final design. By using a combination of the top three ranking concepts from each subsystem, we were able to generate four proposed concepts from which we selected our final design. In that selection, we used an Analytical Hierarchy Process (AHP) matrix to determine which concept contained the highest scoring metrics.

Sequence of Prototypes

Using a sequence of prototypes allows for the design to be improved upon after the first prototype is made. This chance to improve is important because, more often than not, the first work is not the best work. The sequence of prototypes for the small-scale wind turbine progressed in the order alpha 1, alpha 2, then beta.

The first real design for our wind turbine was our alpha 1 prototype, shown in Figure 2 (left). Our team's alpha 1 prototype featured 3D printed, traditional style blades, a welded support structure, and a direct drive transmission design. Following the testing of this prototype, our team came up with a list of improvements we could incorporate into our alpha 2 prototype. Instead of using the direct drive transmission, we decided to use a spur gear system that would allow us to increase the power that we could generate. Additionally, we wanted to incorporate a bearing to reduce friction, as well as increase our blade length and infill percentage to produce greater momentum during rotation.

For our team's alpha 2 prototype, shown in Figure 2 (center), we worked to implement the design changes we came up with from the previous prototype. By increasing the blades' length and infill, as well as using a spur gear system, our turbine was able to produce a much greater power output than in our alpha 1 prototype evaluation. We also mounted a bearing to the back end of the nacelle to hold the rotor shaft in place. By adding an additional bearing, we were able to decrease concerns that we had for frictional energy loss as well as allowing the shaft to rotate freely. Our alpha 2 prototype produced 0.45 watts, which was less than our target specification of 1 watt; therefore, to produce 1 watt of power we intend to use two wind turbines in series with target power outputs of 0.5 watts each.

To move our alpha 2 prototype to a beta prototype, our team made a few important improvements. We first printed new blades to allow a tighter fit in the rotor hub. More detailed instructions on how to fit the blades into the hub can be found in Appendix B. The new blades made it much easier for us to adjust the angle of pitch so that we could find the optimal angle. Also, we mounted a top cover on the nacelle for extra protection and noise reduction. Additionally, we painted the support structure gloss black to give our turbine more aesthetic appeal. If our team were to continue developing our beta prototype, we would make a few more improvements which can be seen in Appendix A.

Figure 2. Sequence of prototypes for our team's small-scale wind turbine: (left) alpha 1 prototype, (center) alpha 2 prototype, and (right) beta prototype.

Performance of Final Design

In order to see if our wind turbine satisfied our metrics and specifications, we analyzed the beta prototypes' performance. The highest power output that we were able to generate from our wind turbine was 0.801 watts, which gave us an overall efficiency of 37.5%. A more in-depth analysis of our power output calculations can be seen in Appendix C. The satisfied metrics include withstand wind speed, and time to manufacture. Our wind turbine was able to endure the high-speed wind test for more than our target value of 13 seconds. Additionally, we came in under our set time for manufacturing which was 10 hours. The metrics that we were not able to satisfy included power generated and cost. While the original goal for our wind turbine was to have it produce a power output of 1 watt, the highest power output we have been able to produce is only 0.801 watts. We were able to achieve our maximum power output by testing different blade pitch angles and resistances on the decade box. Also, while we had a set budget of $20.00, we slightly exceeded this value by spending a total of $25.01 on components including metal gears, bearings, screws, and other small parts. Figure 3 shows our final design.

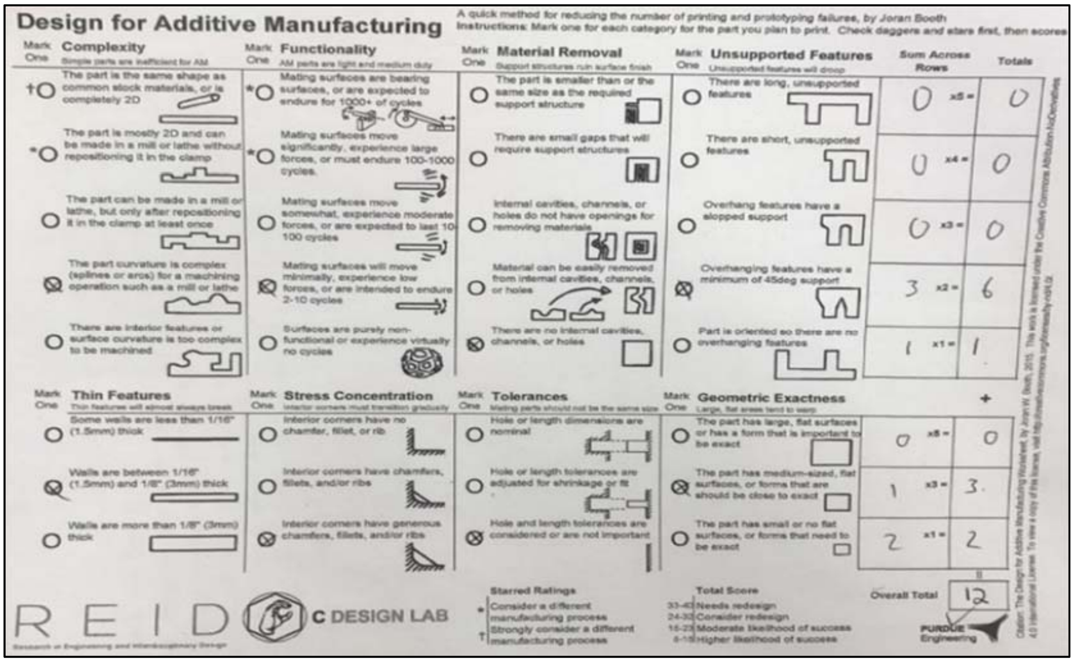
Figure 3. Final design of our wind turbine: (right) 3D printed blades and welded support structure and (left) bearings, shafts, spur gears, machined coupler, and generator in the nacelle.

Appendix A: How the Design Could Have Been Improved

This appendix reflects on the areas of the small-scale wind turbine that could have been improved and done differently in the design process. The first of this appendix's subsections presents the areas of the turbine that functioned properly and would be designed the same way. The next subsection details the areas of the turbine that did not perform optimally; moreover, this subsection will discuss what could be improved in the design process for better performance. Following this subsection, we will then propose an improved design process for the construction of our wind turbine.

Areas that Functioned Properly

The aspects of the turbine that functioned properly include the 3D printed rotor blade assembly and the welded steel support. The rotor blade assembly, which includes three traditional style blades connected together with a hub, was completely 3D printed outside of connection screws for the hub. The turbine rotor's performance was better than expected, reaching up to 1317 rpm. Moreover, the rotor blade assembly received an acceptable score of 12 on the Design for Additive Manufacturing (DFAM) worksheet shown in Figure A-1. For these reasons, the turbine rotor would be designed the same way for a later prototype. The welded steel support, which includes multiple forms of 1/8th inch thick steel, was welded into the appropriate shape to provide the turbine with a sturdy base and a nacelle to conceal the rotor shaft, gears, and generator. The support performed as expected, since it was able to prevent the turbine from experiencing any motion from the wind outside of the rotor and transmission. Because of these reasons, the turbine support would be designed the same way for a later prototype.



Design for Additive Manufacturing

A quick method for reducing the number of printing and prototyping failures, by Joran Booth
Instructions: Mark one for each category for the part you plan to print. Check daggers and stars first, then scores

Complexity (Mark One) — Simple parts are inefficient for AM
- †○ The part is the same shape as common stock materials, or is completely 2D
- *○ The part is mostly 2D and can be made in a mill or lathe without repositioning it in the clamp
- ○ The part can be made in a mill or lathe, but only after repositioning it in the clamp at least once
- ⊗ The part curvature is complex (splines or arcs) for a machining operation such as a mill or lathe
- ○ There are interior features or surface curvature is too complex to be machined

Functionality (Mark One) — AM parts are light and medium duty
- *○ Mating surfaces are bearing surfaces, or are expected to endure for 1000+ of cycles
- *○ Mating surfaces move significantly, experience large forces, or must endure 100-1000 cycles.
- ○ Mating surfaces move somewhat, experience moderate forces, or are expected to last 10-100 cycles
- ⊗ Mating surfaces will move minimally, experience low forces, or are intended to endure 2-10 cycles
- ○ Surfaces are purely non-functional or experience virtually no cycles

Material Removal (Mark One) — Support structures ruin surface finish
- ○ The part is smaller than or the same size as the required support structure
- ○ There are small gaps that will require support structures
- ○ Internal cavities, channels, or holes do not have openings for removing materials
- ○ Material can be easily removed from internal cavities, channels, or holes
- ⊗ There are no internal cavities, channels, or holes

Unsupported Features (Mark One) — Unsupported features will droop
- ○ There are long, unsupported features
- ○ There are short, unsupported features
- ○ Overhang features have a sloped support
- ⊗ Overhanging features have a minimum of 45deg support
- ○ Part is oriented so there are no overhanging features

Sum Across Rows		Totals
0	x5 =	0
0	x4 =	0
0	x3 =	0
3	x2 =	6
1	x1 =	1

Thin Features (Mark One) — Thin features will almost always break
- ○ Some walls are less than 1/16" (1.5mm) thick
- ⊗ Walls are between 1/16" (1.5mm) and 1/8" (3mm) thick
- ○ Walls are more than 1/8" (3mm) thick

Stress Concentration (Mark One) — Interior corners must transition gradually
- ○ Interior corners have no chamfer, fillet, or rib
- ○ Interior corners have chamfers, fillets, and/or ribs
- ⊗ Interior corners have generous chamfers, fillets, and/or ribs

Tolerances (Mark One) — Mating parts should not be the same size
- ○ Hole or length dimensions are nominal
- ○ Hole or length tolerances are adjusted for shrinkage or fit
- ⊗ Hole and length tolerances are considered or are not important

Geometric Exactness (Mark One) — Large, flat areas tend to warp
- ○ The part has large, flat surfaces or has a form that is important to be exact
- ⊗ The part has medium-sized, flat surfaces, or forms that are should be close to exact
- ○ The part has small or no flat surfaces, or forms that need to be exact

+		
0	x5 =	0
1	x3 =	3.
2	x1 =	2

Overall Total = 12

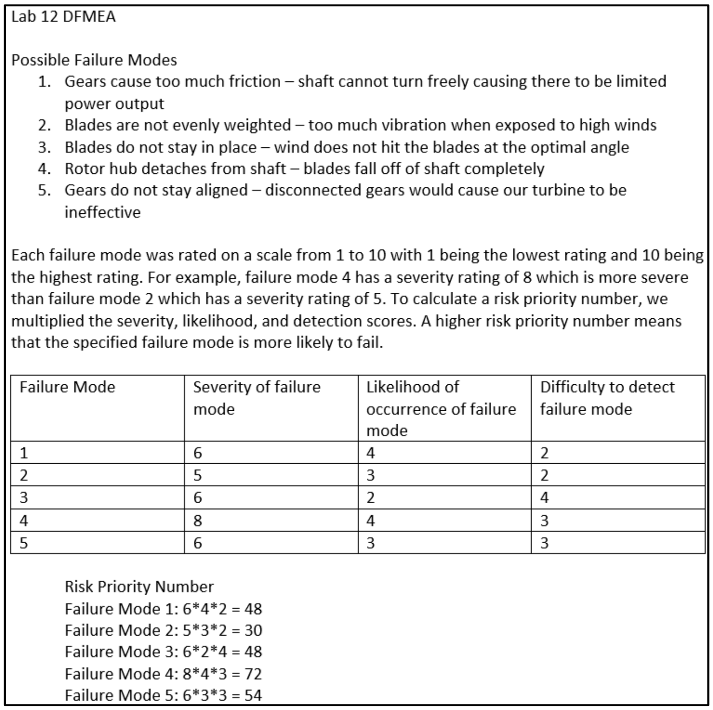
Starred Ratings
- * Consider a different manufacturing process
- † Strongly consider a different manufacturing process

Total Score
- 33-40 Needs redesign
- 24-32 Consider redesign
- 15-23 Moderate likelihood of success
- 8-14 Higher likelihood of success

Figure A-1. Design for Additive Manufacturing (DFAM) worksheet

Areas that Could Have Been Improved

The aspects of the turbine that could be improved include the concentricity of the machined coupler, and the overall alignment of the shafts, bearings, and gears. The aspect of misaligned gears was identified as a risk by our Design Failure Mode and Effect Analysis (DFMEA) chart, as shown in Figure A-2. The machined coupler, which connects the generator shaft to the gear shaft, could be machined on a more precise tool to ensure concentricity. The current coupler forces the mesh of the gears to vary as they rotate, which decreases the rpm of the generator shaft and thus lowers the efficiency of the turbine. The coupler was not the only aspect that caused a decrease in efficiency; moreover, the overall alignment of the transmission system also prevented the turbine from achieving optimal performance. The misalignment is because of imprecision in the mounting of the bearings and generator, which could not be avoided since all of the mounting holes needed to be drilled with hand tools. These mounting holes could be improved by drilling with a mill for better precision.



Lab 12 DFMEA

Possible Failure Modes

1. Gears cause too much friction – shaft cannot turn freely causing there to be limited power output
2. Blades are not evenly weighted – too much vibration when exposed to high winds
3. Blades do not stay in place – wind does not hit the blades at the optimal angle
4. Rotor hub detaches from shaft – blades fall off of shaft completely
5. Gears do not stay aligned – disconnected gears would cause our turbine to be ineffective

Each failure mode was rated on a scale from 1 to 10 with 1 being the lowest rating and 10 being the highest rating. For example, failure mode 4 has a severity rating of 8 which is more severe than failure mode 2 which has a severity rating of 5. To calculate a risk priority number, we multiplied the severity, likelihood, and detection scores. A higher risk priority number means that the specified failure mode is more likely to fail.

Failure Mode	Severity of failure mode	Likelihood of occurrence of failure mode	Difficulty to detect failure mode
1	6	4	2
2	5	3	2
3	6	2	4
4	8	4	3
5	6	3	3

Risk Priority Number
Failure Mode 1: 6*4*2 = 48
Failure Mode 2: 5*3*2 = 30
Failure Mode 3: 6*2*4 = 48
Failure Mode 4: 8*4*3 = 72
Failure Mode 5: 6*3*3 = 54

Figure A-2. Design Failure Mode and Effect Analysis (DFMEA) chart

Improved Design Process

To correct for the misalignment of mounting holes, the design process will begin with drilling the mounting holes in the 1/8th inch thick steel using a mill for precision. The steel will then be welded together to make the nacelle and support. Next, the bearings and generators can then be bolted to the nacelle using the pre-drilled holes. The shafts and gears will then be installed, and the turbine rotor will be 3D printed, assembled, and attached. This professional form of manufacturing will correct for the misalignment, allowing the turbine to achieve its optimal performance and power output.

Appendix B: How to Assemble the Wind Turbine Blades and Rotor Hub.

The wind turbine blades and the rotor hub are considered crucial parts for the wind turbine's operation. If these two parts are not assembled correctly, they will cause inefficiencies and will be safety hazards. In order to avoid any functionality issues, the assembly steps are listed below.

1. *Insert 3D printed blades into the bottom-rotor-hub.* Fully insert the three 3D printed blades into the bottom-rotor hub socket. Make sure that the blades are flush with the hub. You should also make sure that the leading edge of the blade is on the left side as indicated by the red arrow in Figure B-1.

Figure B-1. 3D printed blade inserted into bottom-rotor hub.

2. *Place top-rotor-hub onto blades.* There is no particular orientation that the top-rotor hub should be placed. Figure B-2 shows the completed step.

3. *Fasten the rotor-hubs with three 6-32 pan head screws.* Make sure that the screws are ¾ inch long. You should first fasten the three screws by hand so that they thread with the bottom-rotor hub. Then, completely fasten the screws using a phillips head screwdriver. To avoid unbalanced rotation, tighten the screws by the same amount. Figure B-3 shows the three screws fastened.

Figure B-2. Top-rotor hub securing the blades in place.

Figure B-3. Rotor-hub fastened with screws.

If these three steps are followed correctly, the turbine blades and rotor hub will function as a single part. Although the blades are fully secured, the blade pitch angle could be adjusted to achieve the optimal settings. Following these steps will also ensure that the blades do not detach while spinning; therefore, the turbine will comply with the safety requirements.

Appendix C: Physical Principles to Make Design Choices

This appendix reflects on the physical principles used to make certain design choices for our small-scale wind turbine. The first of this appendix's subsections describes the wind turbine blade analysis performed to obtain the optimum blade design. The next subsection details the torque plots used to determine the theoretical performance of the beta prototype and how it actually performed. The last subsection will then discuss how different blade pitch angles were tested to achieve the fastest rotation.

Wind Turbine Blade Analysis

After concept scoring, it was determined that the top-ranking concept included a traditional three blade design. In order to find the optimal blade design, standard NACA airfoil design shapes were used. Using a wind turbine simulation software called QBlade, several airfoil shapes were tested for the best performance as shown in Figure C-1. After multiple tests, NACA 4418 was chosen as the optimal airfoil design.

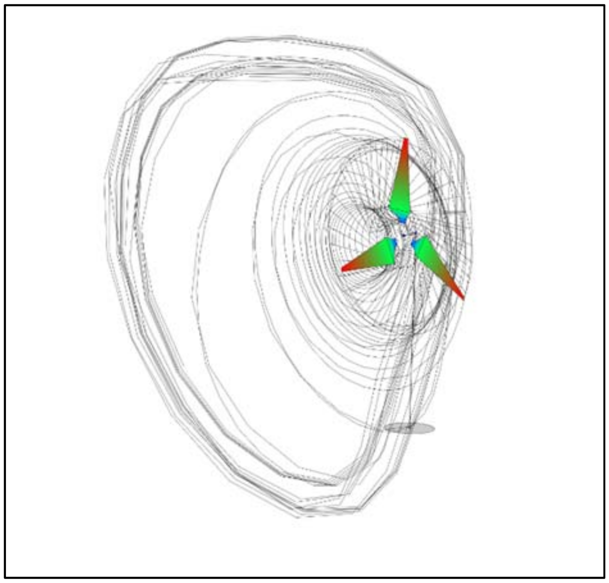


Figure C-1. Simulation of a specific NACA airfoil design.

Power Generation of Final Concept

Torque plots for a three-blade design were used to determine the required rotor angular velocity to generate 1 watt. Upon inputting the beta prototype parameters, the determined rotor angular velocity was 614 rpm to produce 1.07 watts, as shown in Figure C-2. The theoretical overall efficiency was calculated to be 50.2%. Even though the beta prototype had a rotor angular velocity of more than 700 rpm, the highest output obtained was only 0.801 watts. The actual overall efficiency was calculated to be 37.6%. The beta prototype did not perform as the torque plot calculations suggested, which could be because the torque coefficients used are for large-scale wind turbines.

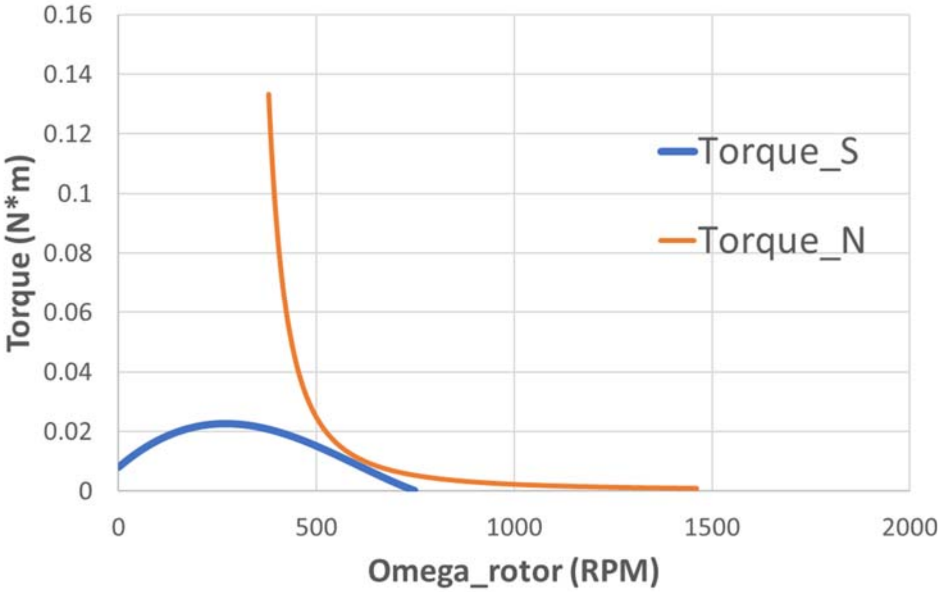


Figure C-2. Torque versus rotor angular velocity using beta prototype parameters.

Optimal Blade Pitch Angle

The overall efficiency of the wind turbine is also dependent on the chosen blade pitch angle. More angular velocity can be obtained with a slight adjustment of the blade pitch angle. Several angles were tested by using a printed template with the center of the blade as the reference. Using a tachometer, the rotor angular velocities were recorded in Table C-1. The highest angular velocity was obtained with a pitch angle of 7.5 degrees. Please note that this test was performed, without using any resistance.

Table C-1. Pitch angles tested for highest rotor angular velocity.

Pitch angle (degrees)	rpm
0	0
5	0
7.5	1317
10	1226
15	1020
20	776
25	532
30	528
35	456
40	383
45	336

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