Turbine Integrated Pitching System
Final Design Report

Team F96

Members:
Elizabeth Costley
Cameron Jackson
Jeff Larson
Josephine Maiorano

Sponsor:
Cal Poly Wind Power

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo
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Abstract

The Cal Poly Wind Power Club (CPWP) tasked this senior project to design, manufacture, test, and deliver a mechanism to pitch the blades for their small-scale horizontal axis wind turbine. CPWP competes in the Collegiate Wind Competition (CWC) against schools across the country, and as such it was critical to comply with the provided competition rules in addition to the design requirement from CPWP. The purpose of the pitching mechanism is to improve the performance and efficiency of the wind turbine by allowing the blades to adjust angles with different wind speeds. Specifically, this project aimed to minimize hub size, minimize power draw, minimize axial depth, increase blade strength, decrease blade switch time, in addition to being a durable and lightweight mechanism. The mechanism was designed with safety and reliability in mind and has been integrated into the CPWP wind turbine. The system utilizes two actuators to push and pull a swashplate connected to a 4-bar linkage to create the rotational motion in order to effectively pitch the blades. The team used a combination of CAD software and physical prototypes to evaluate the effectiveness of the mechanism. All of the manufacturing was completed by the team in the Cal Poly machine shops using a combination of manual machines and CNC. In addition, the team conducted various component and mechanism testing, including full turbine wind tunnel tests to validate the design. The final product was delivered to CPWP in time for the CWC competition, where it was put to the test against other universities' wind turbine designs.
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1. Introduction

The Turbine Integrated Pitching System senior project was tasked with designing and building a small-scale blade pitching system for Cal Poly Wind Power’s, hereafter referred to as CPWP, small-scale competition turbine. They compete in the Collegiate Wind Competition (CWC), which provides an additional set of rules and design requirements this project will have to follow [1]. The purpose of the pitching mechanism is threefold. At startup it allows the turbine to start spinning at low wind speeds by pitching to an optimal cut-in angle. Until 11 m/s its function is to hold and provide rotational motion control to the turbine blades, in order to optimize energy capture at different wind speeds. At high wind speeds it allows for curtailment of power production and rotational speed. The design needs to be as light and compact as possible, while still maintaining structural integrity and accurate blade rotation. The team built a physical mechanism while the club will provide the mechatronic controls for the project.

The senior project team is composed of four mechanical engineers, concentrating in energy resources, manufacturing, and general mechanical engineering. Combined they have 16 years of experience in mechanical engineering and 11 years of which in wind turbine design.

This report serves to provide an overview of the design, manufacturing, testing, and use of the mechanism. It covers the material procurement, manufacturing plan, assembly procedure, and details on the software and electronics involved. This includes details on usage of the mechanism for the current CPWP turbine, and how to integrate it for future turbine designs. The verification of the design is also included, including the testing performed and the results of this testing. Lastly, this report includes a discussion of what was learned through this project as well as recommendations for improvements on the current design.

2. Design Overview

2.1 Design Description

2.1.1 Overall Design

The pitching mechanism system (Figure 1) consists of several subsystems including the actuators, blade connection, and hub. The actuators subsystem consists of the two linear actuators, swashplate, and linkage arm. It initiates the motion for pitching from the linear actuator and carries this through to the blade connections. The blade connection subsystem is comprised of the blade spar, bearing, and blade spar root, and attaches the blade to the pitching mechanism, and converts the linear force to a rotation pitch moment. The hub subsystem consists of the hub and hub caps which hold the blade connection in place, as well as transmit the rotation
of the blades to the shaft. More details on the parts required, the part numbers and sourcing can be found in the project budget in Appendix C.

![Diagram of pitching mechanism system]

**Figure 1.** The full pitching mechanism system with visible components labeled.

2.1.2 Actuation subsystem

For initiating motion in the system, it was decided to use two linear actuators to prevent binding of the swashplate along the shaft (Figure 2), and the two HLS12-50380-6V Hitec Linear Servo work in tandem to push the non-rotational portion of the swashplate (Figure 3). This is connected to the rotation portion of the swashplate (Figure 4), connected to the linkage arms (Figure 5) to transmit force to each blade assembly.

![Diagram of actuation subsystem]

**Figure 2.** The actuation subsystem.
The non-rotational swashplate (Figure 3) connects to the linear actuator at the two M5 holes (Figure 3-3) by M4 shoulder bolts. There is a bearing press-fit into the inner diameter of the swashplate (Figure 3-2). This allows the non-rotational swashplate and rotational swashplate to interface with nominal friction losses while spinning above 4000 RPM. The lips on each side (Figure 3-1, 3-2) allow the mechanism to transmit axial force through the bearing without solely relying on the pressfit. The lip at one edge is created by the top plate, which is held in place by two M4 bolts (Figure 3-4).

![Figure 3](image)

**Figure 3.** The non-rotational swashplate.

Figure 4 is the rotational portion of the swashplate which allows the linear actuation to be transmitted to the spinning blades. The boss (Figure 4-1) is the same diameter as the inner diameter of the bearing that is pressed into the swashplate and threaded at the end with a nut (Figure 4-2) to hold it in place axially. The inner bore is a tight clearance fit to allow the rotational swashplate to slide axially along the shaft, and the D-feature will ensure it rotates at the same speed without requiring the linkage arms to carry shearing loads. The prong and hole (Figure 4-3) serves as an attachment point for the linkage arms, with one corresponding to each blade in the system.
Figure 4. The rotational swashplate.

Figure 5 is the design for the linkage arm, three of which are used in the design. The rotational swashplate is connected to the linkage arms using M3 shoulder bolts, which are also used on the other side to connect to the blade spar. It serves as one link in the four-bar slider-crank linkage used to convert linear motion of the actuator to rotational motion at the blade spar. The part is identical on each side to allow for easier assembly. The top hole is an M4 (Figure 5-2), while the bottom is a threaded M3 hole (Figure 5-3) for the shoulder bolt to fit into. The holes are countersunk (Figure 5-1) on one side to allow the head of the bolt to fit in to allow for clearance of the part’s motion as it rotates past the hubcap and blade. The gap in the middle (Figure 5-4) is a clearance fit to allow for a wide range of rotation at the pin joints with the rotating portion of the swashplate and the blade spar.

Figure 5. The linkage arm.
2.1.3 Blade Connection Subsystem

The blade connection subsystem (Figure 6) consists of the blade spar (Figure 6-1), bearing (Figure 6-2), and blade spar root (Figure 6-3). They work together to allow the blade to rotate within the hub. Additionally, they provide an attachment point for the blade to the pitching mechanism while providing additional strength to the blade. They are held together by a low profile M3 screw that is accessible via the base of the blade spar root. As the blade connection system is locationally, but not rotationally fixed, it serves as the pivot point for the blade to pitch (rotate) about.

![Figure 6. The blade connection subsystem.](image)

The goal of the blade spar (Figure 7) is to securely attach the blades to the hub without inducing large stress concentrations to the blades. Three blade spars are used, corresponding to the three bladed turbine this mechanism is for. The arm on the side of the blade spar (Figure 7-3) forms the final bar in the 4-bar slider crank linkage system, and connects to the linkage arm via the previously mentioned M3 shoulder bolts (Figure 7-4). The inner diameter of the bore on the base (Figure 7-6) will match the outer diameter of the blade spar root. Additionally, there is an M5 threaded hole at the bottom of the counterbore (Figure 7-7) that allows the blade spar root to fix to the blade spar. The outer diameter (Figure 7-2) matches the inner diameter of the through hole on the hub cap with a generous clearance fit. The flat portion of the spar (Figure 7-1) slides inside of the blades, allowing for transmission of the pitching torque from the mechanism. The threaded hole (Figure 7-5) allows a bolt to secure the blade from centrifugal forces, completing the secure attachment of the blades.
The blade spar root (Figure 8) partially enters the base of the blade spar and serves to hold and affix the bearing, allowing low friction pitching rotation. As expected, three of these are used in the pitching system. The hidden edges shown on the blade spar root (Figure 8) to illustrate the counterbore (Figure 8-2) as well as the M5 clearance hole (Figure 8-3) that will allow a low profile M4 bolt to connect the blade spar root to the blade spar. The diameter of the root (Figure 8-1) corresponds to a press fit size for the sourced bearing, and the shoulder (Figure 8-4) will locate the bearing. The bearing sits on a shoulder within the hub and is held down by the hub cap. The base of the blade spar root fits within a clearance hole in the hub.
2.1.4 Hub Subsystem

The hub subsystem secures the three blade connection subsystems and connects the mechanism to the shaft of the turbine to transmit torque. It consists of the hub and hubcap components.

The hub (Figure 9) transmits torque to the shaft via a ‘D’ feature (Figure 9-1). At the surface at the bottom of each large hole (Figure 9-4) the bearing sits, radially locating it. To reduce the weight of the hub, the holes for the blade spar root are extended all the way into the part (Figure 9-4). The three large M27 threads (Figure 9-2) are to attach the hub cap to the hub, allowing for easy assembly/disassembly. These are located as close to one another as possible, in addition to selecting a small bearing, to help minimize the diameter at the base of the blades. The holes (Figure 9-3) are used in manufacturing to locate the part.

![Figure 9. The hub.](image)

The design of the hub cap (Figure 10) racially constrains the blade connection subsystem by securing the top of the bearing. There are two flats (Figure 10-1) and an M27 thread (Figure 10-3) that will allow for a wrench to tighten the hub cap to ensure that it does not come loose due to the rotation or vibration of the system during operation. The center bore (Figure 10-2) will allow for the blade spar to pass through with clearance for rotation.
2.2 Design Function

The main function of this design is to pitch the rotating blades through a four-bar slider-crank linkage system that is initiated from stationary linear actuators. The linear actuators are operated with the turbines’s controls system (out of the scope of this project), which adjusts the actuation distance to achieve the desired pitch angle. The linear actuators push the non-rotational portion of the swashplate which transmits the linear activation to the rotation portion via a bearing. The swashplate moves axially along the shaft, and the rotational portion further pushes the linkage arms. The linkage arms are all pushed the same distance to ensure a consistent pitch angle is maintained between the blades. These are connected to the blade spars causing a rotation. This rotation occurs because the blade spars are connected to a ball bearing via the blade spar root which is constraining in the hub, allowing only for rotation of the blade spar. The hub cap holds the blade spars in the hub, and the hub transmits the torque generated by the blades to the shaft via a ‘D’ feature. The blades are connected to the blade spars through a slot in the blades that matches the geometry of the blade spar as well as an M3 bolt to secure the blade.

2.3 Design Changes Since CDR

There were four overall design changes since the critical design report. Two are related to manufacturability of the parts and two are related to assembly of the system. The width of the blade spar was increased for manufacturing purposes as they were initially too thin to fixture without major deflection. This also allowed the material of the blade spar to be switched from titanium to aluminum, which was much easier to machine. The next change was to the non-rotational swash plate. Since it was not manufactured on a CNC machine, the outside was changed to a square from the circular shape as seen above in Figure 3, as the outer profile is not critical and thus machining a circular profile was unnecessary. This change was not structural in any way, as such, the CAD was not updated to match the actual model. Both the hub and hubcaps had thread reliefs added to the bottom of their threads. This was done because the
threadmill used to machine the threads could not machine them as far down as needed. This prevents the linkage arms from aligning between the blade spar and rotational swashplate prior to the change.

3. Implementation

3.1 Procurement

Purchased materials include metal stock and off-the-shelf parts such as tooling, fasteners and bearings. The purchasing was done by the project sponsor, CPWP, for items selected by the team. The stock, fasteners, and bearings were purchased from McMaster-Carr. Most of the additional tooling needed was purchased from HAAS, and the electronic actuators were sourced from goBILDA. Further details on the exact material and pricing can be found in the project budget (Appendix C).

3.2 Manufacturing

3.2.1 CAM Programming

The manufacturing programming for all CNC manufactured parts was completed using the machining add-on in Fusion 360 to generate the appropriate G-code. The rotational swashplate, hubcaps, and lade spare all required 3-axis CNC machining for which no machine models or soft jaws were required. An example of one of the generated tool paths is shown in Figure 11 below.

![Figure 11. Tool paths generated in Fusion360 for the rotating swashplate.](image)
However, for the hub a HAAS VF2 with trunnion (5-axis CNC) was used which was fully modeled in Fusion 360 along with all the tools and tool holders that were used (figure 12). This was necessary to ensure that there were no collisions during the machining process, given the tight clearances involved.

![Figure 12. VF2 with trunnion machine model](image)

3.2.2 Machining Processes

The hub was manufactured on a HAAS VF2 with a trunnion attachment allowing for 5 axes to be used (Figure 13). This was by far the most complicated part to manufacture. Initially thread reliefs were not added to the hub so the part had to be rerun with this additional feature.

![Figure 13. Partway through hub manufacturing on the VF2 with trunnion.](image)
The hub caps and blade spars were made on a HAAS VF4 (Figure 14). The spars were initially made out of titanium but after making design changes and breaking a carbide tap in one of the spars, it was determined that with some minor redesign they could be made out of aluminum. Like the hub, the hub caps did not initially contain thread reliefs and had to be rerun with the addition of thread reliefs to allow them to screw all the way down on the hub.

![Figure 14. The blade spars part way through manufacturing.](image)

The rotating part of the swashplate was made on a HAAS Super Minimill and the 3 holes to connect to the linkage arms were drilled on a manual mill using a rotary vise (Figure 15).

![Figure 15. The rotational swashplate partway through manufacturing, scrapped due to incorrect Y axis offset.](image)

The non-rotational swashplate was made on a Bridgeport manual mill.
The swashplate bearing cap was made on a waterjet since tolerances were not critical, and it is a flat part.

The blade spar roots were made on a manual lathe.

The linkage arms were made on a Bridgeport manual mill. During manufacturing all the holes were drilled at the same time from a single block of aluminum to ensure the distances between the two holes in the linkage arms are all the same as shown in Figure 16.

![Figure 16. Manufacturing of the linkage arms on a manual mill, with the holes drilled and before separating the arms.](image)

Several of the fasteners were shortened on a grinding wheel to meet our small size requirements.

3.2.3 Tolerancing and Fits

To ensure that all components fit together seamlessly, wear offsets were utilized in the CAM programming for all critical features. Wear offsets were applied to all bearing fits and thread milling operations. This offsetting technique enables the machinist to adjust the tool's theoretical diameter being used for machining a feature. This will cause the machine to think the tool is slightly larger or smaller than it is in reality, allowing for making the feature larger or smaller as needed. The process involved incrementally adjusting the wear offset by .001 of an inch until the desired fits were achieved with the corresponding components. Without the use of wear offsets, the project would not have fit together as precisely as it does.

Due to the thickness of the treadmill used, the threads could not be milled as deeply as they were modeled in CAD. To resolve this issue, thread reliefs were milled into both the hubcap and the hub. This solution eliminated the fitting problem and allowed the blade spars to sit at the intended depth. As a result, all three linkage arms were able to align correctly with the rotating swashplate.
3.3 Assembly

The first step of assembly was press fitting all the bearings in the mechanism: to the blade spar roots and the non-rotational portion of the swashplate. Next the blade spars were attached to the blade spar roots with their respective bolts and the hubcap held in between the linkage arm and the bearing. The blade spar subassembly was then attached to the hub by screwing down the hubcap. For the swashplate subassembly the plate was attached to the back of the non-rotational swashplate with four bolts. Next the bearing on the non-rotational swashplate was fit over the rotational swashplate and secured in place with the bearing nut.

![Figure 17. The bearing press fit onto the blade spar roots.](image)

The rest assembly of the components was done on the CPWP turbine, as the shaft is required for proper alignment of the components. The swashplate subassembly was placed on the shaft, taking care to align the D features, with the rotating portion facing the front of the turbine. Next the hub was placed on the shaft, and secured with a snap ring in the appropriate groove on the shaft. The linkage arms were then attached between the prongs of the rotation swashplate and the taps on the blade spars, with the shortened fasteners used for the blade spar connection while ensuring all the spars were pitched in the same direction. The final step of the assembly was to attach the linear actuators. These were first attached to the baseplate in the nacelle of the turbine. The front of the actuation arm was then attached to the pitching mechanism at the non-rotational swashplate.

To attach the blades to the mechanism, the blade spar was inserted into the hole in the blade such that the leading edge of the blade faces forward. The blade spar screw was then used to fix the blade to the spar through the hole in the side of the blade and spar.
For the final assembly of the mechanism, the bolts used to attach the linkage arms were secured in place using blue loctite, to ensure they do not loosen as a result of vibrations during operation. Furthermore, care was taken to ensure they are not overtightened and still allow for free range of motion of the mechanism.

![Figure 18. The fully assembled pitching mechanism.](image)

### 3.4 Software and Electronics

The pitching system is powered using two linear actuators. These are controlled using an Arduino Uno microcontroller. While the control and operation of the mechanism for turbine operation were initially out of the scope of this project, basic code was produced to showcase the functionality of the mechanism. This included a code that ran on user input to actuate a specified distance (Appendix D). These are not intended to be the final code, but rather to verify the functionality of the mechanism, and as a starting point for the sponsor to understand the functionality of the system and incorporate the pitching into a more sophisticated turbine control system.
4. Design Verification

4.1 Specifications

In order to verify our design meets or exceeds the desired function set forth by the sponsor, a list of design specifications was generated (Table 2). These specifications were verified with experimental tests, or through inspection depending on the nature of the specification. More details on the experimental tests can be found in the design verification plan table (Appendix E), and complete test procedures can be found in Appendix F.

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Specification Description</th>
<th>Target Value</th>
<th>Verification type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pitch Angle Range</td>
<td>45 [deg]</td>
<td>Test (#1)</td>
</tr>
<tr>
<td>2</td>
<td>Base Circle Radius</td>
<td>3 [cm]</td>
<td>Inspection</td>
</tr>
<tr>
<td>3</td>
<td>Axial Depth</td>
<td>7 [cm]</td>
<td>Inspection</td>
</tr>
<tr>
<td>4</td>
<td>Weight</td>
<td>50 [g]</td>
<td>Inspection</td>
</tr>
<tr>
<td>5</td>
<td>Axial Blade Load Strength</td>
<td>9 [N]</td>
<td>Test (#2)</td>
</tr>
<tr>
<td>6</td>
<td>Blade Torque Strength</td>
<td>.5 [Nm]</td>
<td>Test (#3)</td>
</tr>
<tr>
<td>7</td>
<td>Actuator Strength</td>
<td>40 [N]</td>
<td>Test (#6)</td>
</tr>
<tr>
<td>8</td>
<td>Actuator Voltage</td>
<td>5 [V]</td>
<td>Inspection</td>
</tr>
<tr>
<td>9</td>
<td>Pitch Angle Accuracy</td>
<td>3 [deg]</td>
<td>Test (#4,7)</td>
</tr>
<tr>
<td>10</td>
<td>Blade Switch Time</td>
<td>15 [s]</td>
<td>Test (#5)</td>
</tr>
<tr>
<td>11</td>
<td>Mate with Shaft</td>
<td>pass/fail</td>
<td>Inspection</td>
</tr>
</tbody>
</table>

Test #1: For the first specification, the pitch angle range, the experimental test is to verify that the mechanism can pitch 45 degrees. This is performed by using the mechanism in combination with the club turbine and pitching control system to measure the pitch angle at the start and end of the linear actuator range using an optical comparator in the metrology lab.
The second, third, and fourth specifications: base circle diameter, axial depth, and weight respectively, are verified by inspection. These are values that are measured from the verification prototype after manufacturing is complete using calipers and a balance.

Test #2: The fifth specification, axial blade load strength, is tested using static blade spar testing. This was performed using a testing fixture and adding load by way of masses hung from the blade attachment hole. This verifies that the blade spar is strong enough to withstand the expected loading by the turbine.

Test #3: The blade torque strength, specification 6, is another experimental test. A testing fixture is used to fix the blade spar in a vice. A moment arm is attached to the blade spar, and masses are attached to apply the torque load to the blade spar and verify strength.

Test #6: The seventh specification, actuator strength, is tested by affixing masses of various sizes to the linear actuator. While affixed in a vertical position the actuator’s ability to move the mass and the speed at which it does so was tested.

The actuator voltage, specification 8, is determined by inspection by measuring the input voltage required to run the actuators.

Test #4: The pitch angle accuracy, specification 9, is verified with an experimental test and corresponding data analysis and error propagation calculations. To perform this test a functional turbine drivetrain and linear actuator code from CPWP are required, as well as an optical comparator available in the metrology lab. This test is performed by entering a pitch angle into the code and verifying the output pitch angle of the turbine blade using the optical comparator.

Test #5: Specification 10, the blade switch time, will be verified by testing done with volunteer participants who have not seen the pitching mechanism before. They are asked to switch a blade (providing them with all the tools required, but no additional prompting). This action is timed and repeated several times to ascertain the amount of time it takes to switch a blade for someone unfamiliar with the mechanism, as well as once the participant learns how it works. To ensure compliance with the goal of the test, it will be phrased as a competition and a menial prize will be awarded to the winner to encourage motivation.

Specification 11, mating with the shaft, is verified by inspection when the pitching mechanism is assembled on the turbine. This is a pass/fail test, depending on whether or not it fits securely and allows for the transmission of torque from the hub to the shaft.

4.2 Testing and Results

The tests above were performed and a complete summary of the results can be found in the DVPR (Appendix E).
The pitch angle minimum adjustment was validated. It was determined that using the actuators’ constrained motion of 12.6mm, the blades can be pitched over a range of 48 degrees.

Four of the five specifications to be verified by inspection all passed. The base circle radius measured 2.98 cm, less than the allowed 3 cm, and the axial depth of the assembly fits within the allowed 7 cm. The total mechanism has a mass of 270 grams, which is above the target weight, but was as small as the team could physically manufacture. The actuator voltage requirement was verified when performing test #4, when the actuator could be operated using a similar 5V Arduino to what will be employed in the integration with the turbine. The ability of the mechanism to mate with the shaft was confirmed by sliding the pitching mechanism onto the shaft, where it fit.

Two of the tests, #2 and #3, validated the strength of the blade spars to ensure their capability to withstand the loading that they will experience during turbine operation. From blade simulation, the predicted loading was applied to each of the spars as described above, and then the spars were loaded beyond the requirement to provide a factor of safety and confidence that they will remain intact should unexpected conditions arrive. Sample spars were loaded to the extent of our capability using the resources available and reached loads of greater than 30N axially and 1.5Nm in torsion, which earned the design an experimental safety factor of greater than 3 for both loading conditions (Figure 19). The quantity of loading available meant that the spars could only be tested up to this capacity, though no permanent deformation had been achieved. In the future, access to more robust testing equipment could be employed to determine the limits of the spars and provide a concrete maximum safety factor, but for the sake of this project, the spars met the criteria.

One of the requirements to perform the pitch angle accuracy validation, Test #4, was functional code provided by the sponsor. Due to circumstances out of the team’s control, the code for the actuators was not provided, so the test was modified. The actuation distance of the actuators was coded and measured instead. An uncertainty analysis of the input to the expected traveled
distance showed that the average variance from the target value is approximately two millimeters. Additional tuning and testing should be employed to refine this value.

Once the distance capability of the actuators was confirmed, it was verified that they would be able to overcome the forces applied back by the blades to change or maintain position. Using the hanging mass method described above, the actuators were each able to lift 5kg and maintain their position under such loading (Figure 20). The operation of the actuators was not affected by the mass, which provided a 49N load. Using this load, the actuator strength has a safety factor of greater than 1.2. As with the blade loading, a wider range of test equipment could be used to push the actuator to failure for a more accurate safety factor, but the actuators meet and exceed the requirements for this project.

![Figure 20. Strength testing of the linear actuator.](image)

The small competition for the blade switch test was carried out with CPWP members not belonging to the senior design team. The average time needed for a first attempt, having never used the mechanism before, was 35 seconds. However, it took the average contestant only four attempts to switch a blade in under 15 seconds. The mechanism is considered to meet this specification. During the course of this test, suggestions were also made for the type of equipment used for those doing the blade switching. After the test, a larger screwdriver was employed for switching blades and was well received by those performing the action.

With CPWP, the pitching mechanism was tested as a part of the whole turbine in wind tunnels on campus and at the CWC. In testing on campus, the pitch angle was varied while holding the turbine’s load and the wind speed constant. The graph in Figure 21 shows the variation in power
produced at varying pitch angles using the team’s mechanism at a constant wind speed and load. The change in power production based on pitch angle validates the necessity, usefulness, and effectiveness of this project when integrated to the CPWP system. Additionally, during the testing at the CWC, the larger, competition-specific wind tunnel subjected the turbine and mechanism to higher loading cases than produced on campus. During this event, the pitching mechanism was validated at wind speeds up to 22 m/s and 4500 RPM. Under these conditions, the mechanism did not fail or show signs of strain or wear. Furthermore, the blades did not break under these conditions, which validated the strength added by the blade spars.

![Power Production at 5 m/s .5 Ohm](image)

**Figure 21.** Wind tunnel testing data showing the change in power production due to a change in pitch.

5. Discussion and Recommendations

5.1 Discussion

One of the biggest challenges of this project was the size of the components. In the first quarter, most of the work designing was done in CAD with no physical parts or models. As such parts were perceived as larger than they actually were. When the design was 3D printed at the end of the fall quarter, we realized that there were some major redesigns needed. Mainly due to the inability to source screws in the sizes and dimensions that were needed. Screws were then sourced and the affected components were redesigned around the screws. We also adjusted some parts for manufacturability. This reinforced the importance of building higher validity prototypes sooner, to get a better sense of the scale of the design and interface between parts.

Another design challenge during this project was working to interface with other parts of the turbine before those designs were finalized, so the design parameters kept changing. While this
did allow for flexibility in making changes from both sides, sometimes we were using outdated values when designing or were unsure of the sizing of certain mating components. We found that having effective communication channels with those working on the adjacent components was helpful in navigating this.

5.2 Recommendations and Next Steps

Our recommendation for future use of the pitching mechanism by the CPWP club is to use the same physical components as much as possible. They are designed to be durable and outlast the one-year lifespan of the turbine. It is recommended that future shafts and blades be designed to interface with the current mechanism, details for which can be found in the user manual (Appendix A) along with more detailed instructions for using the mechanism. One aspect of the design that we do recommend changing and remanufacturing, if necessary, is the non-rotational swashplate. This will allow for different actuator positions and accommodate future turbine developments. Furthermore, we believe that the manufacturing of this part is within the club’s capabilities. By incorporating a more flexible and adaptable swashplate design the CPWP club could have more options when deciding how to upgrade our design and make it work with future competitions.

The other recommended next step for this project is to incorporate the pitching mechanism into a passive control system for the wind turbine. While this was outside the scope of our project, it is a crucial part of utilizing this mechanism effectively. The control system provided by this project requires manual inputs from a computer (code in Appendix D), but ideally, a control system would ensure the blades are pitched at the cut-in angle prior to initiation of rotation, then optimize power production up to levels corresponding to 11 m/s, and then pitch to reduce the effectiveness of the blades to maintain those power production levels at higher wind speed. Such a control system would likely be based on rotational speed, voltage, and current information collected from the generator, in addition to specific set points collected from experimental testing. If a variable load gets incorporated into the turbine's electronic design, the optimization of these variables would have to be synchronized during operation. This would result in a slightly more complex control system, but greatly increase the potential power output over a range of conditions. It is also recommended that the club allocate ample time for designing and testing the turbine control system, to ensure proper function and refinement of the system.

Another recommended improvement is replacing the snap ring used to secure the hub with a more secure attachment mechanism. While the general wind force pushes the hub back, in testing due to vibrations and fluctuating load we found that sometimes this came loose. Potential ideas to explore include a retaining nut, or configuring the nose cone to push on the hub.

Broadening the scope of potential future improvements, it would be worthwhile to investigate single linear actuator options. By exploring alternative actuator mechanisms we can potentially
simplify the control system and reduce the power draw of the pitch adjustment mechanism. Using a single linear actuator would eliminate the problem of actuator synchronization. However, this option would require more research into how to prevent binding from uneven driving force distribution.

6. Conclusion

We take immense pride in the wind turbine pitching mechanism that we designed, manufactured, tested, and delivered to the CPWP club for their participation in the Collegiate Wind Competition. Throughout this journey, we are grateful for the unwavering support we received from our senior project coach, Ramanan Sritharan, our project sponsor Trevor Ortega, and the esteemed professors who have played a pivotal role in shaping us into the proficient mechanical engineers we are today.

Our team has successfully provided the CPWP club with a robust pitching mechanism that will serve them well for years to come. We have taken care to thoroughly explain the intricacies of our design to the continuing members of the club, enabling them to refine and enhance our work for future competitions. While there is undoubtedly further progress to be made, the senior project team is committed to remaining a valuable resource for the CPWP club. We are eager to assist in perfecting the design and ensuring its continued success.

While we accomplished a great deal, it is essential to acknowledge what we were unable to achieve. One aspect that remained incomplete was the full implementation of the feedback control system. We were unable to integrate with dynamic internal control capabilities that would adjust the pitch based on rotor RPM and power production. Additionally, our system’s flexibility and usability could be improved with future research into a redesigned swashplate with single actuator control.

We are pleased to announce that our results will be made publicly available, serving as a valuable resource for any educational institution participating in the Collegiate Wind Competition. By sharing our findings, we aim to foster collaboration, innovation, and advancement within the wind power community.
References


[6] Development of swashplateless helicopter blade pitch control system using the limited angle direct-drive motor (LADDM)


[23] Reduction of Helicopter Blade-Vortex Interaction Noise By Active Rotor Control Technology


Appendix

Appendix A: User Manual

This guide is meant to be an overview for the Cal Poly Wind Power club to operate the pitching mechanism, and continue to use it in future years with future turbine designs. Further details on the function and operation of the mechanism can be found in the Final Design Report, but this provides a good starting point to become familiar with the mechanism.

A.1.0 Safety Hazards

The main safety hazard of the pitching mechanism is pinch points. During blade installation be careful not to pinch between the blade and the spar. During pitching, take care not to pinch between the moving swashplate and the shaft and at all of the pin locations on the linkage arms (Figure A.1). When rotating, people should not be near the mechanism as the portions of the mechanism will move at high velocities and could cause damage.

Figure A.1. Potential pinch points
A.2.0 Overview of Design and Repairability

A.2.1 Physical System

Figure A.2. Labeled components in the pitching mechanism. Overall the pitching mechanism works through a four-bar linkage system in combination with a swashplate. The motion is initiated by the two linear actuators. The actuators used are the Hitec Linear Servo (part number: HLS12-50380-6V) if they are damaged and need to be replaced. The pins from these actuators are ground, power, and signal as shown in Figure A.3. The linear actuators are attached to the swashplate using M3 bolts. The team has provided some M3 shoulder bolts, however, due to the tight fit with the hole in the actuators this would require a larger outer hole in the non-rotational swashplate and increase installation time, so it is up to future teams if they prefer this over a standard threaded M3 bolt.

Figure A.3. Linear actuator pin connections (from the linear actuator spec sheet, and turbine respectively)
The non-rotatational swashplate, and press-fit bearing, is the only component recommended to remanufacture if the club desires. This part is relatively simple to manufacture on a manual mill, and additionally, future turbines might want to space the linear actuators differently within the nacelle which would require a slight redesign of the part. Additionally, if the turbine is not stored in careful conditions the swashplate bearing, housed within the non-rotational swashplate might need to be replaced. If the team wishes to replace the non-rotational swashplate, it is recommended to maintain the same inner diameters, as well as thicknesses, labeled in Figure A.4. Note that while most of these dimensions should remain the same, the 2 mm edge thickness is a minimum, this could be thicker for manufacturability.

![Critical Non-rotational swashplate dimensions](image)

**Figure A.4.** Critical Non-rotational swashplate dimensions

The outer profile can change, as long as it does not interfere with blade pitching, and the linkage arm slots can be placed wherever needed to accommodate their location within the nacelle. Depending on the outer profile of the new non-rotational swashplate, a new swashplate cover might need to be manufactured. Also, the bearing used by the club is the McMaster-Carr 5972K311, which will need to be press-fit into the new non-rotational swashplate component.

The non-rotational swashplate is secured to the rotational swashplate by an M16x1.5 bearing nut. The linkage arms are attached to the swashplate by an M2.5 shoulder bolt, and extra shoulder bolts and an extra linkage arm have been provided to the club. The linkage arms attach to the blade spar with the same shoulder bolt, although the tip of the bolt has been slightly ground down to prevent interference with the hubcap (and an extra of this shortened bolt has also been provided). The linkage arm bolts are all secured in place using blue Loctite to prevent loosening due to vibrations, and if they are disassembled or replaced this should be cleaned off and then reapplied before testing with an operating turbine.

The blade spars are held into the hub with the hubcap, which is hand threaded into place. Below the blade spar, it is attached to the blade spar root using an M5 bolt with a narrow head, and the blade spar root is press fit onto the blade spar bearing. It is not recommended to disassemble this
if it can be avoided, but if necessary, the hubcap needs to be placed between the blade spar bearing and the blade spar, before the blade spar and blade spar root are bolted together. The club has also been provided with an extra blade spar.

To attach the blades to the blade spar, an M5 bolt is used. Spares have been provided to the club. This bolt is to be ground down such that the face does not protrude from the surface of the blade, and this might vary with future blades requiring a slightly different bolt length.

A.2.2 Control System

For operating the pitching mechanism, in the current setup, the limits for the linear actuator are 1230 and 1500 in the control system code. This correlates to pitch angles of 43° and 0°, respectively. Operating out of these bounds can damage the mechanism. Designing the control system is outside of the scope of this project, but some sample code for interfacing with the mechanism can be found in Appendix D. This mechanism is designed to be operational when the turbine is both stationary and rotating. No binding between the shaft and swashplate has been observed, but if this becomes an issue in the future, lubricants, such as graphite can be used.

A.3.0 Designing to interface with the mechanism

A.3.1 Interfacing with a shaft

This hub of the pitching mechanism is designed to interface with an 8 mm shaft with a 2.5 mm D feature as pictured in Figure A.5. The hub should be axially secured on both sides, the current solution for which is a step on the nacelle side and a snap ring on the nose cone side. These two axial locators should be 30 mm apart. When installing the hub on the shaft, the side with filets around the D should be facing the nacelle/step. The swashplate is designed to interface with a 10 mm shaft with a 3.79 mm D feature as pictured in Figure A.6. It is also recommended to end the D feature to create a hard stop for the mechanism and prevent damage to the rest if it happens to be actuated too far. When manufacturing the shaft it is desirable for the surface finish on the portion that interfaces with the swashplate to be as smooth as possible (and for corners to be filed off), to allow for smoother movement of the mechanism.

The actuator limits described above are constrained by a step in the current shaft to protect the turbine. In the future, the step in the shaft could be moved back up to another half centimeter to increase the pitch range.
A.3.2 Interfacing with the blades

The pitching mechanism connects to the blades by the blade spar entering a slot in the blades and held in place with a short screw. The dimensions of the spar are 12 mm x 3.5 mm x 25 mm, but it is recommended for the 3D printed blades for the hole to be 12.25 mm x 3.71 mm x 28 mm (Figure A.7). This allows for a tight fit between the blade and the spar once some carving is done to clean up the edges/corners. The aluminum spar and wood block provided are useful for this process. The location of the hole with the screw should be 17 mm from the root of the blade, located in the center of the spar. The hole should be 5.75 mm with a 7.5 mm hole for the countersink. Ideally, the center of the spar hole should be centered over the quarter chord of the blade since this is approximately the aerodynamic center of the blade and thus will have minimal moments. The center spar is not centered over the axis of rotation, but instead has been moved
up 2.1 mm and left 1.5 mm, as shown in Figure A.8. Additionally, the spar is angled to aid in achieving the optimal pitch angle.

**Figure A.7.** Blade spar sizing (Blade spar, and print hole)

**Figure A.8.** Blade Spar center location (to the center axis of rotation, and quarter chord on this year’s blade design respectively). Not that both these perspectives are looking at the root of the blade with the tip further into the page.

With the above limits to the linear actuators, the angles the spar can travel to are from 0 to 43 degrees. For the current blades, the spar hole was angled a further 4 degrees from the chord, as shown in Figure A.9, however, it is recommended in future years to increase this angle by 10 degrees to allow for testing at lower pitch angles (current testing showed optimal power production near the end of the current range), or by increasing the distance the swashplate can move back since the linkage arms could be extended further than the current configuration (however care must be taken that the linkage arm to blade spar connection never reaches its maximal extension as this can cause the mechanism to flip and pitch the opposite direction when moving forward again). It is also important to note that pitch angle is measured from the tip airfoil, and the blade spar connects to the root airfoil, so the chord twist of the blade must be taken into account when calculating the blade spar to pitch range.
Figure A.9. Blade Spar Angle, looking at the root of the blade with the tip further into the page.
## Appendix B: Risk Assessment

<table>
<thead>
<tr>
<th>Item ID</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity</th>
<th>Probability</th>
<th>Risk Level</th>
<th>Risk Reduction Methods / Control System</th>
<th>Final Assessment Severity</th>
<th>Probability</th>
<th>Risk Level</th>
<th>Status / Responsible / Comments / Reference</th>
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</thead>
<tbody>
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<td>1-1-1</td>
<td>Testing user Assembly</td>
<td>mechanical: pinch point, distortion components together</td>
<td>Minor</td>
<td>Unlikely</td>
<td>Negligible</td>
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<td>Unlikely</td>
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<td>Moderate</td>
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### Appendix C: Final Budget

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<th>Link</th>
<th>Quantity</th>
<th>Internal Part #</th>
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<th>Shipping &amp; Tax</th>
<th>Total Cost</th>
<th>How Purchased</th>
<th>CPWP Account Used</th>
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<th>Location</th>
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**Notes:**
- CPWP purchase: totals spent on date 7/1/13
- Total spent to present: 7/1/13
Appendix D: Arduino Code

```cpp
#include <Servo.h>

Servo hls12_590;

void setup() {
    hls12_590.attach(9);  // attach the servo to pin 9
}

// The minimum is 1275, the maximum is 1500, and it should be linear in between
void loop() {
    // move the servo to the specified length
    hls12_590.writeMicroseconds(1200);  // adjust the value for your specific servo
    delay(10000);
}
```
## Appendix E: Design Verification Plan and Report (DVPR)

<table>
<thead>
<tr>
<th>Test #</th>
<th>Specification</th>
<th>Test Description</th>
<th>Measurements</th>
<th>Acceptance Criteria</th>
<th>Required Facilities/Equipment</th>
<th>Parts Needed</th>
<th>Responsibility</th>
<th>TIMING</th>
<th>NOTES ON TESTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45 degree pitch angle range</td>
<td>Test max and min linear actuation input and measure corresponding blade spar angle</td>
<td>Blade spar angle</td>
<td>45-50 degrees</td>
<td>Functional linear actuator control system (position) + optical comparator=angular</td>
<td>available in metrology lab</td>
<td>Elizabeth</td>
<td>5/13/2023</td>
<td>Will the actuator reliably deliver the specified angles to the blade spar?</td>
</tr>
<tr>
<td>2</td>
<td>Axial blade spar strength</td>
<td>Multi-blade spar testing</td>
<td>Applied load, deflection</td>
<td>No failure</td>
<td>Functionality in high stresses/low loads</td>
<td>bore testing fixture</td>
<td>Josephine</td>
<td>4/20/2023</td>
<td>All spars were capable of withstanding greater than 20kN, giving a safety factor greater than 3 under operating conditions.</td>
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<tr>
<td>3</td>
<td>Torsional blade spar strength</td>
<td>Modified torque wrench</td>
<td>Applied load, deflection</td>
<td>No failure</td>
<td>Functionality in high stresses/low loads</td>
<td>Flex stock</td>
<td>Josephine</td>
<td>4/20/2023</td>
<td>The blade spars are stiffer enough to maintain the loads applied by the blades and wind loading.</td>
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<tr>
<td>4</td>
<td>Pitch angle accuracy</td>
<td>Nut mechanism code in optical comparator to check validity of pitch angle</td>
<td>Linear actuator code + blade spar angle</td>
<td>0.1 degree</td>
<td>Optical comparator = pitch angle</td>
<td>available in metrology lab</td>
<td>Elizabeth</td>
<td>5/2/2023</td>
<td>The nut mechanism code was able to generate a code to control the actuator based on the desired pitch angle.</td>
</tr>
<tr>
<td>5</td>
<td>Blade switch time</td>
<td>Competition between people who have been trained on the laser beam position before to see how long it takes them to switch blades (first time, and after several times)</td>
<td>Time</td>
<td>15 seconds</td>
<td>Performance of operator</td>
<td>Blade switches</td>
<td>Josephine and Elizabeth</td>
<td>4/25/2023</td>
<td>After 10 tests, all participants were able to switch a blade in under 15 seconds.</td>
</tr>
<tr>
<td>6</td>
<td>Linear Actuator Force</td>
<td>Test the strength of the linear actuators by testing the ability to dispense different forces</td>
<td>Mass</td>
<td>up to 5 kg</td>
<td>Linear actuator code</td>
<td>None</td>
<td>Josephine</td>
<td>3/27/2023</td>
<td>Successfully loaded 5 kg.</td>
</tr>
<tr>
<td>7</td>
<td>Linear Actuator Displacement Accuracy</td>
<td>Set the actuator to specific displacements and measure the actual displacement</td>
<td>Displacement</td>
<td>within 2 mm of specified displacement</td>
<td>Linear actuator code</td>
<td>None</td>
<td>Josephine</td>
<td>3/27/2023</td>
<td>See results spreadsheet. Displacement was accurate, but the code to set the displacement is incorrect.</td>
</tr>
</tbody>
</table>

The test results indicate that the system meets the specified requirements and is capable of delivering accurate pitch angles and forces as well as maintaining the necessary stiffness and strength under operating conditions. Further testing may be needed to address any issues identified in the notes on testing.
Appendix F: Test Procedures

Test #1: Pitch Angle Range Test

Purpose:
- To determine the pitch angle range of the mechanism
- To verify that the system can pitch at least 45 degrees

Scope:
- Verifies the function “pitch the blades”
- Verifies the pitch angle range is at least 45 degrees

Equipment:
- Optical comparator
- TIPSY completed mechanism, assembled and attached to corresponding turbine locations
- CPWP Shaft
- CPWP Baseplate
- Control system on connected computer

Diagram of apparatus:

Hazards:
- Minor electrical hazard if linear actuators are incorrectly connected
- Pinching concerns from the rotation of the spars and the movement of the actuators
PPE Requirements:

- Safety glasses

Facility:

- Mustang ’60 Metrology Lab

Procedure: (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Affix the pitching mechanism and position the optical comparator to the blade spar
2) Set the pitching mechanism to the minimum pitch value and measure the x and y coordinates of two corners of the blade spar and use this as the baseline value
3) Increase the angle to the maximum pitch angle and measure the corresponding x and y coordinates of the same two corners.
4) Using the coordinates collected at each angle, determine the slope of the blade spar
5) Use the slopes to determine the angle of the blade spar and record in the data sheet.
6) Calculate the pitch range by subtracting the angles from one another.

Results:

Pass Criteria: The pitch range is at least 45 degrees

Fail Criteria: The pitch range is less than 45 degrees

Number of Samples to Test: one blade spar

Design Analysis Equations/Spreadsheet:

- Convert the x and y values collected to angles using trigonometry based on the difference in slopes
- Subtract the min from the max to calculate range

Test Date(s): April 13, 2023

Test Results: Test results will be collected in this spreadsheet.

Performed By: Josephine
Test #2: Axial Blade Load Strength Test

Purpose:
- To ensure there is no egregious deflection in the blade spar during loading
- To verify that the blade spars can withstand the expected loads during worst case operation conditions, with a safety factor

Scope:
- Verifies the function “withstand wind loads”
- Verifies the strength at 9N (at root equivalent moment)

Equipment:
- Blade Spar
- Masses
- Jig to hold blade spar
- Clamp to affix jig to worksurface
- Calipers
- Optional: Moment arm extension

Diagram of apparatus:

Hazards:
- Minor hazards if masses drop when affixing
- Minor hazard with pinch points when setting up and attaching masses
- Moderate hazard if the spar breaks during testing

**PPE Requirements:**
- Safety glasses

**Facility:**
- Josephine’s House

**Procedure:** (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Affix the blade spar to the testing jig, and secure the jig to the work surface with a clamp
2) Hang a mass from the hole in the blade spar and measure the distance to the root (attempt to hang the mass such that it does not introduce a torsional moment, or alternate hanging masses on each side)
3) Gradually add additional masses, and observe for any visible deflection, and record each successful additional mass in the results spreadsheet
4) Add mass until the calculated moment (in the results spreadsheet) exceeds the target moment.

**Results:**
- **Pass Criteria:** the spar can withstand the 9N loads, and there is not visible deflection at this weight
- **Fail Criteria:** the spar breaks at or below 9N of force, or there is visible deflection in this range
- **Number of Samples to Test:** one blade spar

**Design Analysis Equations/Spreadsheet:**
- Convert the attached mass to a moment value
- Compare the moment value to the target moment

**Test Date(s):** March 27, 2023

**Test Results:** Test results will be collected in this spreadsheet.

**Performed By:** Josephine
Test #3: Blade Torque Strength Test

Purpose:

- To ensure there is no additional pitching caused by bending of the spar
- To verify that the blade spars can withstand the expected loads during worst case operation conditions, with a safety factor

Scope:

- Verifies the function “withstand wind loads”
- Verifies the strength at 9N (at root equivalent moment)

Equipment:

- Blade Spar
- Masses
- Jig to hold blade spar
- Clamp to affix jig to worksurface
- calipers
- Moment arm extension

Diagram of apparatus:

![Diagram of apparatus](image)

Hazards:

- Minor hazards if masses drop when affixing
- Minor hazard with pinch points when setting up and attaching masses
- Moderate hazard if the spar breaks during testing

PPE Requirements:

- Safety glasses

Facility:

- Josephine’s House
**Procedure:** (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Affix the blade spar to the testing jig, and secure the jig to the work surface with a clamp
2) Place the moment arm over the blade spar, and affix a loop to the hole at the end of the moment arm
3) Measure the length of the moment arm and add to the data sheet to convert masses to moments
4) Hang a mass from the loop at the end of the moment arm
5) Gradually add additional masses, and observe for any visible deflection, and record each successful additional mass in the results spreadsheet
6) Add mass until the calculated moment (in the results spreadsheet) exceeds the target moment.

**Results:**

Pass Criteria: the spar can withstand the .5 Nm loads, and there is not visible deflection at this weight

Fail Criteria: the spar breaks at or below .5 Nm of force, or there is visible deflection in this range

Number of Samples to Test: one blade spar

Design Analysis Equations/Spreadsheet:

- Convert the attached mass to a moment value
- Compare the moment value to the target moment

**Test Date(s):** March 27, 2023

**Test Results:** Test results will be collected in [this spreadsheet](#).

**Performed By:** Josephine
**Test #4: Pitch Angle Accuracy Test**

**Purpose:**
- To determine a correlation between the pitch angle input to the code and the actual output angle of the blade spar achieved by the actuator
- To verify that the system can pitch to the desired angles within the tolerance

**Scope:**
- Verifies the function “pitch the blades”
- Verifies the tolerance of ±1°

**Equipment:**
- Optical comparator
- TIPSY completed mechanism, assembled and attached to corresponding turbine locations
- CPWP Shaft
- CPWP Baseplate
- Control system on connected computer

**Diagram of apparatus:**

**Hazards:**
- Minor electrical hazard if linear actuators are incorrectly connected
- Pinching concerns from the rotation of the spars and the movement of the actuators
PPE Requirements:

- Safety glasses

Facility:

- Mustang '60 Metrology Lab

Procedure: (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Affix the pitching mechanism and position the optical comparator to the blade spar
2) Set the pitching mechanism to 0° and measure the x and y coordinates of two corners of the blade spar and use this as the baseline value
3) Increase the angle in the control system by increments of 5° up until 45° is reached. For each increment, measure the corresponding x and y coordinates of the same two corners.
4) Using the coordinates collected at each angle, determine the slope of the blade spar
5) Use the slopes to determine the angle of the blade spar and compare to the input angle
6) Repeat this process 3-5 times (as time allows) without zeroing the mechanism, but alter approaches to each angle from below and above the target value

Results:

Pass Criteria: all calculated angles for all target angles are within ±1° of the target angle

Fail Criteria: at least one of the trials for one of the target angles has an angle out of tolerance

Number of Samples to Test: one blade spar

Design Analysis Equations/Spreadsheet:

- Convert the x and y values collected to angles using trigonometry based on the difference in slopes
- Calculate the average output angle for each input and the deviation from the input angle
- Compare how error changes when approaching from above or below
- Perform uncertainty calculations

Uncertainty Analysis: The uncertainty analysis will account for resolution of the measurement of the x and y locations and the calculations done to convert them from position measurements to angles.

Test Date(s): April 13, 2023

Test Results: Test results will be collected in this spreadsheet.

Performed By: Josephine
Test #5: Blade Switch Time Test

Purpose:
- To determine if the blades can be switched quickly by someone not familiar with the mechanism

Scope:
- Verify specification 5: switch a single blade in under 5 seconds.

Equipment:
- Blade Spar
- Jig to hold blade spar
- Clamp to affix jig to worksurface
- Blade
- Blade Screw
- Screwdriver

Diagram of apparatus:

Hazards:
- Minor hazards if masses drop when affixing
- Minor hazard with pinch points when setting up
- Minor hazard with sharp corners of blade spar

PPE Requirements:
- Safety glasses

Facility:
- Josephine’s House
**Procedure:** (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Affix the blade spar to the testing jig, and secure the jig to the work surface with a clamp
2) Attach the blade to the spar
3) Provide the participant the screwdriver and ask them to remove the blade and attach it again as fast as they can
4) Time the participant as they switch the blade
5) Have the participant repeat 3-4 10 times
6) Repeat 3-5 with 10 different participants all of whom have never seen the design before

**Results:**

Pass Criteria: The median fastest blade switch time is under 15 seconds
Fail Criteria: The median fastest blade switch time is over 15 seconds

Number of Samples to Test: one blade spar

Design Analysis Equations/Spreadsheet:

- Find minimum time for each participant
- Calculate median fastest switch time

**Test Date(s):** March 27, 2023

**Test Results:** Test results will be collected in [this spreadsheet](#).

**Performed By:** Josephine
**Test #6: Actuator Strength Test**

**Test Name:** Actuator Strength Test

**Purpose:**
- To verify that the actuators are strong enough to apply the forces necessary to pitch the blades

**Scope:**
- Contributes to the function “pitch the blades”
- Verifies actuator specifications

**Equipment:**
- Linear Actuator
- Control code for linear actuator
- Unit masses

**Diagram of apparatus:**

![Diagram of apparatus](image)

**Hazards:**
- Minor electrical hazard if linear actuators are incorrectly connected
Pinching concerns from the movement of the actuator
- Weights may be dropped onto feet or hands

**PPE Requirements:**
- Safety glasses

**Facility:**
- Classroom

**Procedure:** (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Affix the linear actuator in a vertical orientation, such that the moving component is facing downward. There should be ample space below the actuator to allow for the actuator to move and for the addition of masses onto the end of the actuator (~12 inches).
2) Extend the actuator to 50% of its farthest reach using the control system.
3) Add masses to the end of the linear actuator in 50g increments up to 5 kg
4) Between each increment, retract the actuator up to its shortest configuration.
5) Record any failure of the actuator to retract or any slip in the actuator, elongating it when a mass is added.
6) Repeat an additional time for two trials per actuator.

**Results:**
- **Pass Criteria:** all mass values could be lifted and do not cause slip in the actuator
- **Fail Criteria:** at least one of the masses causes a slip or cannot be lifted
- **Number of Samples to Test:** two actuators
- **Design Analysis Equations/Spreadsheet:**
  - Each mass value will be parked as a pass or fail for each trial
- **Uncertainty Analysis:** The uncertainty analysis will account for resolution of the values of the masses

**Test Date(s):** April 13, 2023

**Test Results:** Test results will be collected in this spreadsheet.

**Performed By:** Elizabeth
Test #7: Linear Actuator Displacement Test

Purpose:
- To ensure the linear actuators can move to the specified location during testing

Scope:
- Verified the function “pitch the blades
- Verifies the accuracy of displacement of the linear actuators

Equipment:
- Linear actuator
- Calipers
- Linear actuator code (displacement input)

Diagram of apparatus:

Hazards:
- Minor hazard with pinch points when using calipers

PPE Requirements:
- Safety glasses

Facility:
Josephine’s House

Procedure: (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1) Measure the initial displacement of the linear actuator
2) Use the program to move the actuator a specified amount (see result sheet)
3) Measure the final displacement of the linear actuator
4) Repeat for all the values in the spreadsheet, in the correct order

Results:

Pass Criteria: The actuator is within .2 mm of the specified distance
Fail Criteria: The actuator is more than .2 mm of the specified distance

Number of Samples to Test: one actuator

Design Analysis Equations/Spreadsheet:

- Calculate the error in displacement

Test Date(s): March 27, 2023

Test Results: Test results will be collected in this spreadsheet.

Performed By: Josephine