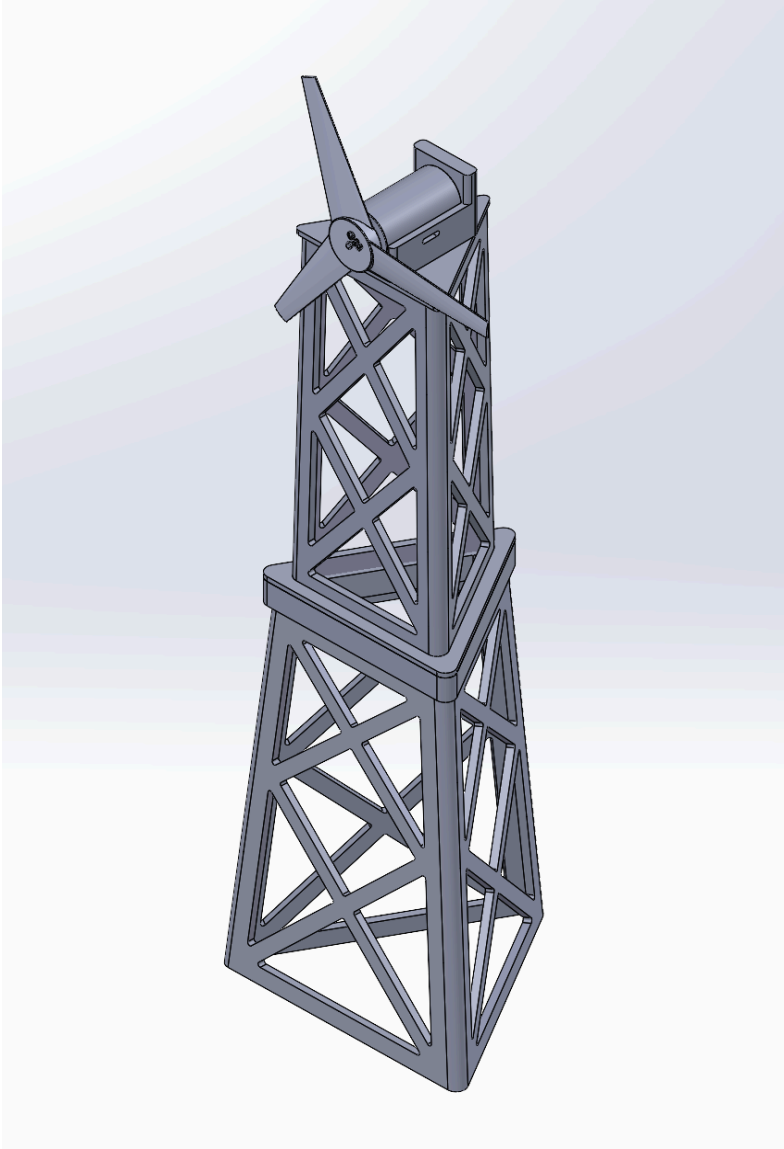
Wind Turbine Design & Testing Report

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Project Summary

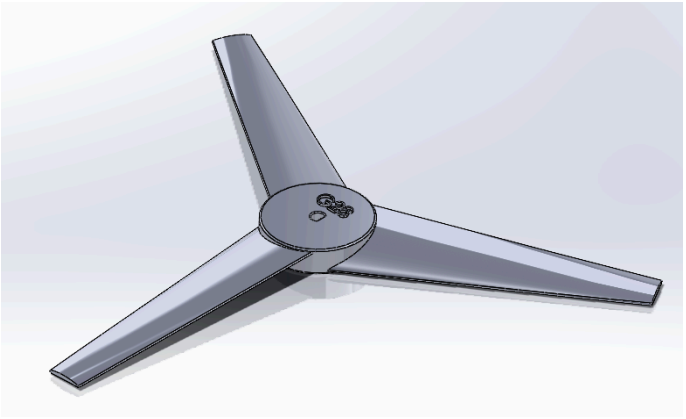


Figure 1. Rotor Design

The goal of this project was to design a wind turbine and maximize its stiffness and the power it could generate while minimizing the weight. The first step was designing a rotor. Our group decided to utilize a design with three blades. We reached this decision as the benefit of additional blades decreases significantly after a third blade is added. More details regarding the specifications of the rotor, such as the angle of twist and angle of attack are included later in the report.

After the rotor, our group moved on to the tower itself. We designed a tower with a triangular frame supported by thinner struts. We believed that this would yield maximal stiffness for minimal weight. We did design the tower with the constraint of a maximum volume, however optimizing volume also optimizes weight, so this had the same effect. The final weight of our tower and rotor was 261.5g. On top of the tower, we placed the motor housing.

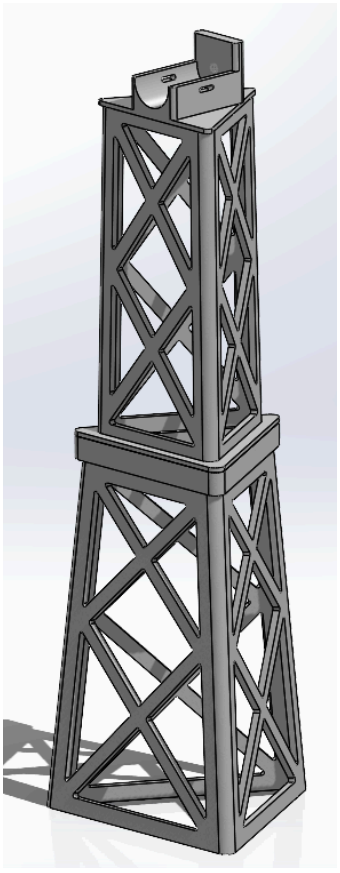


Figure 2. Tower Design

Finally, after fabricating the tower and rotor, we tested them. To test the rotor, we mounted it on a motor on the tower and used a fan blowing wind at 25 mph to test the power output. We found the max power to be 1.56 W. Next, we tested the stiffness of the tower. We did this by attaching an eyebolt to the back of the motor housing and hanging successively heavier weights off of it. We were unable to test our maximum deflection, but when we hung a 1 kg weight, our tower deflected by 0.53 mm. This equates to a stiffness of 18.509 N/mm.

Table of Contents

Project Summary..... i

Table of Contents..... ii

Introduction..... 1

CAD Models..... 4

Assembly and Exploded View..... 4

2D Drawings..... 4

Design..... 5

Blade..... 5

Tower..... 6

Finite Element Analysis (FEA)..... 6

Testing and Results..... 9

Conclusion..... 12

Recommendations for Future Work..... 14

References..... 15

Appendices..... 18

Introduction

Harnessing wind power is one of the oldest methods of power generation in the world. People have used wind to power boats, for example, for upwards of 7,000 years. The windmill has also been used to transform wind into mechanical energy for more than 1000 years. The wind turbine, however, has only existed since the late 19th century. Similar to the windmill, it uses rotating blades to capture the wind's energy, but rather than converting this work into mechanical energy, it converts it into electrical energy. The first wind farm in the United States went online in Southern California in 1975. This farm produced enough energy to power 4,149 homes. Since then, the use of wind turbines to generate electricity has increased rapidly, and in 2016, wind energy accounted for 5.76% of the United State's total electric power generation.

Wind turbines, in theory, are fairly simple. A rotor with blades attached converts the wind to rotational mechanical energy. A generator then converts this mechanical energy into electrical energy. Making a wind turbine actually perform, however, is more complicated. Our project did not deal with the generator or any of the apparatus needed to make said generator sturdy and efficient, such as a gearbox and safety brake. We did, however, design our rotor and blades. The idea behind the blade is that it has an airfoil shape and thereby creates lift which rotates the rotor. Additionally, the airfoil must strike the oncoming wind at a specific angle to maximize lift.

This concept sketch shows how the oncoming wind travels over the airfoil, creating lift via the Bernoulli effect. The angle of attack is the angle of the airfoil relative to the wind direction. Optimizing this angle is crucial to optimizing the performance of the turbine. Our group eventually settled on an angle of 13°.

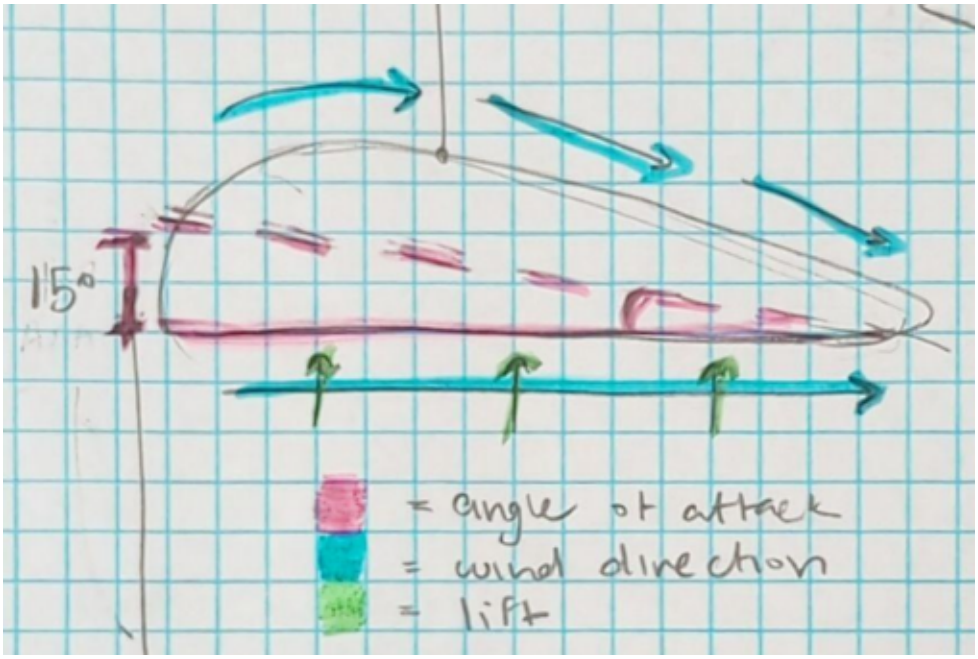


Figure 3. Blade Design Sketch

The other angle of note is the angle of twist which refers to how much the tip of the blade is twisted relative to the base. All rotor blades must twist to ensure an optimal angle of attack along the entire length of the blade. These factors allow the blades to harness wind power to be converted into electrical energy.



Figure 4. Blade Design Sketch

Our group designed our rotor specifically for 25 mph wind. Ordinarily, a wind turbine would have a gearbox to regulate and optimize rotor speed, but again, we did not include a gearbox. Thus to optimize performance at the given wind speed, we adjusted the angle of twist and angle of attack based on relevant studies we found during our research. The size and material of the rotor (3in diameter and ABS plastic) also allowed us more freedom of design. Unlike an actual turbine, our rotor weighed very little and was not under huge amounts of stress. This meant that we could focus entirely on the aerodynamics without having to worry about strength and stability. The diminutive size also meant that the finer details played a much smaller role than they would in an ordinary turbine and that we could even omit some such details. For example, our blades do not come to points and there is no aerodynamic nose on the hub of the rotor.

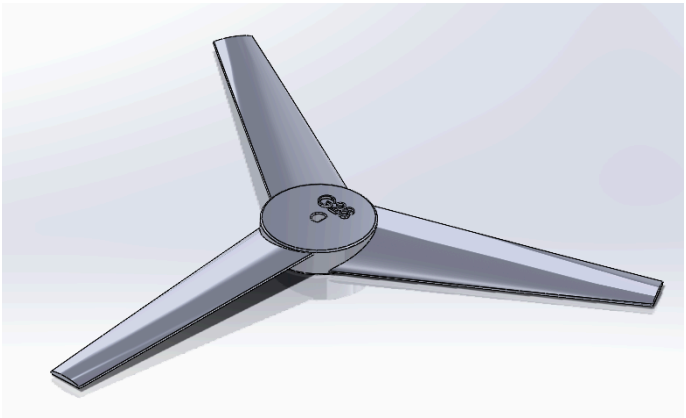


Figure 5. Rotor Design

Our tower also presented unique challenges. We designed it to be as stiff as possible, an attribute which, if found in a full-size wind turbine, would likely lead to structural failure. We also designed it to be 3D printed, which meant that we were not constrained by potential manufacturability or cost. This method of fabrication, however, meant that we had to design the tower in two separate pieces. One piece would have been too large for the printer. We glued the pieces together before testing, but also designed them to slot together so that the gluing would be more precise. The picture below shows how the pieces fit together

along with the motor and rotor. We also utilized a tower footprint which, relative to the size of the rotor, was far larger than would be practical at full size.

The tower, as mentioned above, was designed with only stiffness in mind. This is why it has a large triangular base and systems of crossing trusses. Actual wind turbines also incorporate a certain degree of ductility in the tower to mitigate the risk of fracture. That is why our tower looks nothing like a true wind turbine tower and would not be practical to use. It also uses a large amount of material and would require much effort to erect. Our rotor, on the other hand, relies on the same principles as actual rotors and, with more tweaking and optimization, could potentially be scaled up and manufactured for use on wind farms.

CAD Models

Assembly and Exploded View

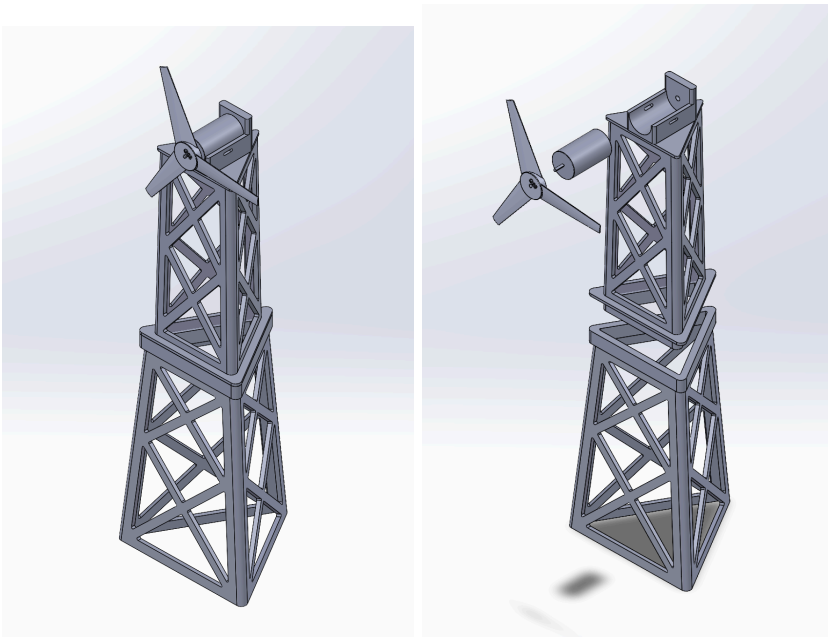


Figure 6. Assembly and exploded views

2D Drawings

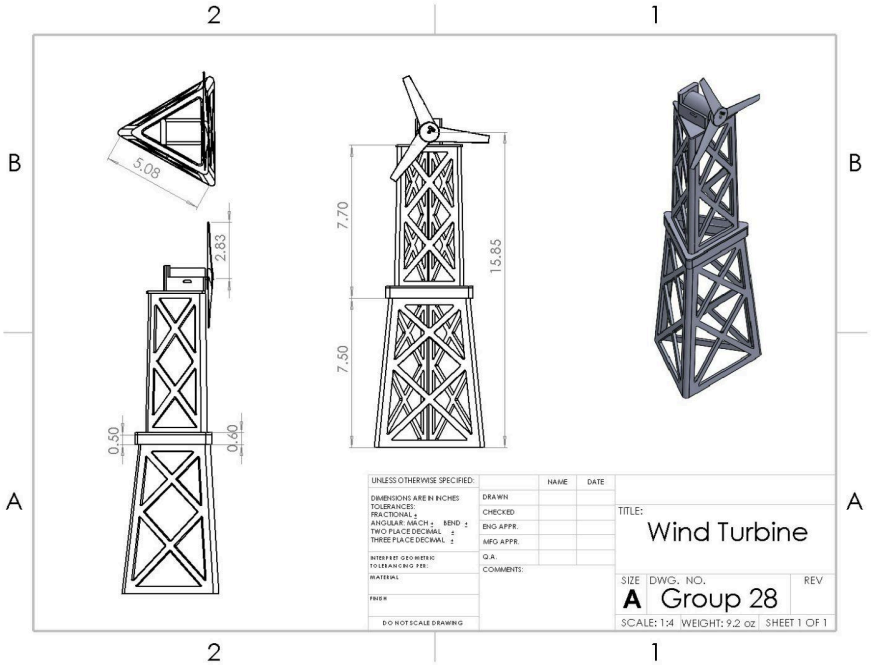


Figure 7. 2D Drawing

Design

In this section, We will cover a detailed description of our rotor blade and tower designs. Most of the features that are presented in the sketches are free-hand drawings but the important features of the designs are backed with research. The tool that was used to design the CAD models is SolidWorks and the material is ABS for all parts.

Blade

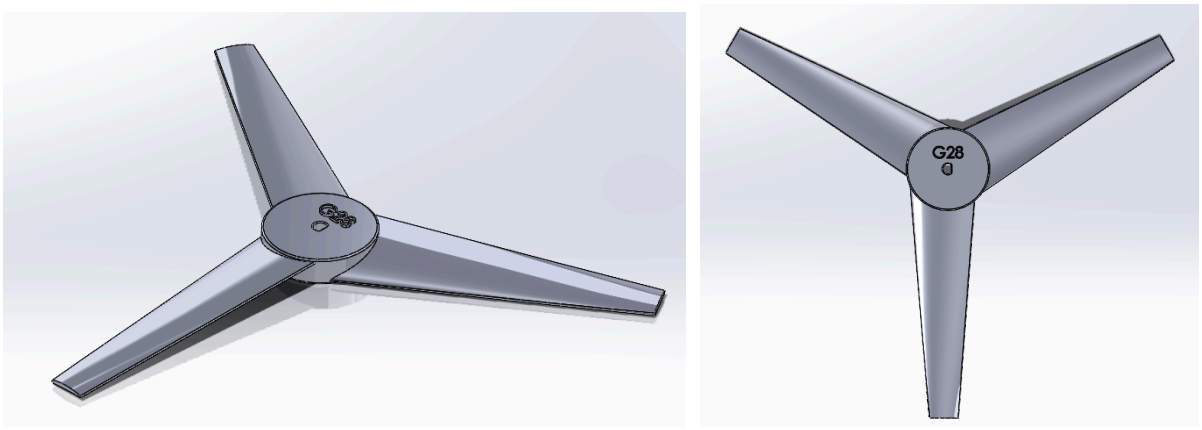


Figure 8. Rotor Design

The group came up with different designs and features, but the final model was based on collective agreement. The detailed description of the blade is as follows:

- Number of blades: 3
- Angle of attack: 13°
- Twist angle: 12°
- Radius from the center of hub: 3 in

All of the above measurements, apart from the radius, are made to optimize power output in a 25 mph wind speed. The decision behind having 3 blades in our propeller is to maximize surface area in contact with the wind by also minimizing the weight of the rotor blade itself. Lighter blades are proven to be more efficient as it would need less wind energy to turn them. Since our rotor blade radius is limited at 6 inches, we believe having 3 blades will maximize power output. The twist angle and angle of attack of the blades are set in a way to not only maximize power output but also minimize drag. For a wind speed of 25 mph, we found that the combination of a 13° angle of attack and a 12° twist angle is a good setting for our wind turbine rotor blade. Finally, the airfoil used was SG6043 from airfoil tools.

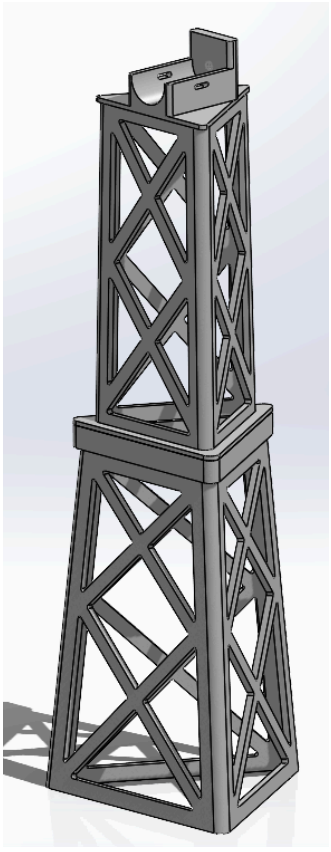


Figure 9. Tower Design

Tower

Our tower design is inspired by the engineering of a transmission tower that has cross-braces as trusses. However, instead of having a square base, we decided to make a triangular base to further strengthen the structure. The general idea of the design is to have an equilateral triangle as the base to make the structure stiff for it being said to be the strongest shape in nature. When a force is applied to any side, it will be equally distributed to each of every other side. Furthermore, the cross-brace trusses allowed us to efficiently design for sturdiness while allowing us to meet the volume requirements. The detailed description of the tower is as follows:

- Overall height: 16.5 in
- Height to the center of motor shaft: 15.9 in
- Base width: 4.8 in
- Volume: 16.83 in^3

Finite Element Analysis (FEA)

In this section, we ran an FEA simulation to measure the deflection specifically on our tower design. This is where we test our design idea to determine whether it is sturdy enough when a force is applied to it. It is important to measure the deflection and stress to mitigate the risk of breaking in the case of strong winds. For our project, we applied a 1 kilogram force that is normal to the backside of the motor housing at the top of the tower and set the base to be the fixed geometry as shown by the figures below.

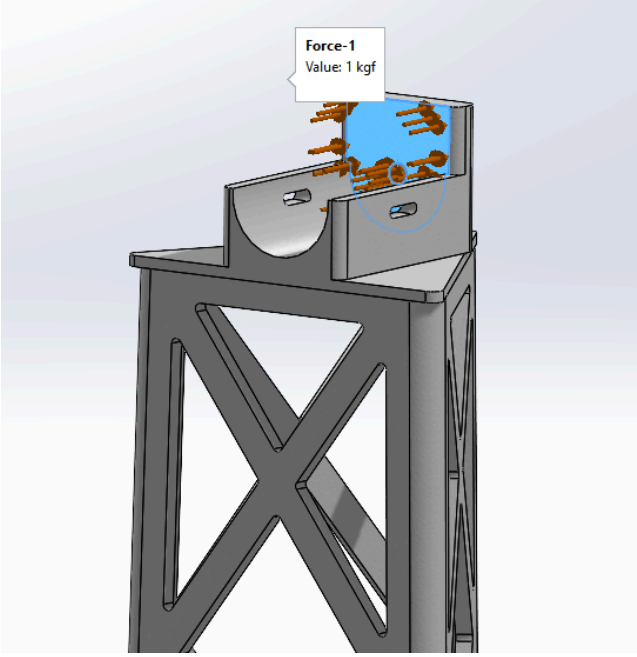


Figure 10. Motor Housing Showing an Area at which Force is Applied to

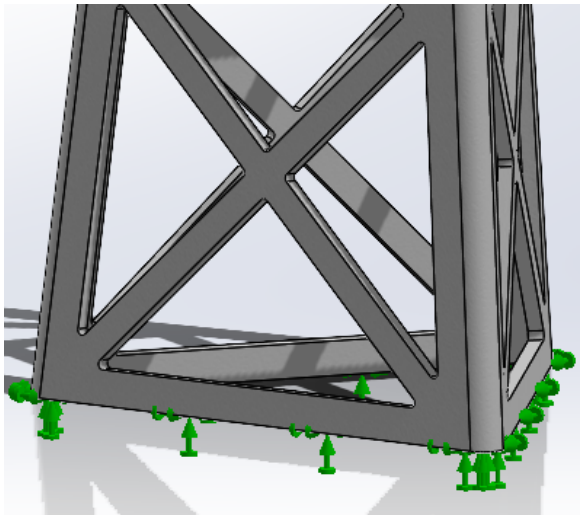
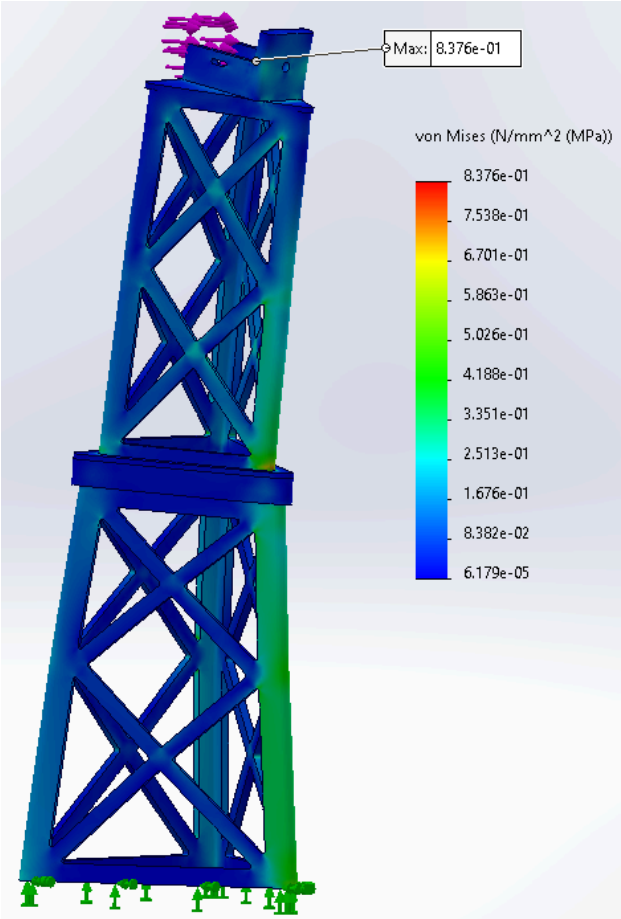


Figure 11. Tower Base as Fixed Geometry

After running the FEA simulation, we obtained the theoretical maximum value of $0.8376\ N/mm^2$ of stress. It can be seen from figure 13 that the section that experiences the highest stress is at the corner points that connect the back wall of the motor housing. Furthermore, we also obtained the theoretical maximum deflection of $0.2758\ mm$ at the top of the tower. It is a relatively smaller result than our maximum experimental deflection $0.53\ mm$ as shown in graph 1. This is because theoretical simulations are done under perfect conditions which is never the case in experimental simulations. An example that may affect the deflection values difference is perhaps the clamps were not strong enough to hold the base plate from moving which causes an inaccuracy when measuring the displacement.



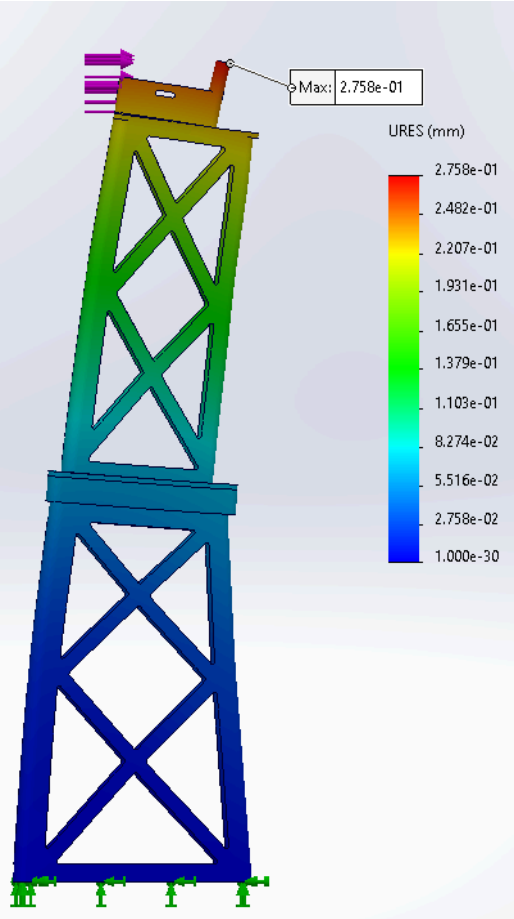
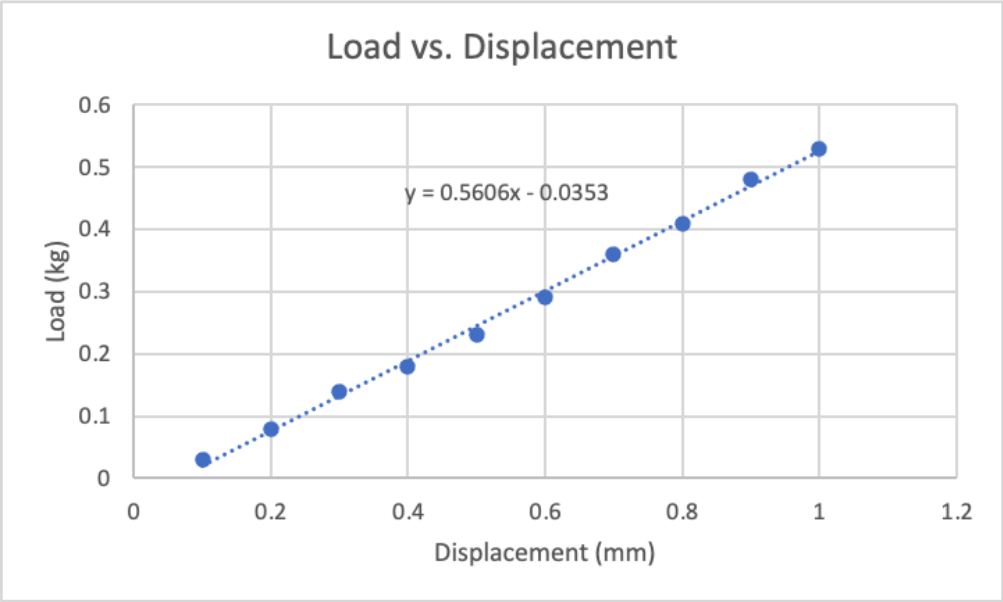


Figure 12 (left) and 13 (right). FEA Results; Stress and Deflection Plot Respectively



Graph 1. Load vs Displacement

Finally, we plotted the factor of safety (FoS) as an evaluation of the structure's material's strength to allowable stress. In short, the higher the value the less likely the object to fail. Solidworks does not define the yield strength of ABS, but Professor Youssefi suggested using the same value as the ultimate tensile strength which is $3e7\ N/m^2$. We obtained a maximum FoS of $4.855e5$ which implies that our tower is very unlikely to break.

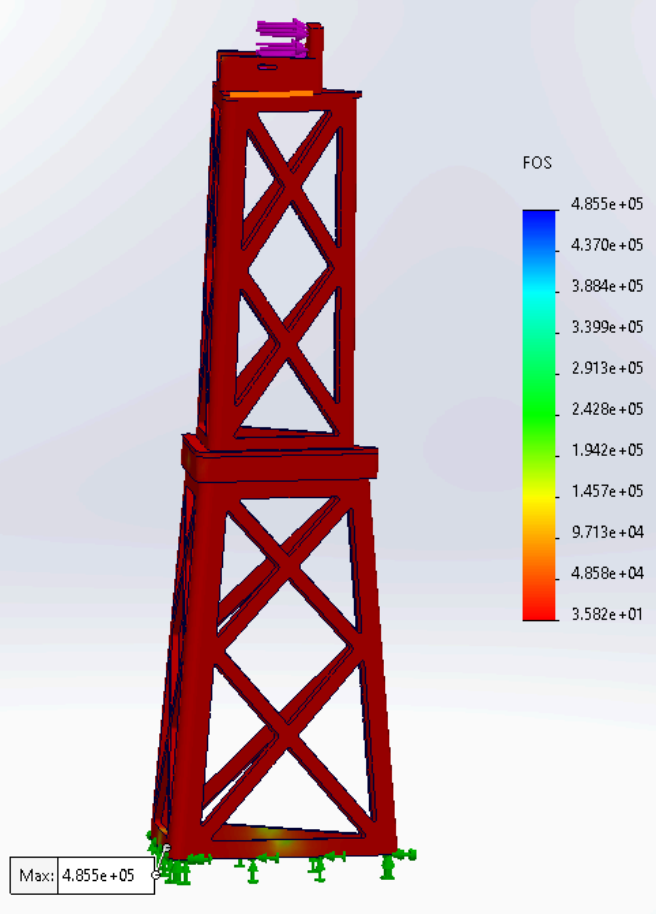


Figure 14. Factor of Safety Plot

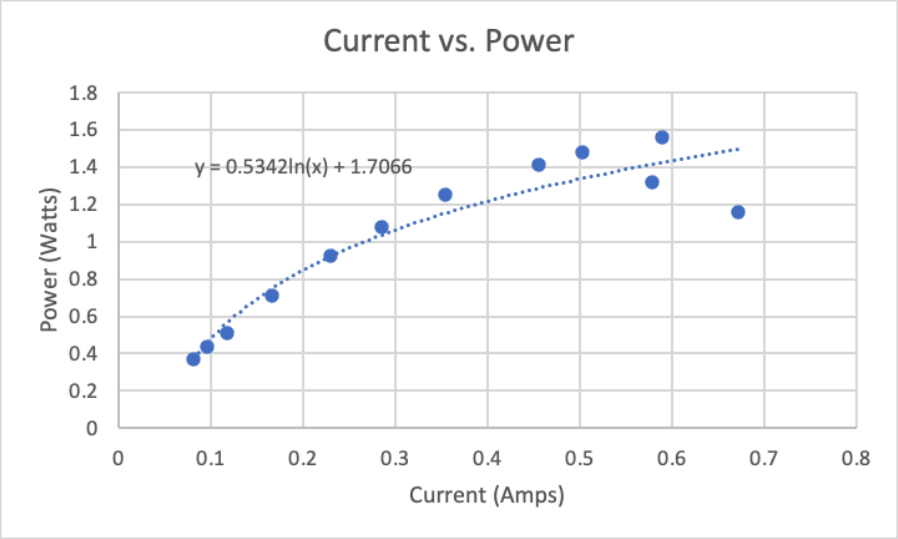
Testing and Results

To measure the power output of the wind turbine we used a power supply, fan, tachometer, zip ties, and clamps. We began by clamping the base plate of our wind turbine to the table. The zip ties kept our motor in place. When checking the wind speed, it was approximately 25.5 mph. Then we measured the distance from the fan to the blades which came out to 18.7 inches. The tachometer was placed in front of the blades at an angle for the laser to catch the reflective tape. The reflexive tape allows the tachometer to accurately read the blade speed. The power supply both provided power and we were able to read off measurements concerning the power supplied, voltage, and current using its control circuit.

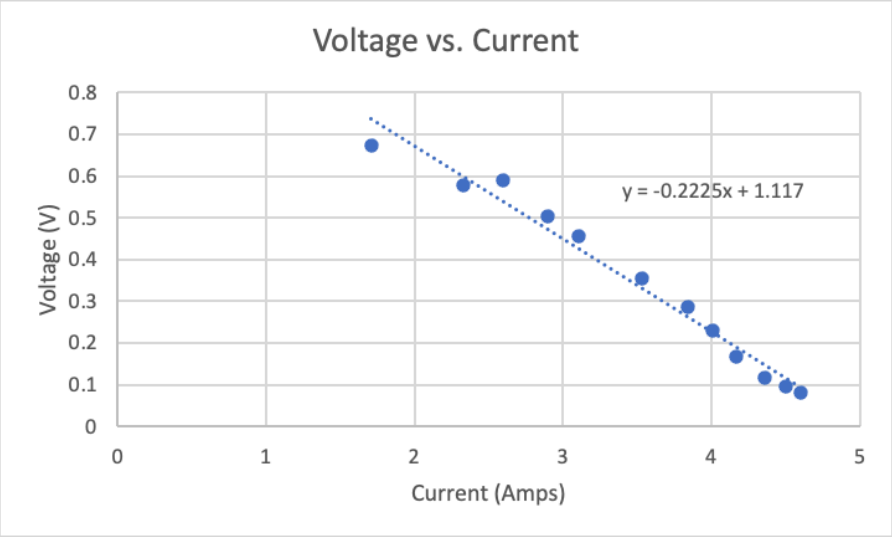
One of our group members began the procedure by fidgeting with the potentiometer which controls power. We adjusted power until we were able to find our maximum. Our estimated maximum power was 1.557 Watts. From the maximum, we adjusted the power until our group obtained 12 data points.

Table 1: Power Measurements

Data Points	Voltage V (Volts)	Current I (Amps)	Power P (Watts)	Blade Speed (rpm)
0	**5.08**			**6970**
1	**4.60**	**0.0819**	**0.3667**	**6640**
2	**4.50**	**0.0961**	**0.4332**	**6540**
3	**4.36**	**0.1181**	**0.5114**	**6390**
4	**4.17**	**0.1662**	**0.7132**	**6270**
5	**4.01**	**0.2305**	**0.9212**	**6160**
6	**3.84**	**0.2859**	**1.08**	**5950**
7	**3.53**	**0.354**	**1.25**	**5640**
8	**3.11**	**0.4562**	**1.416**	**5310**
9	**2.90**	**0.5037**	**1.48**	**5160**
10	**2.60**	**0.589**	**1.557**	**4791**
11	**2.33**	**0.5789**	**1.321**	**4751**
12	**1.71**	**0.6725**	**1.162**	**4024**



Graph 2. Current vs Power

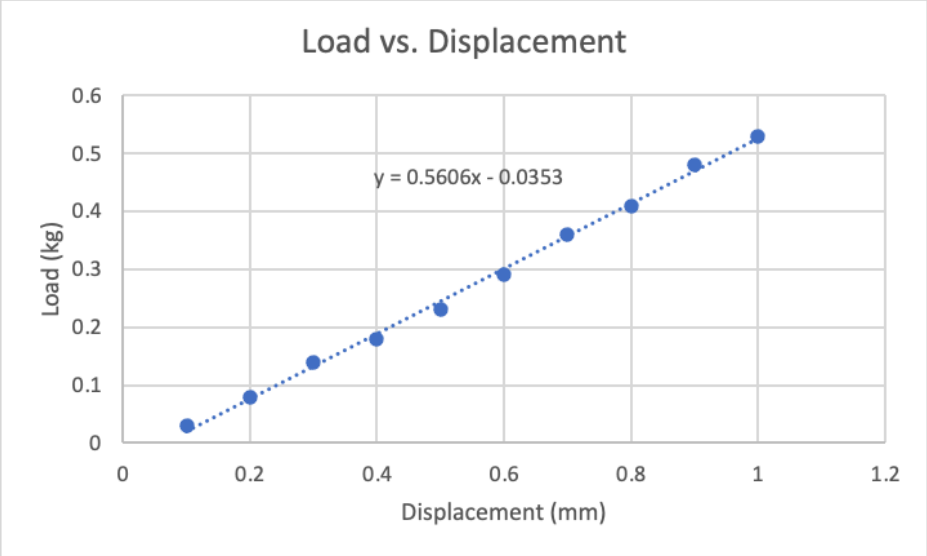


Graph 3. Voltage vs Current

After measuring power, we brought our wind turbine to the deflection measuring station. Our equipment included clamps, a hook, a deflection measuring device, and weights. We clamped our tower to a flat surface. The deflection measuring device was pointed to the center of the motor. The device was zeroed out to make certain that we obtain accurate measurements. We measured deflection by adding 100g weights to the hook in increments until we reached 1kg. After each weight was added, a group member wrote down the corresponding deflection. Tower height and weight were measured at the end of the deflection test. The tower had a height of 16.6in and a weight of 262.5g.

Table 2: Deflection Measurements

Data Points	Load (kg)	Load (N)	Deflection (mm)
1	0.1	0.98	0.03
2	0.2	1.96	0.08
3	0.3	2.94	0.14
4	0.4	3.92	0.18
5	0.5	4.9	0.23
6	0.6	5.88	0.29
7	0.7	6.86	0.36
8	0.8	7.84	0.41
9	0.9	8.82	0.48
10	1.0	9.8	0.53



Graph 4. Load vs Displacement

Conclusion

Beginning at our blade design, our blade consists of 3 rotors, with the radius from the center of the hub at 3in. Three blades was observed to be the most stable, produces the most power at slower speeds, and has more torque than a 2 rotor design. Research also cites that for a 23 mph wind, a twist of 12 degrees was optimal for power output. An angle of attack (AoA) of 13 degrees was chosen as most research cited a range between 10-15 degrees. Additionally, based on research, airfoil SG6043 from airfoil tools seemed to be the best for power output in terms of our application.

Our tower consisted of triangle base, and triangle lofted geometry. We split our tower into two parts for easier manufacturability. We included a series of truss structures along both pieces of the tower. This reduced volume as opposed to a completely solid infill, while offering balanced structural integrity

Our testing procedures involved collecting a series of data points based on the configuration of our control box. For testing power output we placed our turbine in front of a leaf blower, pushing air to a speed of 25.5 mph. We attached the motor to the mount with the use of zipties. We connected the motor to the control circuit with the black and red wires in their respective terminals. We started to collect data points, and for each control configuration we used the tachometer to measure blade speed, and altered the potentiometers bit by bit, eventually reaching the peak recorded power output, and the subsequent deterioration. In total, 12 measurements were recorded. Deflection testing involved connecting the eyebolt to a pulley system, and a strain gauge to our motor mount. Then we slowly added weights in increments of 100g to eventually reach 1kg.

Our numerical analysis yielded the following. Our tower produced a peak power output of 1.557W. For a load of 1kg, our tower displaced 0.53mm. Measuring the tower on a scale, the total mass was 262.5g. Observing height, the distance from bottom to was was 16.6in, and from bottom to motor shaft was 15.9in. Our volume was additionally 16.83in^3 constructed of ABS plastic. Peak blade speed was 6970 RPM, with a voltage of 5.08V. When checking the wind speed, it was approximately 25.5 mph, with a distance from the fan to the blades being 18.7 inches. Our base also measured to be 4.8in.

In graph 2 we drew a relationship between current and power. Looking at graph 3, drawing a connection from our data, we see that the voltage vs current graph produces a linear shape. This makes sense as the relationship between voltage and current is defined as V=I*R, which is linear. We also find that the load vs. displacement relationship is linear in graph 4.

For our FEA, a 1 kilogram force that is normal to the backside of the motor housing was applied and our triangle base was set to be fixed. The theoretical deflection came out to be 0.2758mm, almost half of the realistic deflection. We obtained a factor of safety (FoS) from our FEA coming to $4.855*10^5$, signifying incredible stability, and a high likelihood to yield from shear from a 1 kilogram force.

Recommendations for Future Work

As this was our team's first attempt at designing, prototyping, manufacturing, and testing a wind turbine, there exists room for improvement. Below are some considerations that can be made to improve the performance of our turbine.

Blade Design and Filet Limitations

Airfoils such as SG6043, found on airfoil tools, are very precise in their design. Due to our 3D printing limitations, the ends of the blade needed to be fileted to accommodate for the printer's limitations. This changes the airfoil and its aerodynamic properties. Finding an airfoil that can fit under the printer's constraints and perform better remains a possibility.

More In-Depth Truss Analysis

Analyzing our tower design for a solid mechanics standpoint, the exact number and configuration of the truss structures were arbitrarily chosen, aside from the fact of conforming to the volume constraints. Researching truss stress analysis and design, or using solidworks to run an optimization program for the truss structures could have aided in minimizing the deflection.

Motor Mount Security

Our design for the motor mount proved insufficient as running the zip ties through the intended slits raised the motor out of its hub. Utilizing a modified design would better secure the motor.

More FEA Testing

From our FEA results, we found that the estimated deflection was half of the realistic value. This could have arisen from a number of factors. Doing an analysis, and creating a more accurate simulation could have provided a closer prediction.

Possible Duct Implementation

Some turbine designs utilize a duct to better harness the wind. Through having the ability to create multiple prototypes we could have tested a multitude of designs, potentially generating more power.

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Author links open overlay panelNaveen Prakash Noronha, N., AbstractThe objective of the present research work is to identify a suitable airfoil for the design of a small horizontal axis wind turbine. For the present study, M., Ozgener, O., Wang, F., Mayer, C., Henriques, J. C. C., Clausen, P. D., Habali, S. M., & Akour, S. N. (2021, February 19). *Aerodynamic performance comparison of airfoils suggested for small horizontal axis wind turbines*. Materials Today: Proceedings. https://www.sciencedirect.com/science/article/abs/pii/S2214785321004508#:~:text=After%20a%20detailed%20aerodynamic%20comparison,for%20the%20given%20Re%20range

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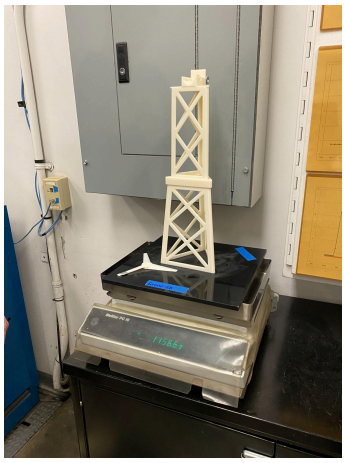
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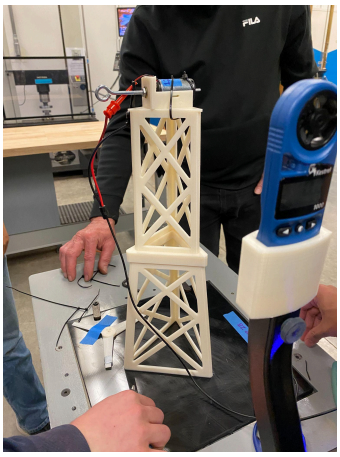
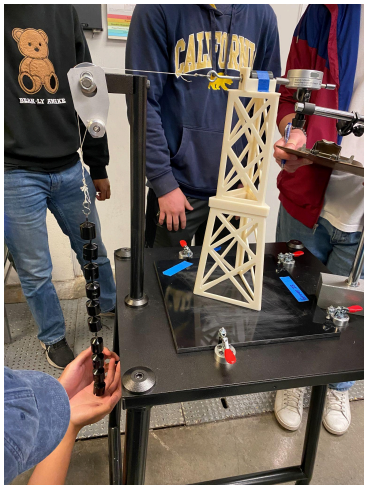
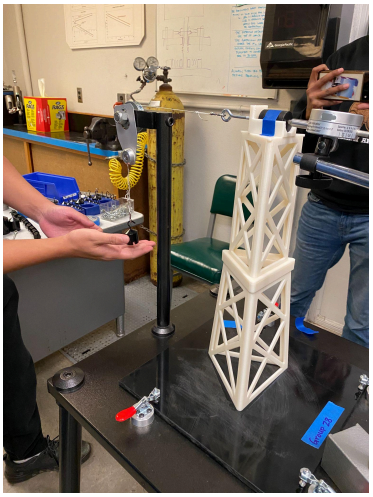
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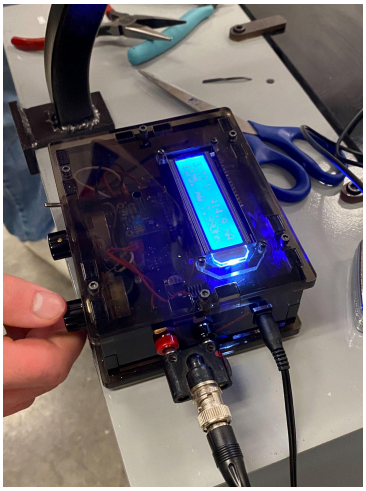
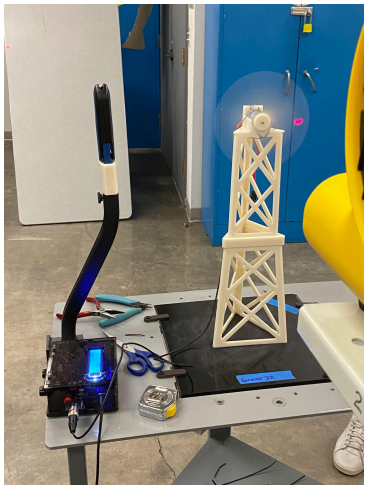
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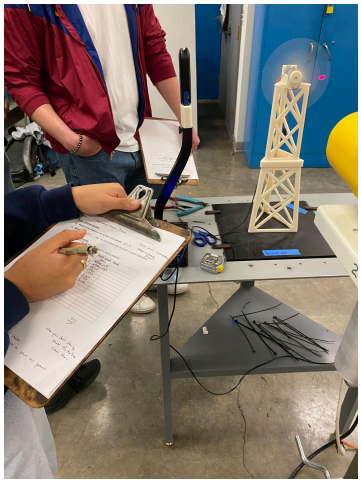
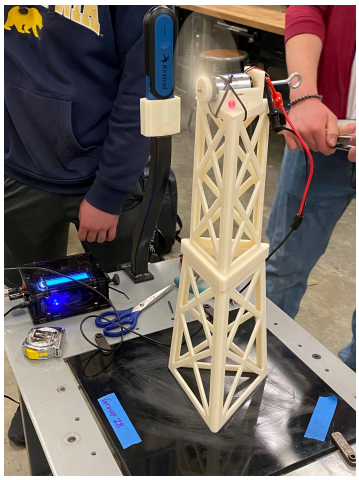
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Appendices



MEIKO
