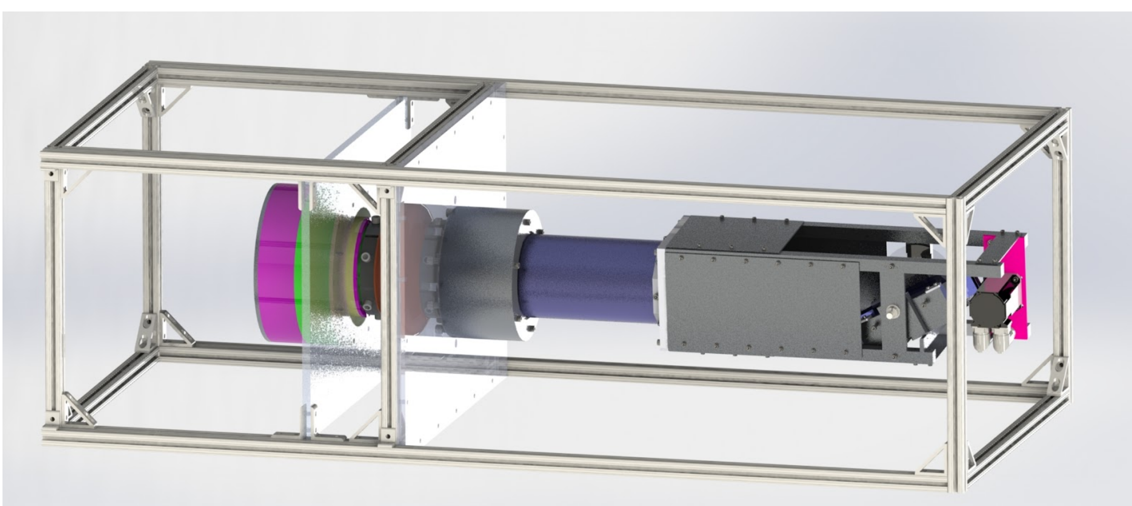
Design of an Aircraft Mounted Doppler LiDAR Scanner



ESRL Earth System Research Laboratories

CSL Chemical Sciences Laboratory

ARS Atmospheric Remote Sensing

Introduction

Light Detection and Ranging (LiDAR) technology became popular after the widespread application of the laser in the 1980s. Simply put, LiDAR determines the distance to an object by shooting a laser pulse at it and measuring the time it takes for the laser light pulse to return.

The National Oceanic and Atmospheric Administration (NOAA) is on the forefront of using advanced Doppler LiDAR instrumentation. Their research involves taking in-situ measurements from the environment which they're studying, whether that be remote "scans" of areas or direct sampling. Their data is then used to investigate wind phenomena of scientific interest.

Last year, NOAA sponsored a project to design and manufacture a LiDAR pointing stabilization instrument for research on ships. They continued a secondary project that our team took on to continue the advancement in LiDAR technology for other research occurring on aircrafts.

In the past, the Atmospheric Remote Sensing (ARS) group used two planes when taking their measurements. One aircraft flew *through* the environment making observations / measurements, while the other aircraft flew *above* the environment. The team that flew above the environment used LiDAR technology to measure wind speed profiles from flight level to the ground by looking downward from the bottom of the aircraft. The ARS group saw the potential of combining these flights allowing NOAA to operate scientific equipment and LiDAR instrumentation in one aircraft.

Our task is to design a LiDAR scanning system that protrudes out the side of the aircraft and can scan vertically up or down and in a conical shape. This will allow LiDAR measurements to be taken either above or below the aircraft where before the LiDAR was limited to measurements below the aircraft.

The scanner will have a "scanning" mode, which will continuously scan in a conical shape, or a "staring" mode that would aim the LiDAR beam on a particular area. The scanner will use a sensor to track the aircraft orientation and movement and adjust itself to achieve these different modes. Scanning the beam (as opposed to a single continuous stare) allows NOAA to measure multiple components of velocity which is important to model validation and measurement efforts.

***Figure 1**: The NOAA-MET Twin Otter measures horizontal and vertical wind fields associated with wildfires and other weather phenomena. This aircraft will house the LiDAR scanner*

Design Considerations

Scanning Range
Scanning in a cone requires two axis motion. To obtain a conical scan, the pitch and roll axes are of interest.

Servo Motors Usage
We decided to use electric servo motors to facilitate motion about our axes. A powerful servo motor on the inside of the aircraft controls the system's motion about the pitch axis, and another servo motor outside the aircraft controls motion about the roll axis.

Mirror Usage for the LiDAR Beam
Our roll axis servo motor connects to a mirror. When both motors are engaged and the LiDAR beam reflects off the mirror, a cone is drawn in the atmosphere.

Window Size and Aircraft Limitation
Due to NOAA-AOC (Aircraft Operations Center) regulations, our scanner can only protrude out of a standard passenger window near the front. The seats next to the window would be removed and our system would be bolted into the seat rails. Our scanner system will only be allowed to protrude a maximum of 24" without being in a dangerous range of the aircraft propellers.

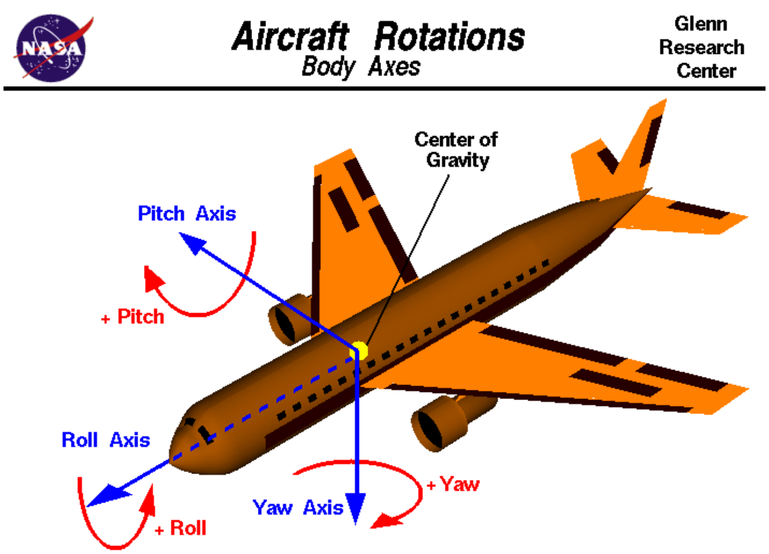


***Figure 2**: An aircraft's principle axes: pitch, roll and yaw*

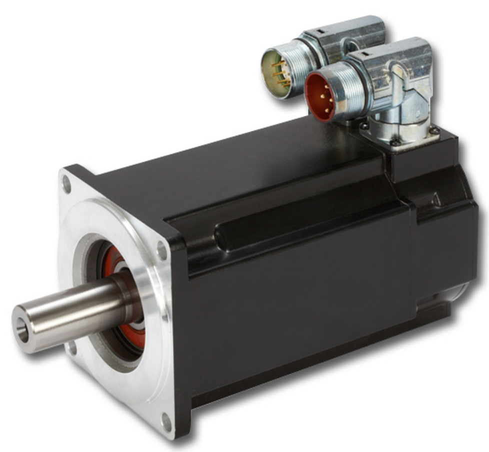


***Figure 3**: Roll axis servo motor*

Intended Aircraft Design

At the beginning of the project, the team was given the following equipment to use in our final design:

- LiDAR (beam 3" diameter)
- Pitch motor

Starting with these components, we were able to brainstorm and iterate through multiple designs that would achieve our project requirements.

Intended Aircraft Design

By the end of our first semester, the team came up with the design shown below. This design is what we intend for NOAA to use in the field. The scanner is shown protruding out of the window of the aircraft. Minimal stress is put on the skin of the aircraft as the forces are transferred back to the seat rails. The rectangular frame holds all the necessary components.

At the bottom of the frame, there is a dark grey model of the actual LiDAR. This is where the LiDAR laser beam will be generated. The LiDAR beam will then be shot towards the top of the frame where it will be reflected by a mirror. This mirror will deflect the beam horizontally through a series of components, out the window of the aircraft, and hit the roll axis mirror, where it will be directed into the atmosphere.

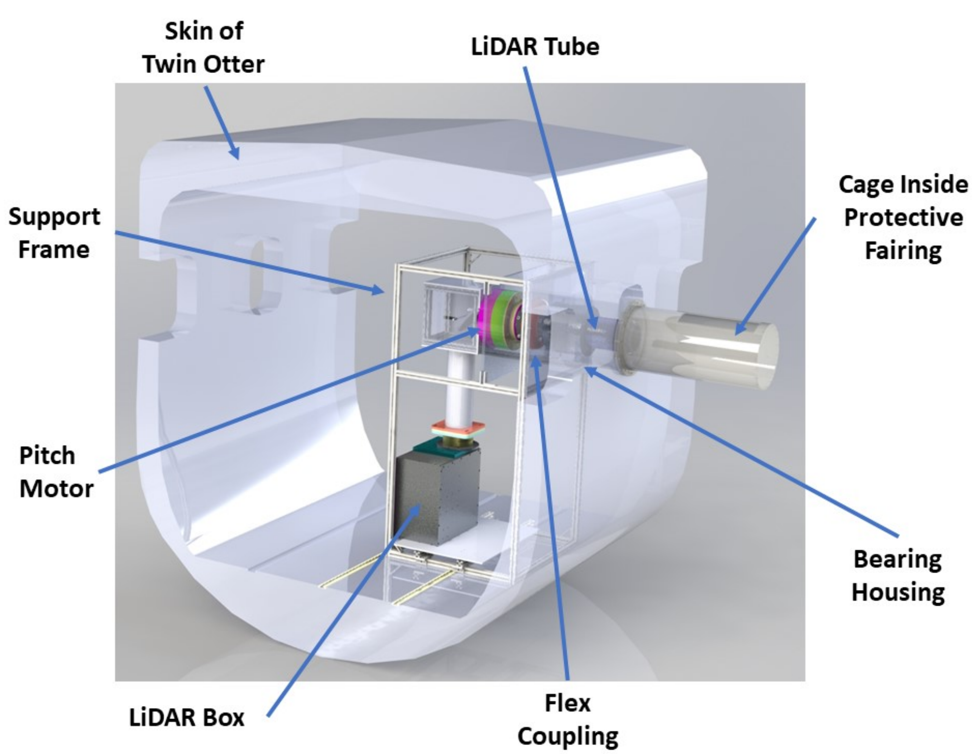


***Figure 4**: The team's final scanner design, as installed on the aircraft*

Final Developed Design

Scope Changes

Diving into the teams remaining time in the second semester, we determined the components below would be the most useful components to NOAA. For that reason, we decided to take on the most technical part of the project and create an "Expo Build" deliverable shown below.

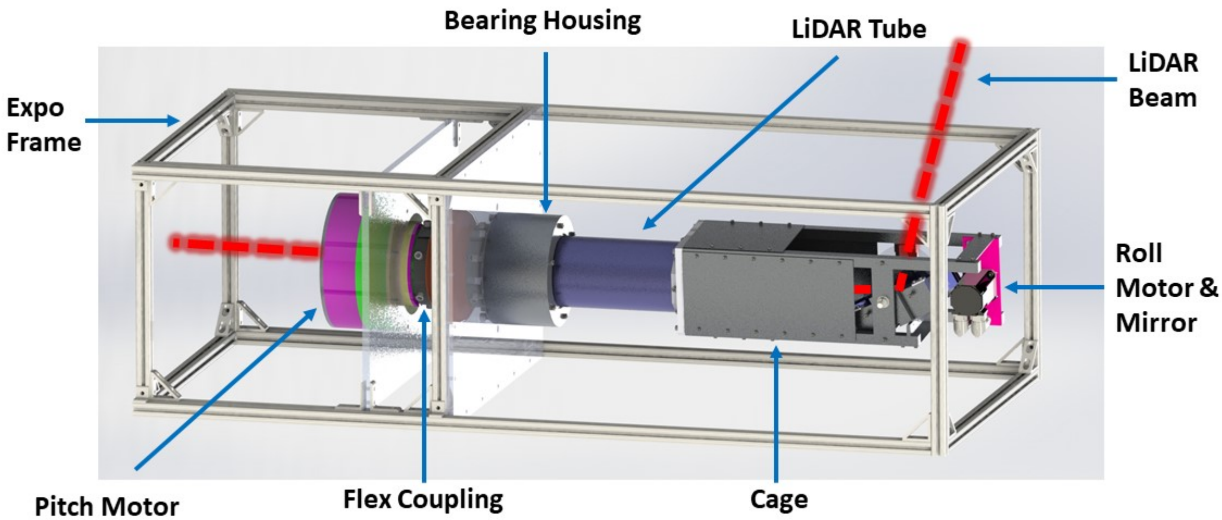


***Figure 5**: The team's final deliverable*

This assembly demonstrates the full range of motion that NOAA required while also having all components that would go into our intended aircraft design, aside from the airfoil fairing. Essentially, the components in this design will be used in tandem with pre-existing NOAA equipment on the Twin Otter aircraft (as shown in Figure 4). This includes the following sub-assemblies:

- Expo frame
- Pitch motor
- Flex coupling
- LiDAR tube
- Bearing housing
- Cage

Final Developed Design Sub-Assemblies

Expo Frame

In order to hold our project, we made an expo frame assembly. The framing is made of 80/20 aluminum for easy and adjustable assembly. In order to hold our entire project, the frame needed to be 56” x 24” x 18”. The framing also contains two ½” thick aluminum plates that are used to hold and support the scanner system.

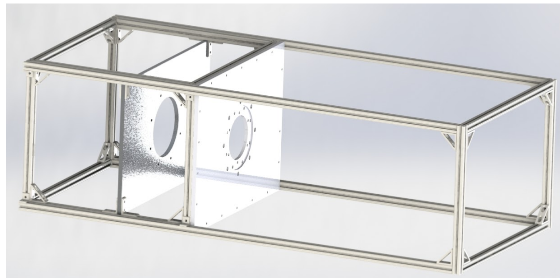


***Figure 6**: Expo frame*

Pitch Motor

The first component the LiDAR beam will travel through is the pitch motor. This servo motor is 9.5” in diameter and can transmit roughly 4,000 lb-in in torque. This motor will rotate our scanner system and account for the pitch of the aircraft. The maximum amount of torque we expect the motor to output is about 800 lb-in.

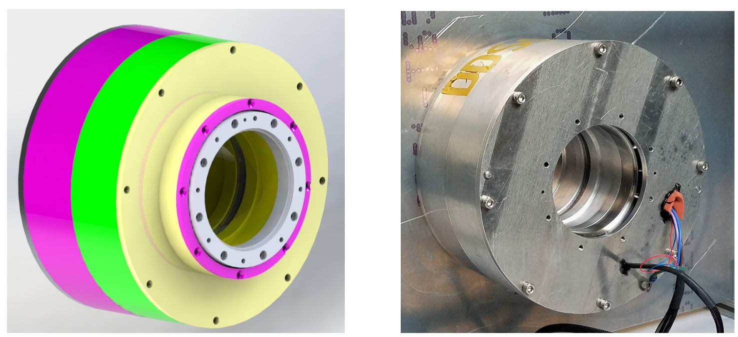


***Figure 7**: Pitch motor*

Flex Coupling

The flex coupling was not in our original design, however after analyzing the system as a whole, we noticed that there would be a high potential for misalignment between the pitch motor and the rest of the system outside of the plane. After some research, we discovered the Rexnord Omega Flex Coupling.

***Figure 8**: The Rexnord Omega Flex Coupling*

Final Developed Design Sub-Assemblies

LiDAR Tube

On the other end of the flex coupling is the LiDAR tube that connects to our cage assembly. The tube is attached to the coupling and will then go through the plate that is attached to the framing. Since the tube handles a heavy load, it will also be supported by a set of bearings.

Figure 9*: LiDAR tube*

Bearing Housing

The cylindrical bearing housing is used for extra support for the scanner system. The bearings used for the housing are 5” in diameter and can withstand roughly 1200 lb-in loadings. The bearing housing is critical because it enables a smooth torque transmission across our system. It also handles the heavy drag loads coming from outside the aircraft. The bearings are in a cylindrical housing that is attached to the same plate the tube goes through.

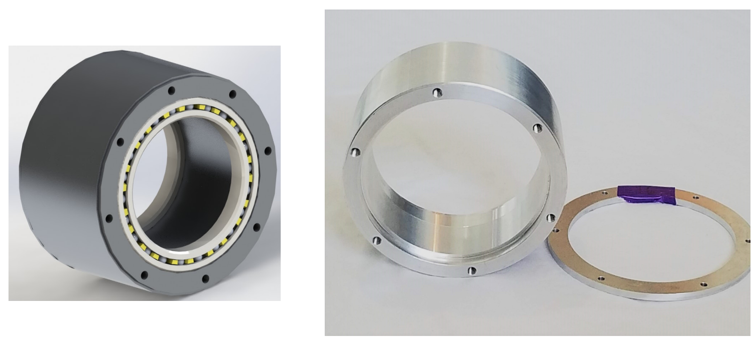


Figure 10*: Bearing housing*

Cage

The cage assembly will be placed inside a fairing that is directly in the airstream. The assembly holds the roll motor and roll mirror. The roll mirror is elliptical shaped and is roughly 9” in major diameter and 4” in minor diameter. The mirror is this size because it must account for the LiDAR beam being deflected across its surface at 23 degree angles.

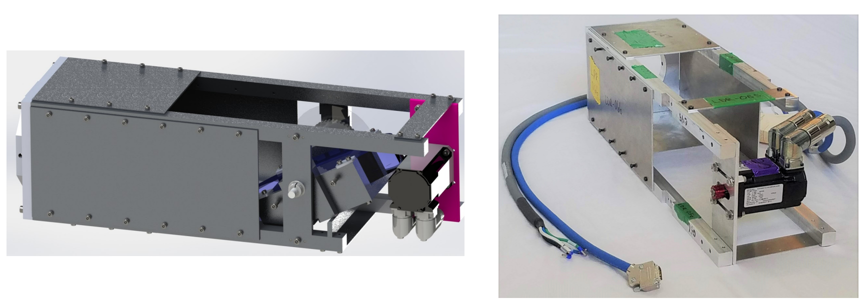


Figure 11*: Cage*

Systems & Algorithms

To obtain useful LiDAR data, it is critical that the direction which the LiDAR beam is redirected can be controlled and remains stable during flight. To accomplish the task of controlling the LiDAR direction, we have one servo motor which controls the motion about the pitch axis and a second servo motor which controls the motion about the roll axis.

By commanding the position of the servo motors about both of these axes, we can redirect the LiDAR beam to the desired direction. To accomplish the task of keeping the LiDAR beam steady while the aircraft experiences disturbances, we have developed a software program through LabVIEW that employs sensory feedback control through a PID algorithm.

The schematic for this control loop is shown below. This feedback control program uses a VectorNav, which is a six axis accelerometer, on the back of the roll axis mirror to detect any aircraft motion in the pitch and roll axes. If the sensor does detect motion in one of those axes, the control loop automatically compensates for the motion by making a counter-acting adjustment in that axis to keep the LiDAR beam fixed on its desired position.

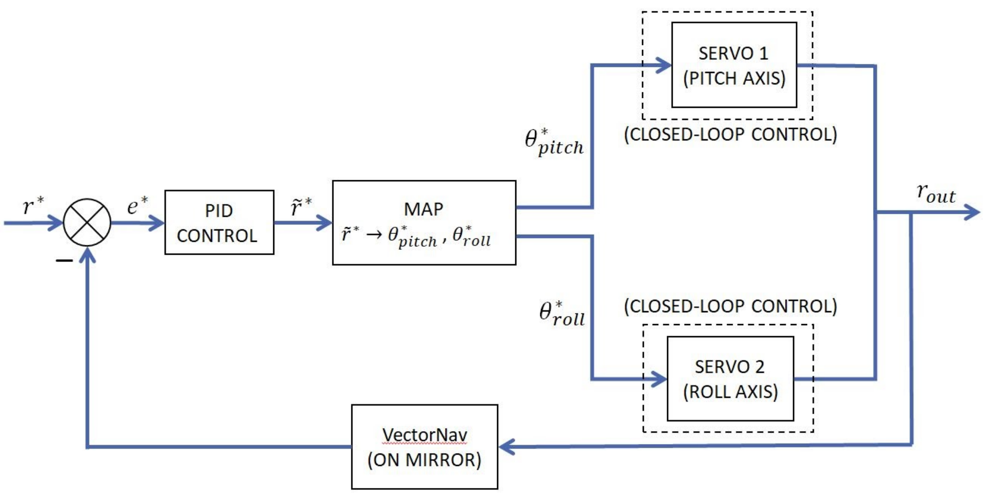


***Figure 12**: Control scheme*

***Figure 13**: VectorNav-300, used for motion compensation of scanner*

Testing

Our team considered three main tests to holistically assess the structural and functional performance of the design:

Test 1: Determining the spring constant of the flex coupling

Using a torsional test machine we found the spring constant of the flex coupling. This was necessary to determine if the flex coupling would be sufficient in handling the potential misalignment in our system. We concluded that under operating conditions the flex coupling will transfer a phase shift from our pitch motor to the rest of the assembly. Moreover, the coupling would impart noise in the form of unwanted oscillations. Therefore, to assess the magnitude of the phase shift and noise we would conduct a step response test.

Test 2: The latency of our control algorithm

To measure our system's response time, we sent a sinusoidal signal to our motors and recorded their responses. By superimposing the input signal to the output of our motors we can quantify the latency of our PID controller. We recorded 150 ms of latency, meaning the controller needs to be further tuned.

Test 3: Performance of our system

The final test relies on the previous two to measure the time our fully assembled design takes to reject pitch and roll disturbances. By inputting real flight data from NOAA into our system we can measure how well our assembly tracks it and thus simulate real operating conditions. This will give NOAA an operating manual to extract the most performance out of our design.

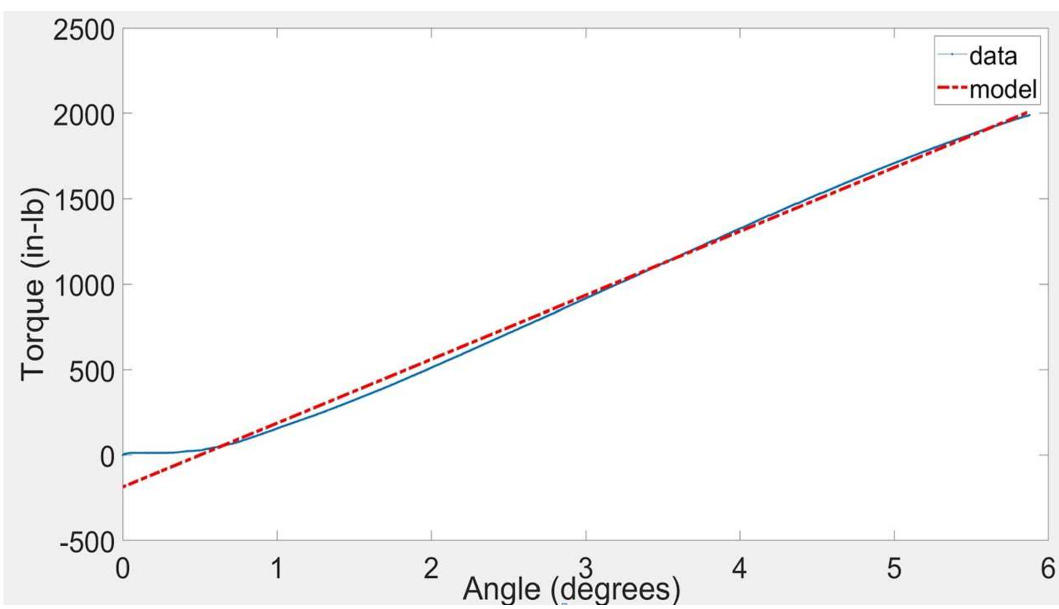


Figure 14: Torsional test to determine spring constant of flex coupling

Conclusion & Disclaimer

Despite completing the manufacturing of the individual components of our design, our team was not able to fully finish the project due to the campus closure as a result of COVID-19. We had planned to test our fully manufactured design and take the next step based on the results.

We will be working with NOAA to develop sufficient documentation so that their engineers can pick up where we left off. We are excited see NOAA take this project for extraordinary scientific research and for the opportunities this scanner gives them to advance their LiDAR technology.

Bios

Project Manager, Kelsea Keenan: Kelsea has used her past leadership experience and her technical skills from the mechanical engineering curriculum to keep the senior design project moving forward. Her organizational and planning skills allowed the team to stay on task and deliver a final design that exceeded NOAA's expectations. Keeping the team and the project together was her number one priority and, even with the unfortunate circumstances towards the end of the project, we worked optimistically to deliver the best possible design.

Logistics Manager, Adam Davis: Adam started the project interested in and working with the controls portion of this motion compensating LiDAR scanner. As time passed, it became more important for Adam to switch his focus to the design and manufacturing of this project. Adam's willingness to learn helped him manufacture over half of the project's parts, on top of balancing the organizational duties which a logistics manager must take on. Adam loved working with all of his teammates and is interested in the energy industry after college.

Financial Manager, Derek Twarowski: Derek came into the project with an interest in handling the finances of a larger scale project as well as developing more detailed design and manufacturing skills. Derek began by analyzing key components of the project such as developing models for the mirror scanning range and mirror optimization. As the project design progressed, Derek worked with suppliers to source over 100+ parts and was able to work with his teammates to manufacture a majority of the project's parts. After college Derek plans to work in the construction industry as a Project Engineer, where he will be able to continue to fuse together finance and engineering.

CAD/Manufacturing Engineer, Colin Baxter: The CAD/Manufacturing Engineer is in charge of moving the project forward from the initial CAD design to the assembly of the prototype. With Colin's prior manufacturing experience, he led the team in machining efforts, creating very good relationships with shop machinists. He is very meticulous when it comes to organizing CAD drawings and the on-time delivery of finished parts. He is disappointed with not being able to see the project become fully assembled but put NOAA in the best position possible to be able to finish the project through thorough documentation.

Test Engineer, Pedro D. Reyes Ricardez: Pedro planned and designed tests to evaluate the functionality of critical components and their effect on the project. He documented test results and provided a summary report to further improve the project's performance. He worked closely with Jonathan Bosnich to implement a control algorithm in LabVIEW and meet our client's performance requirement. After completing his undergraduate studies, Pedro will pursue a Master of Science in Mechanical Engineering at CU and plans to work overseas as an expat.

Systems Engineer, Jonathan Bosnich: Jonathan has applied his technical knowledge of control systems, system dynamics, and programming to help develop a control scheme for the system and code it in LabVIEW. Jonathan also worked on appropriate tests to determine if the control system would meet the specified performance metrics. After receiving his undergraduate degree, Jonathan is hoping to pursue a PhD in control theory.

Image References

Figure 1**:** "FIREX-AQ Platform: NOAA-MET Twin Otter." ESRL, 2019, www.esrl.noaa.gov/csd/projects/firex-aq/twinotterMET/.

Figure 2**:** Hall, Nancy. Glenn Research Center / NASA, 5 May 2015, https://www.grc.nasa.gov/www/k-12/airplane/rotations.html.

Figure 3: "AC Synchronous Servo Motors – AKM™ Series." Kollmorgen, https://www.kollmorgen.com/sites/default/files/AKM41_LARGE_2.jpg.

Figure 13: https://www.vectornav.com/products/vn-300