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Doppler Lidar Motion Stabilization Platform for NOAA P-3 Hurricane Monitoring

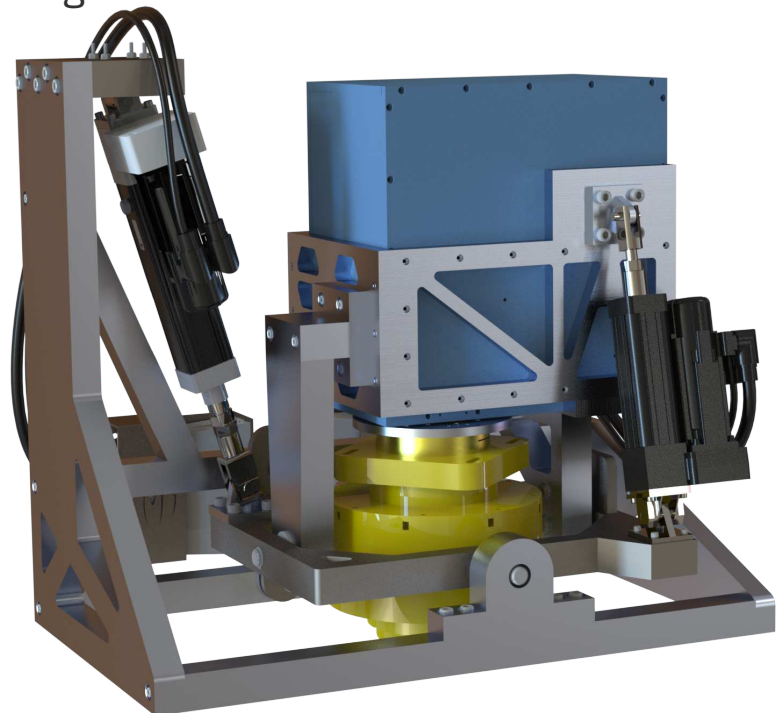


Team 24

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Introduction

Over the course of the 2020 hurricane season, 13 tropical storms developed into hurricanes. Combined, these storms cost the US over \$51.8 billion in damages. Studying storm formation and intensification can help meteorologists better predict when, where, and how hard a hurricane will strike land.

The NOAA Atmospheric Remote Sensing (ARS) Group uses a Doppler lidar (light detection and ranging) instrument to study the dynamics of atmospheric processes related to wildfires, pollution and climate dynamics. Lidar is a sensing method that uses laser pulses to determine the distance to an object (Fig. 1). The distance to the object is calculated by measuring the amount of time it takes for the laser light pulses to bounce off the object and return to the lidar. The technology can be likened to radar or sonar, but it uses light waves instead of radio or sound waves.

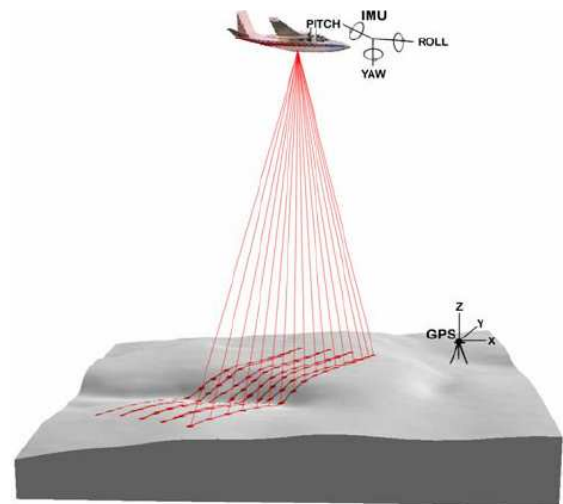


Fig 1: A schematic showing how lidar pulses are used to gather information on terrain and objects in the sky (like air particles).
(Source: ResearchGate)

Project Mission

During the summers of 2021 and 2022, NOAA will be deploying their Doppler lidar instrument on a specially-designed Lockheed P3-Orion aircraft. This aircraft is flown on research missions inside hurricanes, where the lidar will collect data on the wind profiles and turbulence within the storms.

Our team developed a platform (Fig. 2) designed to stabilize the instrument during those bumpy hurricane flights. The platform uses real-time feedback from an on-board inertial navigation unit (INU) to actively correct for airplane pitch and roll. With this stabilized platform, the ARS group will obtain higher quality lidar data than previously possible, gathering important evidence for the world of hurricane research and potentially impacting many lives around the world.

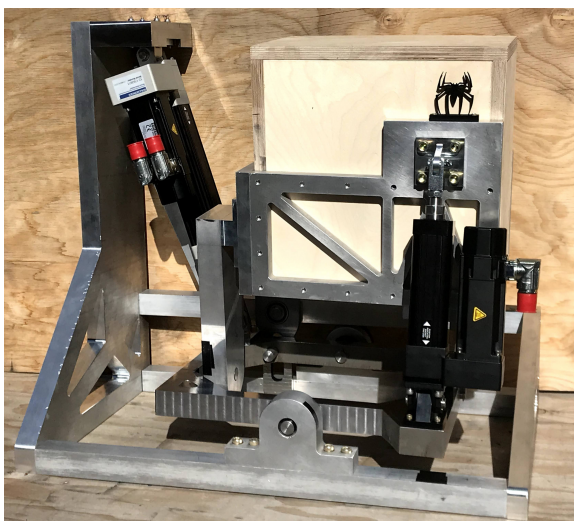


Fig 2: The team's prototype platform.

Design Considerations

Aircraft

Inside the P-3 Orion, the system may be mounted in either the Lower Instrumentation Port Aft bay (LIPA) or the Lower Instrumentation Port Forward bay (LIPF). Since the LIPA bay has smaller dimensions (30"x20"x37"), the platform was designed to be assembled within this bay. The platform and the lidar system cannot interfere with the walls or the floor of the bay during operation. The system must also be positioned so that the laser beam (with a diameter of 3") always points out a 6"x6" window on the bottom of the plane.

Stabilization

On an aircraft, pitch describes forward-backward rotation, and roll describes left-right rotation (Fig. 3). The platform must react to changes in the aircraft's pitch and roll (up to 2 Hz) during flight to keep the beam pointing out of the bay window. It must actuate the lidar system up to $\pm 5^\circ$ in pitch and roll. In "staring" mode, this means the system will need to tilt 15° and stabilize from there.

Operating Modes

In the scanner, the lidar beam passes through an optical wedge to exit the cylindrical scanner at a 15° angle. The lidar instrument has two modes of operation, both of which the platform is required to accommodate: a "scanning" mode, which sweeps the beam around in a 15° conical shape (Fig. 4); and a "staring" mode which will aim the lidar beam vertically down out of the window (Fig. 5). During the "scanning" mode, the platform will stabilize for 5° of rotation in all directions. During the vertical "staring" mode, the platform will rotate the system 15° in roll, and stabilize 5° in all directions from that new origin position.

Scanner Size and Weight

The lidar unit and wedge scanner are approximately 27"x13"x8" and weigh just under 100 pounds. The lidar cannot interfere with the walls and floor of the bay. Additionally, the platform must withstand 10g load ratings as required by NOAA Aircraft Operations Center and the Federal Aviation Administration.

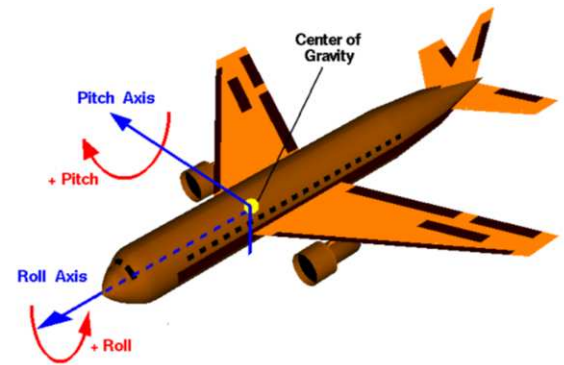


Fig 3: Pitch and Roll axes on an aircraft.
(Source: NASA Glenn Research Center)

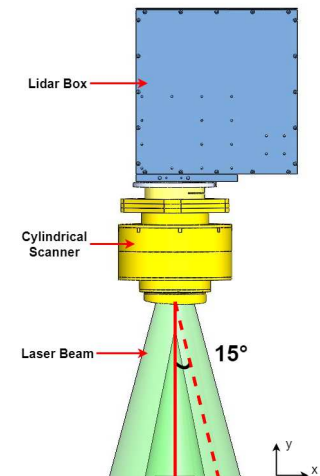


Fig 4: The scanning mode sweeps the laser beam (shown in green) in a 15° cone.

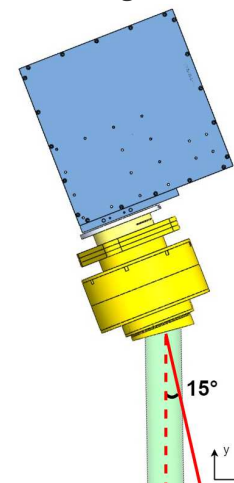
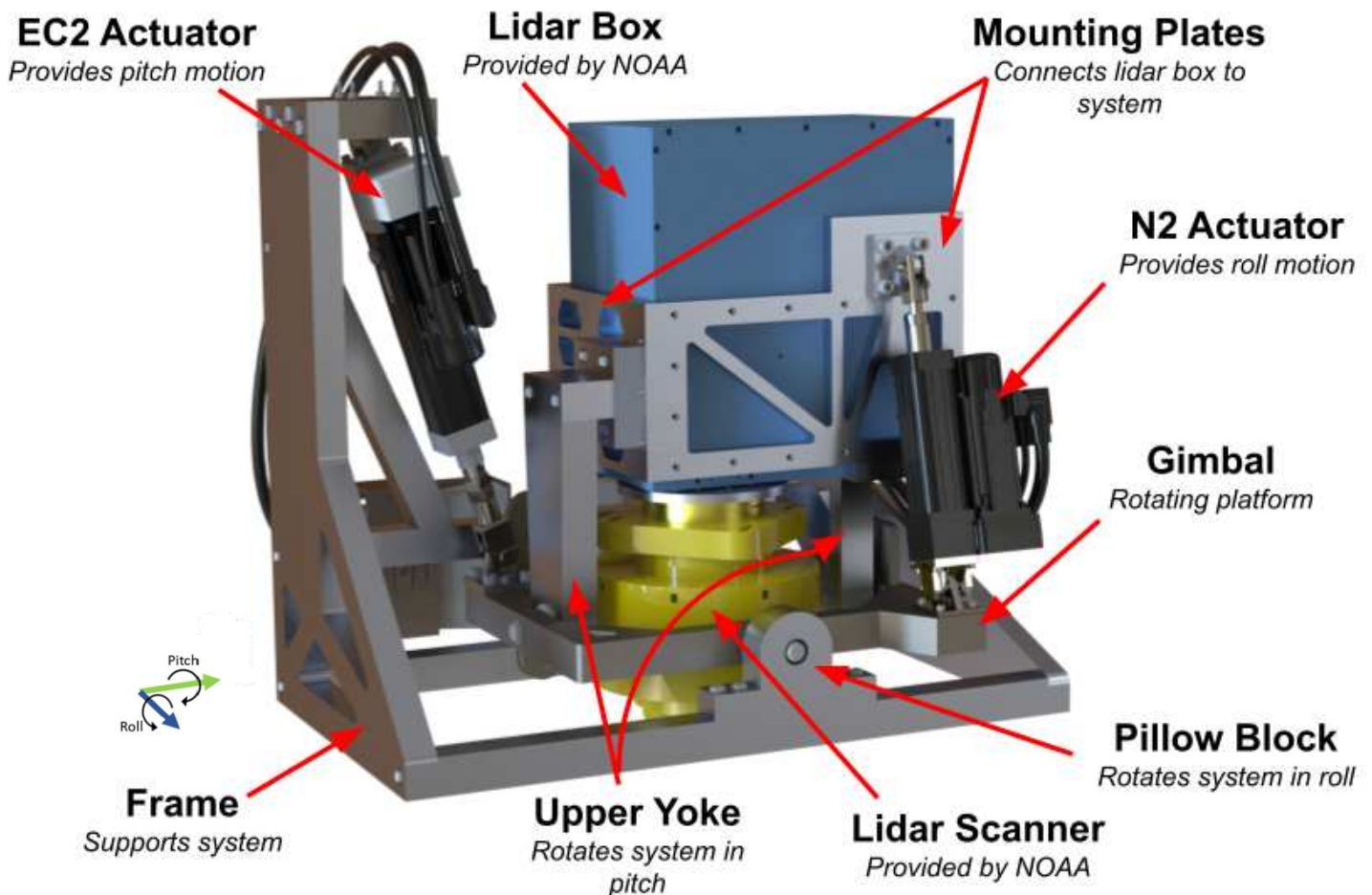


Fig 5: In staring mode, the lidar (shown in blue and yellow) is tilted 15° so that the laser beam (shown in green) points vertically downwards.

Full Design Overview

The motion compensation platform is designed to house the lidar system during flight. The design ensures that the beam is pointed out of the window during flight without interference throughout the system's operational range. It is also designed to be robust enough to withstand the intense conditions experienced by the P-3 Orion in a hurricane.

The primary structures within the platform include the outer frame, the gimbal ring, lower yoke, upper yoke, mounting plates, and two linear actuators. The mounting plates connect the lidar box and scanner to the platform, while the outer frame secures the platform to the bay. The gimbal, lower yoke, and upper yoke were designed to rotate the lidar system in pitch and roll. The two Kollmorgen linear actuators extend and retract with enough thrust to move the lidar system into its correct position based on the plane's flight path.



Subsystems Overview

Two-Axis Gimbal Assembly

Gimbal systems - commonly used in film and photography applications to stabilize cameras and in navigation systems for ships - are pivoting platforms that allow an object to rotate around one or more axes. The two-axis gimbal system in this design, which is made up of the gimbal ring, lower yoke, and upper yoke subassemblies, restricts all degrees of motion except for the desired pitch and roll. Fig. 6 shows how the gimbal ring is connected to the upper and lower yoke.

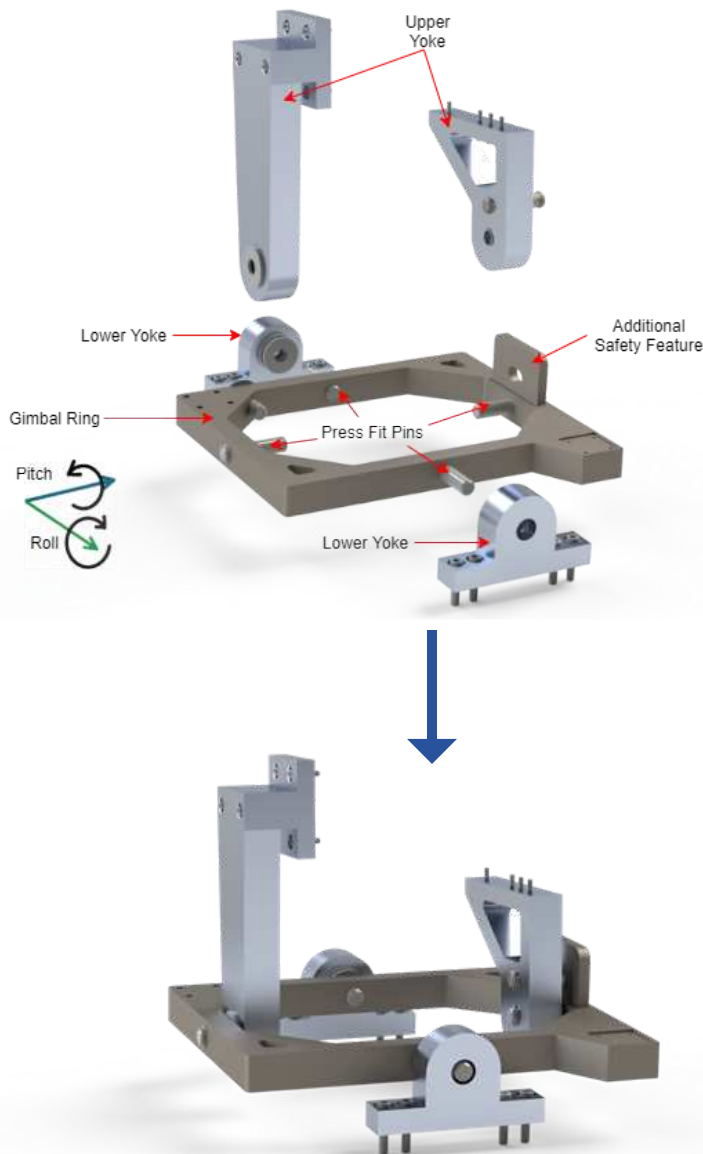


Fig 6: Exploded and assembled views of two-axis gimbal assembly.

Upper Yoke

The upper yoke connects the gimbal system to the lidar scanner mounting plates (pg. 7), and allows the scanner to move about the pitch axis.

Made up of two vertical “struts” whose height was calculated to optimize the scanner head’s position in relation to the bay window, the upper yoke can take up to 1000lb of vertical force, or 10g loading.

Gimbal Ring

The gimbal ring - the main supporting structure in the gimbal assembly - was designed to ensure the scanner had an unobstructed view through the scanning window of the bay. With press-fit pins that connect the ring to both the pillow blocks and the upper yoke, this ring also provides a platform for each linear actuator to control the motion of the system.

Lower Yoke

The lower yoke consists of two custom pillow blocks that secure the gimbal to the frame subassembly (pg. 7). Inside each pillow block is a press-fit bearing, which allows the gimbal ring to pivot around the roll axis.

Subsystems Overview

Mounting Plates Assembly

The mounting plates assembly (Fig. 7) houses the lidar scanner and wedge scanner. Additionally, it provides connection points to the rest of the system. The subassembly consists of four mounting plates that are fastened to the lidar box. Each mounting plate has cutouts to help decrease the weight of the system, without compromising strength.

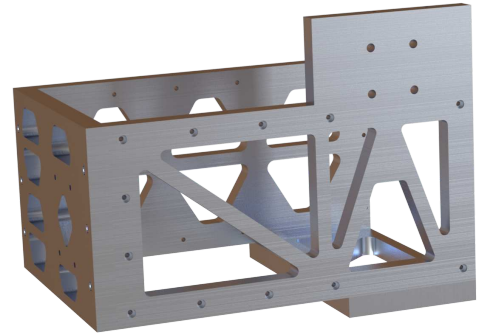


Fig 7: Mounting Plates Assembly

Frame Assembly

The frame assembly (Fig. 8) was designed to optimize the structural strength of the system, while still enabling the assembly of the entire system within the instrumentation bay.

This frame design provides several different mounting options for the various bays the system might be mounted in. The tall boot-shaped plate supports the roll actuator during system motion, and though measures were taken to reduce the weight of this piece, rigidity and strength were of utmost importance in maintaining precision control of the system.



Fig 8: Frame Assembly

Safety Features

With a large heavy scanner and many moving parts, our team knew it was imperative to add numerous safety features for future users. These features include physical travel limits that prevent the system from rotating further than designed, electronic limit switches that cut power to the system when triggered, and an emergency “kill” switch (Fig. 9) that allows any user to halt the system from outside the bay.



Fig 9: Emergency “kill” switch, used to shut down the system if needed.

Actuation & Controls System

Linear Actuators

The motion of the two-axis gimbal system is entirely controlled by two Kollmorgen linear actuators (Fig. 10). The EC2 and N2 Series linear actuators - controlling roll and pitch, respectively - were selected for inclusion in the team's design due to their combination of thrust capabilities, accuracy, resolution, and size. The NOAA ARS group also had previous experience with the controls systems of the Kollmorgen family, making Kollmorgen actuators a logical choice for Team 24's design.

Based on sample INU data from a NOAA P-3 hurricane flight and our project requirements, these actuators must be able to control the system in conditions up to 2.5g loading and remain structurally sound up to 10g loading. The EC2 and N2 series actuators are capable of between 450 and 500 lbf of thrust at 5 inches per second, and will be able to control the system's rotation under all required conditions. With a lead accuracy of 0.002 inches and repeatability of 0.0005 inches, these actuators can also position the lidar unit as accurately as one tenth of a degree.

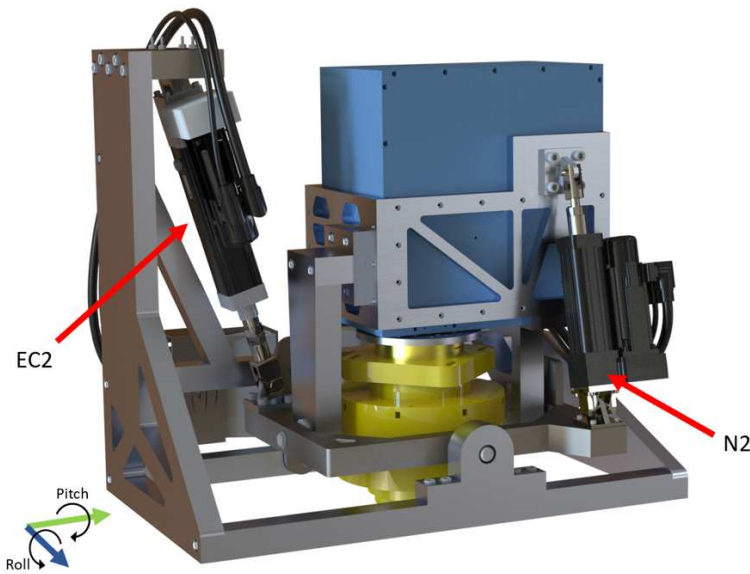


Fig 10: Placement of each Kollmorgen linear actuator.

Feedback

To achieve the necessary stabilization during flight, the actuators are simultaneously controlled by a LabVIEW program developed jointly by our team systems engineer and a NOAA engineer. This program employs sensory feedback control through a PID algorithm. A VectorNav VN200 six-axis INU located within the lidar unit provides the orientation of the lidar every 8 milliseconds. When the INU detects any change in position, the control loop automatically compensates for the change by directing the linear actuators to move the lidar beam to the desired position.

The team has worked closely with a NOAA engineer to begin building this program, and it will be developed further by NOAA separately following the end of the semester.

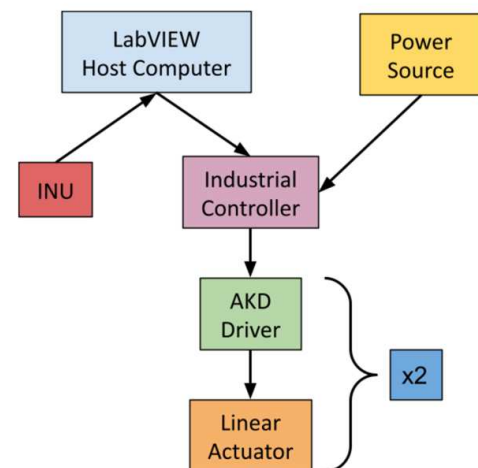


Fig 11: A simplified block diagram for the control system.

Structural Analysis & Testing

Loading Requirements

It was crucial for our team to ensure the motion compensation platform could withstand the 10g loading requirements. The entire assembled system and each individual component needed to be verified. It was impractical to physically test the 10g loading, so our team used Finite Element Analysis (FEA) to ensure our design met this specification. Using ANSYS (Fig. 12) we were able to replicate the forces each component might face during the flight on the P-3 Orion Aircraft. Our calculations and analysis were also independently verified by a structural engineer hired by NOAA. The structural engineer has certified that our platform meets the load requirements needed to go on the P3-Orion.

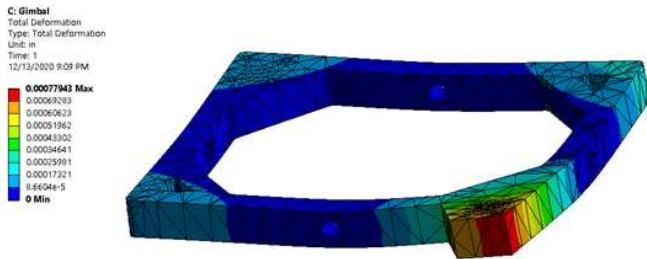


Fig 12: An image of the ANSYS finite element analysis of the gimbal ring. This image is exaggerated for effect, but shows the ring under 10g loading from the N2 actuator.

Assembly

As the P3-Orion aircraft is kept in Florida, our team built a replica LIPA bay to simulate the assembly of the platform in the real bay. The team also created a replica lidar box as a stand-in for the expensive technology that the system would eventually hold. The platform was assembled in the replica bay (Fig. 13) so that the team could practice the installation process and create an assembly guide for the NOAA ARS group. Additionally, the team verified the placement of the platform over the window to ensure the lidar beam was continuously aimed through the window.



Fig 13: The full system assembly inside the replica LIPA bay.

Controls

As a final test before the end of the semester, our platform will be placed on a large balance board to replicate in-flight conditions. The system will be tilted in each direction to test the response of the controls program and linear actuators to various disturbances. As the actual lidar beam is invisible, the beam motion will be tested using a set of laser pointers, placed in a circle with the same diameter as the beam. The lidar system will be moved to its worst-case positions to verify that the beam stays inside the window at all times. Depictions of these worst-case positions can be found in Fig. 14.

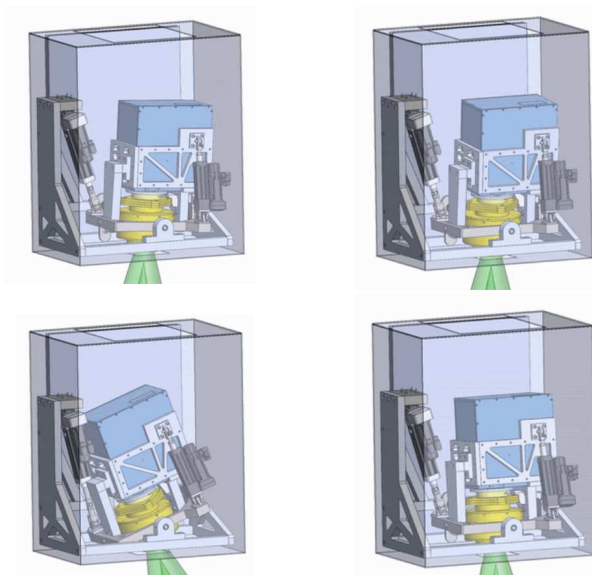


Fig 14: Clockwise from top left: -5° roll, 5° pitch, -5° pitch, 20° roll.

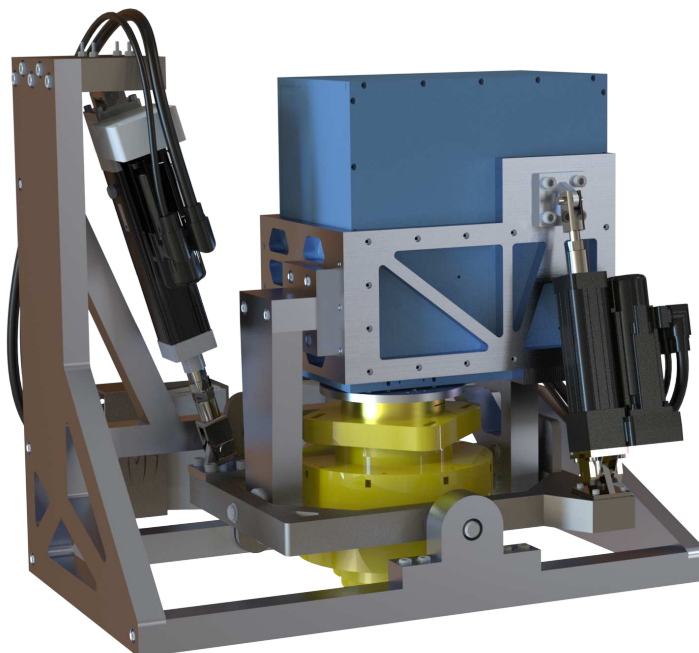
Conclusion

After two action-packed semesters of work, our team is proud to present our Doppler lidar motion compensation platform. Our team has exceeded the NOAA ARS group's expectations, and we have crafted a true-to-size, functional platform prototype. While there is more work to be done by the ARS group to ensure the controls system is ready for flight, we are excited to hand off a project that is so close to completion.

The team has successfully assembled and disassembled the system several times, and has created an assembly manual to hand off to the NOAA team once the semester comes to a close. Using our replica bay, we created instructions specific to assembling the system in the constrained LIPA space. While the team did not perform shock or physical loading tests on any parts due to their replacement costs, the extensive ANSYS FEA testing and calculations will ensure the system remains structurally sound under any loading up to 10g.

Our team's initial testing indicates that the actuators will be able to effectively control and stabilize the system under the required 2.5g loading conditions. The program will need to be further developed by NOAA to ensure the lidar system is stabilized within 0.1° of accuracy.

Given the difficulties involved in designing, manufacturing, and building a project of this scale in the COVID era, the team is extremely proud of our work this year. After overcoming numerous obstacles and delays related to manufacturing and shipping, we are excited to see our system in action on a NOAA hurricane flight in the coming summers.



Meet the Team



Adam Bradshaw
Logistics Manager

Adam is a senior in Mechanical Engineering with a minor in Biomedical Engineering at the University of Colorado, Boulder. As the Logistics Manager, Adam served as the primary point of contact for several of the team's vendors, and co-led the linear actuator selection process. After graduation, Adam is interested in working in biomedical engineering or consumer product design.

Justin Buenviaje
CAD Engineer

Justin is a senior undergraduate student studying Mechanical Engineering with a minor in Biomedical Engineering at the University of Colorado, Boulder. As the team's CAD Engineer he was the primary contributor for leading the design phase, along with manager of all CAD related features and files. Justin plans to pursue a career in biomedical engineering post-graduation, with an emphasis on 3D-printed biosystems.



Ryan Cochran
Financial Manager

Ryan is a senior in Mechanical Engineering with a minor in Business at the University of Colorado, Boulder. As the team's Financial Manager he was responsible for the budget and purchasing all of the necessary items and materials that were not provided to the team by NOAA. Ryan is interested in working in the aerospace or automotive industries following graduation.

John Cunningham
Systems Engineer

John is a senior in Mechanical Engineering at CU Boulder. As systems engineer, he was responsible for creating a LabVIEW program with feedback control to achieve system stabilization. He worked alongside Adam in selecting the Kollmorgen linear actuators and alongside Jack in creating test plans. After graduation from CU Boulder, John plans to pursue a career in consumer product design or R&D.



Devon Kroeker
Project Manager

Devon is a senior in Mechanical Engineering at the University of Colorado, Boulder and will be graduating in August 2021. As the Project Manager, Devon managed the project schedules, deliverables, and team meetings. She also assisted other team members with deliverables and reports, design, and testing in both a technical and managerial capacity. Devon is interested in working the biomedical engineering or space industries post-graduation.

Meet the Team



Emma Martin
Manufacturing Engineer

Emma is a senior studying Mechanical Engineering at the University of Colorado, Boulder and will be graduating in Fall of 2021. As the team's Manufacturing Engineer, Emma was responsible for coordinating all fabrications required to meet final functionality requirements. After graduation, Emma plans to pursue a career in the sustainable architecture or automotive industry.

Jack Moran
Test Engineer

Jack is a senior in Mechanical Engineering with minors in Astronomy and Planetary Science, Engineering Management, and Space at the University of Colorado - Boulder. As the team's test engineer, Jack was responsible for writing a test plan and conducting thorough tests to ensure the project met all project requirements. After graduation, Jack plans to pursue a career in the aerospace industry.



Acknowledgements

Our team would like to thank the following people for their invaluable support and assistance with our project. Without their time and insight, this project would not have been possible. We would like to thank:

- From NOAA: Dr. Alan Brewer, Dr. Amanda Makowiecki, Mike Zucker, and Scott Sandberg for their support and assistance during this project.
- Our director, Dr. Paul Ibanez, for all his guidance and advice throughout the year.
- From CU Boulder: Dr. Daria Kotys-Schwartz, Dr. Julie Steinbrenner, Greg Potts, Chase Logsdon, Lauren Wheeler, Victoria Lanaghan, Josh Coyler, and the incredible PA team for all their assistance and suggestions.
- Mark Lord, who ensured our platform met specifications and would be allowed on the P3-Orion.
- Dan Thompson from Front Range Engineering, for fixing our gimbal ring at a time when we thought all hope was lost.