NORTHROP GRUMMAN COLLABORATION PROJECT

Final Design Review
(submitted June 12, 2024)

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Statement of Disclaimer

Abstract

The Northrop Grumman Collaboration project, emphasizing the Mechanical Engineering Senior Design team, is focusing on developing the Fire Response Aircraft (FRA) for the autonomous search and rescue system. The goal of this aircraft is to scan a predefined flight path and locate a simulated fire in which other vehicles will respond to the area. This Final Design Review report highlights the overall design, manufacturing, testing, and discussion of the final prototype. Any new changes to the final design since the Critical Design Review report are noted and include appropriate justification. The manufacturing processes for each component are outlined in detail as well as the required steps taken to properly integrate all parts to complete the final prototype. Additionally, testing of the wings, landing gear, and skin adhesion are discussed along with the results to provide verification that the aircraft has met the structural design requirements. Lastly, this document leads into discussion regarding the outcomes of the project and introduces some recommendations and next steps should efforts on the project continue.

Contents

1 Introduction

The Northrop Grumman Collaboration Project is a multidisciplinary project that includes aerodynamics, mechanical structures, and embedded systems teams. Collaboration occurs between the two Cal Poly Universities—San Luis Obispo (SLO) and Pomona. The goal of the project is to respond to a simulated natural disaster consisting of an immobile survivor and an artificial fire at unknown locations. Three unmanned aerial vehicles (UAVs), one unmanned ground vehicle, and a central ground control station will complete individual tasks as part of a larger system that fully responds to the disaster.

In previous years, Cal Poly SLO has overseen the development of only a single hexacopter UAV known as the Medical Evacuation Aircraft; however, in this most recent year, Northrop Grumman has given SLO the opportunity to take charge of the development of the fixed wing Fire Response Aircraft (FRA). The goal of the FRA is to autonomously fly around a specified area to scan for the thermal signatures of a fire and relay the coordinates for the other vehicles to respond. For this aircraft, the Senior Design Team is responsible for the design and manufacturing of the mechanical structures and the integration of all other components from the other teams.

The members of the Senior Design Team are Dominic De La Mora, Michael Hartley, Allison Lee, Chase Pietro, and Seamus Robinson, all of whom are 4th or 5th year Mechanical Engineering students at Cal Poly SLO.

The remaining sections of this review will discuss the final design, including changes made since the Critical Design Review report. In addition, implementation, design verification testing procedures and results, and reflection of the project are discussed.

In the appendices, the product user manual, risk assessment, final project budget, design verification and report, and test procedures can be found.

2 Design Overview

2.1 Design Description

The final design (Figure 1) for the Fire Response Aircraft is broken down into five main subassemblies: the fuselage, wings, tail, electronics payload, and landing gear. For main assembly, the wings, nose, and tail connect to the fuselage by non-permanent connections while the landing gear are mounted with the intent of being permanently fastened. The electronics payload is enclosed inside of a tray that can be easily inserted and secured to the inside of the fuselage. The removable tray is simple and allows for easy transportation or electronic component swapping.

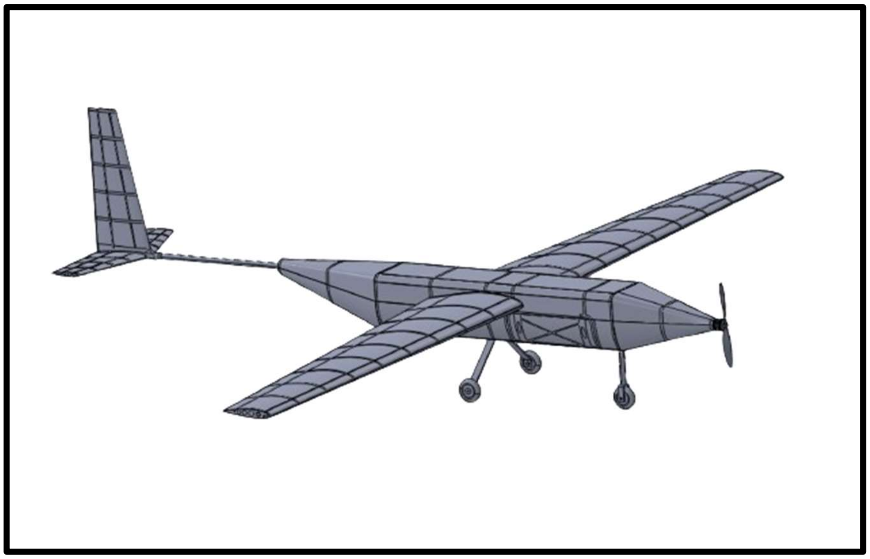


Figure 1. Full CAD Assembly of the FRA

With a total length of 27.5 inches, the fuselage (Figure 2) itself can be further broken down into three subsections: the nose, the main fuselage, and the empennage. Both the nose and the empennage are bolted to the main fuselage and were manufactured out of Polyethylene Terephthalate Glycol (PETG) by using standard Fused Deposition Modeling (FDM) 3D printing processes. A hole runs through the length of the empennage that allows for the insertion of the tail boom to which it is then secured with a nut. The fuselage internal structures consist of eight ribs made of PETG, eight stringers made of birch plywood, two aluminum mounting plates for the landing gear, and two PETG mounting blocks for the wings. Running through the midsection of the main fuselage, a wing box is constructed by carbon fiber tube with an inner diameter that matches the outer diameter of the wing spar tubes. The wing spar tubes slide into the wing box which helps resist bending. The skin of the fuselage is made of s-glass fiberglass and painted grey to hide the internal structures.

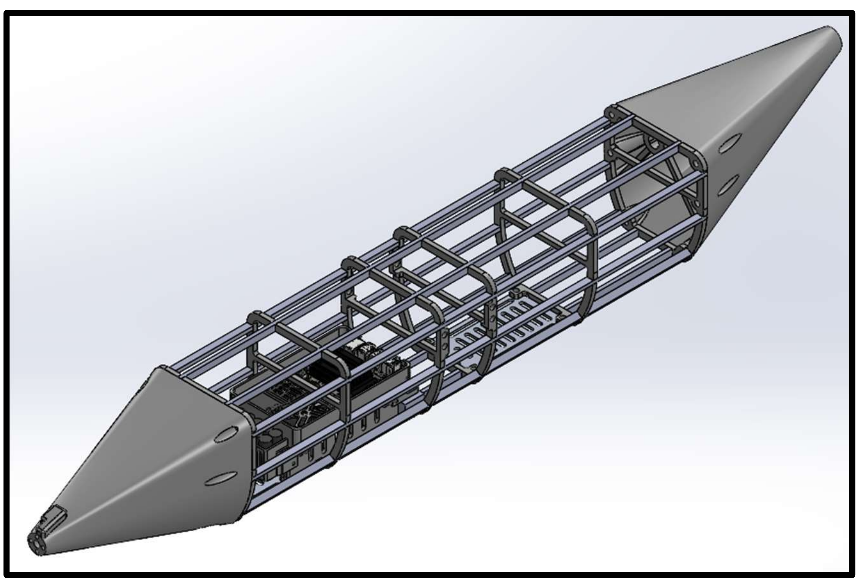


Figure 2. CAD Model of Internal Fuselage Structures

The wingspan of the FRA measures 8.28 feet and uses a high lift AG26 airfoil. Other design details provided by the aerodynamics team include a taper ratio of 0.5, an aspect ratio of 12.5, and twist of 3˚at the wing tip, all of which are meant to reduce the likelihood of stalling the aircraft. Like the fuselage, the wing internal structures also contain ribs and stringers made of PETG and birch plywood respectively (Figure 3). Each wing consists of ten ribs and two stringers that extend the entire semi-span. Also, at the end of the wings, 3D printed PETG ailerons are attached and driven by micro servos via a control linkage mechanism. Moreover, the FRA consists of two removeable wings, each installed with their own carbon fiber spar and utilize a twist-lock to secure to the fuselage.

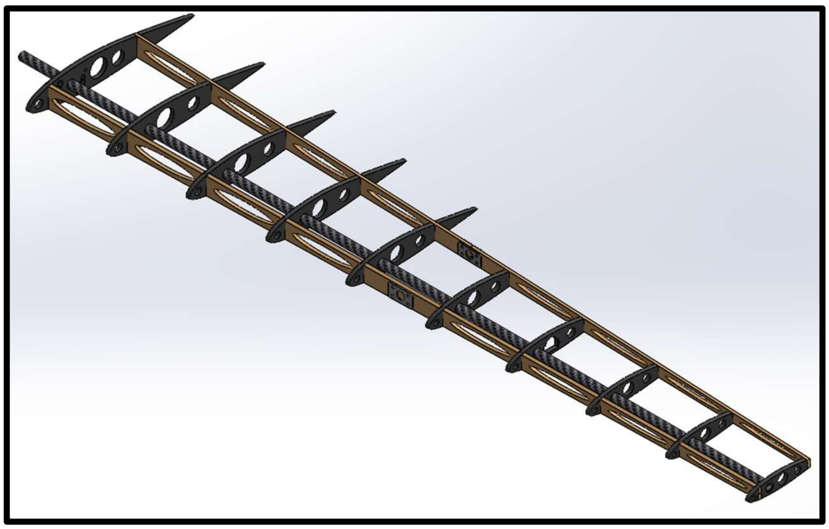


Figure 3. CAD Model of Internal Wing Structures

For the tail section (Figure 4), some of the same design details from the wings were employed. For example, the rudder and elevator utilize a taper ratio of 0.5, and the elevator includes an incidence of 4˚ to reduce stall. The airfoil provided for both tail stabilizers is the NACA 0012. Like the wings, each tail control surface is also driven by micro servos and a control linkage mechanism. For reasons mentioned later, the entirety of the tail is 3D printed using PETG. On the other hand, the tail boom is made of carbon fiber and is screwed into the hub section of the tail for easy removal and transportation.

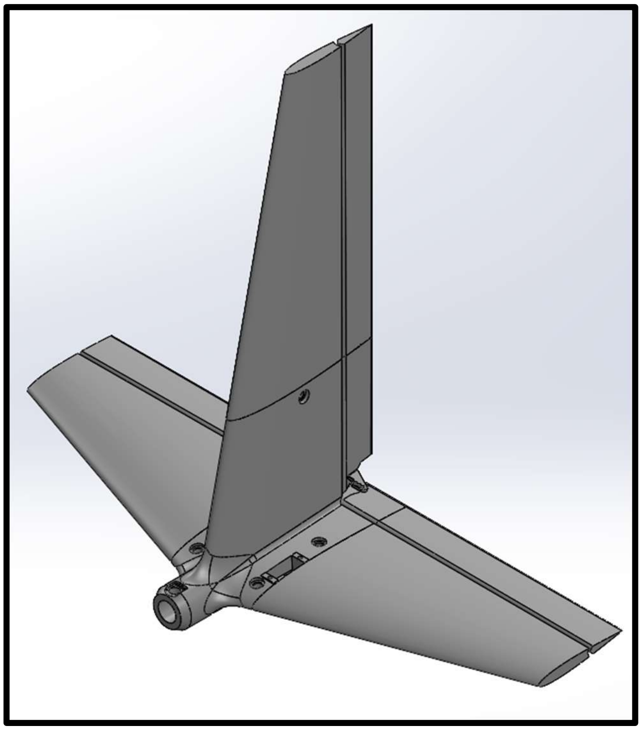


Figure 4. CAD Model of Tail Structures

Landing gear configuration follows the common tricycle design with the main gear (Figure 6) sightly rear of the wings and the front gear (Figure 5) located at the nose. The main gear is made of 6061 aluminum stock that attaches to the wheels. On the other hand, the nose gear is built from a ½" aluminum tube and uses collar clamps and a small spring for the suspension. The landing gear was designed to extend six inches below the fuselage. From the bottom of the main gear to the end of the tail, this creates a 12˚ angle which is plenty to avoid tail strikes during nominal takeoffs and landings. Additionally, the angle between the bottom of the main gear and the center of gravity creates a 25˚ angle which ensures the aircraft can liftoff during rotation speeds.

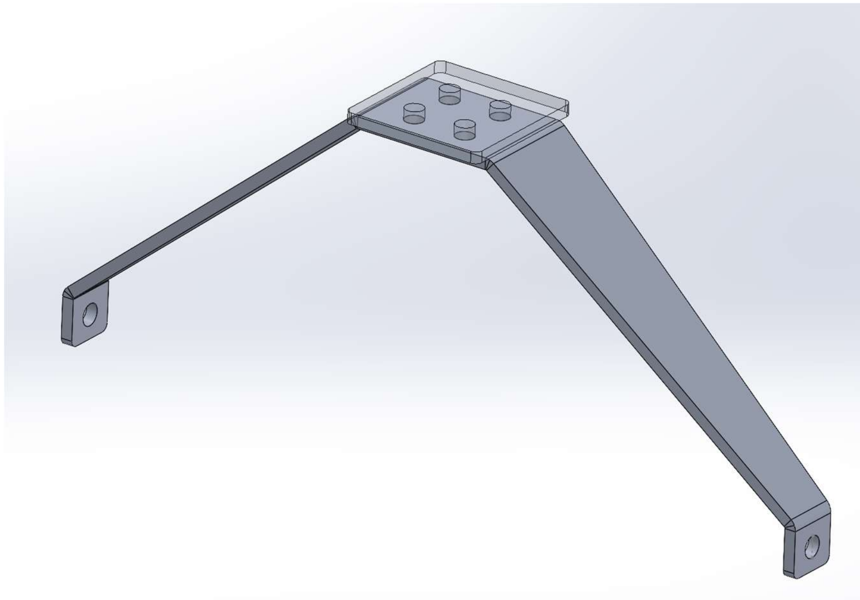


Figure 5. CAD Model of Front Landing Gear

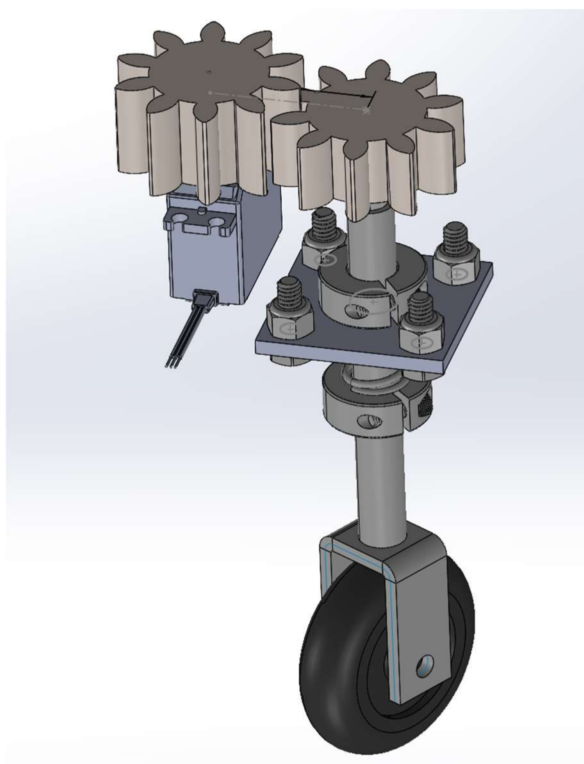


Figure 6. CAD Model of Main Landing Gear

The electronics payload tray (Figure 7) houses the important flight components and batteries. All electronics are enclosed in a 3D printed tray made of Polylactic Acid filament (PLA) and include mounting holes located at the bottom, allowing the tray to be secured to the fuselage. The electronic components contained in the payload tray are the following:

motor battery, electronic speed controller, Jetson Nano mini-PC, Pixhawk 6C flight controller with GPS, OAK DW camera, and additional batteries. Information and justification for these components cannot be provided by the Mechanical Engineering Senior Design team. Components were selected and programmed by the Computer Engineers of the embedded systems team.

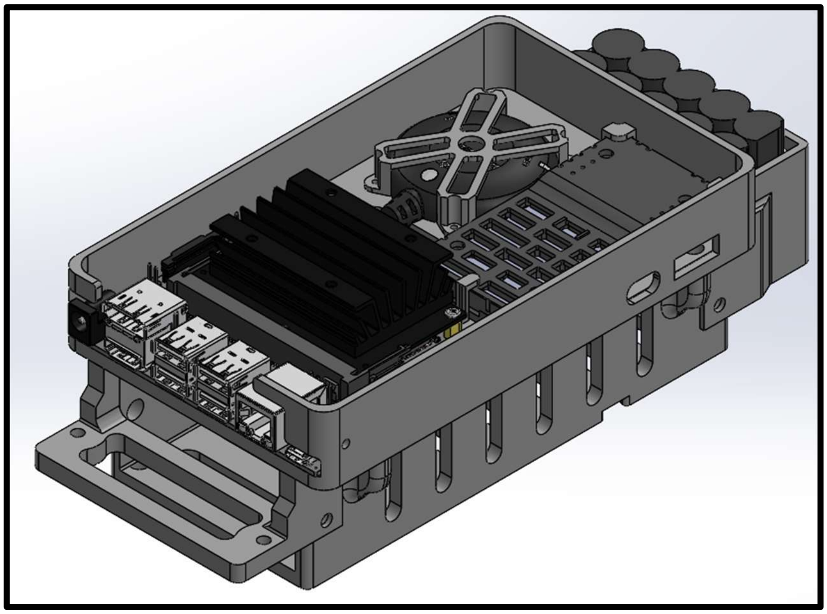


Figure 7. CAD Model of Electronics Payload Tray

2.2 Design Changes Since CDR

Since the Critical Design Review report, various design changes to the fuselage, wings, and the tail. Firstly, the nose and the empennage sections were initially designed to be made of composites, like the rest of the fuselage. There was difficulty in setting up the CNC hotwire to cut some of the complex contours of the components, and the machine was disassembled before the molds could be cut. Instead, it was decided to utilize standard FDM 3D printing to manufacture the aircraft nose and empennage of the fuselage. By following this approach, it increased accessibility to fuselage internals and the electronics payload tray. The selected material was PETG filament since it possesses more favorable material properties like heat and impact resistance. However originally planned to fabricate these components using the Markforged carbon fiber nylon filaments since it offers even better material properties; however, these efforts were cancelled due to availability issues and slow manufacturing times of the Markforged printers in the Mustang ’60 Machine Shop.

Similarly, it was decided to use PETG for the wing ribs and the entirety of the tail section for the same reasons discussed for the fuselage.

Furthermore, the fuselage shape was also redesigned with flatter sides for ease of manufacturing and mounting for the wings. Additionally, the design for a wing box clamp to secure the wings together was abandoned. Considering the component was also manufactured using 3D printing, the component was deemed unreliable under the extreme loading conditions. A carbon fiber tube was used in its place because of its simplicity and added stiffness. Lastly, the feature to drop the electronics payload from the bottom of the fuselage was not pursued due to concerns of weakening the internals. Instead, by the new ability to remove the empennage from the fuselage, the electronics payload tray was now able to be inserted via the rear of the aircraft.

3 Implementation

3.1 Procurement

Composite materials were purchased at a local supply store in San Luis Obispo known as The Craft. There, the 45˚twill weave carbon fiber as well as the s-glass fiberglass were obtained. The common materials and tools required to perform a wet composite layup were also purchased at The Craft.

Much of the remaining raw materials and hardware were procured from McMaster Carr, Amazon, and The Home Depot. Here, installation tools, PETG filament, birch plywood, aluminum stock, and various fasteners were collected. For any electronic, the aerodynamics and embedded systems teams worked together to gather the selected components.

3.2 Manufacturing

To ensure the success of the project, the team decided to manufacture composite skins for the wings and fuselage. The selected approach for manufacturing the composites was to use female molds and perform wet layups on the interior contours. The molds were made of foam board and cut using a CNC hotwire to accurately match the aerodynamic profiles modelled in CAD. Furthermore, to ensure proper distribution of resin, the mold with composites is placed under vacuum for one hour before letting it cure for at least 48 hours. Once the skins have cured, they are released from the mold, trimmed, and glued to the internal structures.

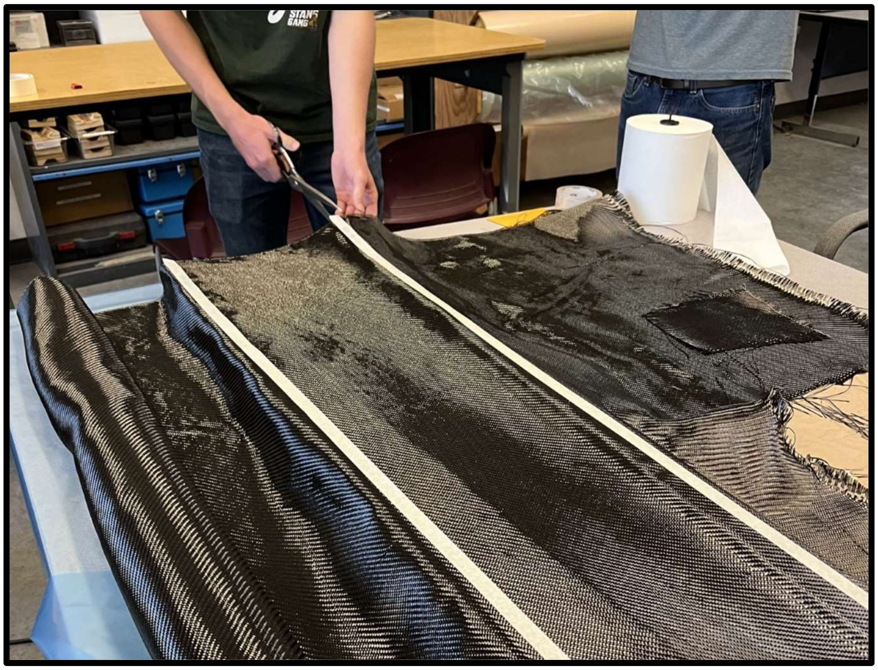


Figure 8. Preparation of Carbon Fiber for Wet-Layup

As mentioned before, the skin for the wings were manufactured using 45° twill weave carbon fiber. Preparing the materials before performing the layup was the first step in this process. Two layers (ply) of carbon fiber with at least one inch of excess over the leading and trailing edge contours of the mold were cut (Figure 8). Other materials such as the peel ply, release film, and breather were cut to match the dimensions of the mold. To ensure a proper vacuum seal and to prevent warping, the mold was placed on a steel sheet and surrounded by a line of tacking tape. The vacuum bag was then cut to be able to cover the mold and the base sheet, taking care to leave extra slack to allow for the material to conform to the contours of the mold while under vacuum. For the resin, West Systems 105 epoxy is mixed with the 206 slow hardener in a 5:1 ratio, totally in roughly the same weight as the fibers (~108g). The fibers were wet out on a section of vacuum bag that was stretch out on a table. Resin is added to the layer and squeegeed to ensure it has completely saturated the fiber. The same steps were followed for the second ply. Once both plies were saturated, the peel ply, perforated release film and a second section of vacuum bag were placed on the fibers. Air bubbles were squeegeed out for each layer as they were placed on. Finally, the complete stack was transferred to the mold on the metal sheet and topped with breather. The mold and fibers were sealed in the large vacuum bag (Figure 9) and vacuumed for approximately one hour and let rest while curing for another 48 hours.

Figure 9. Placing the Carbon Fiber in a Vacuum Bag After the Wet-Layup

After curing, the composite shell is removed from the mold. With proper PPE and ventilation, the excess composite and slot for the ailerons are cut using a Dremel.

For the fuselage skin, manufacturing follows the same steps as the wings that were just previously discussed, but the fuselage utilizes the three ply of s-glass fiberglass. Additionally, the fiberglass was place in taller molds for the fuselage (Figure 10).

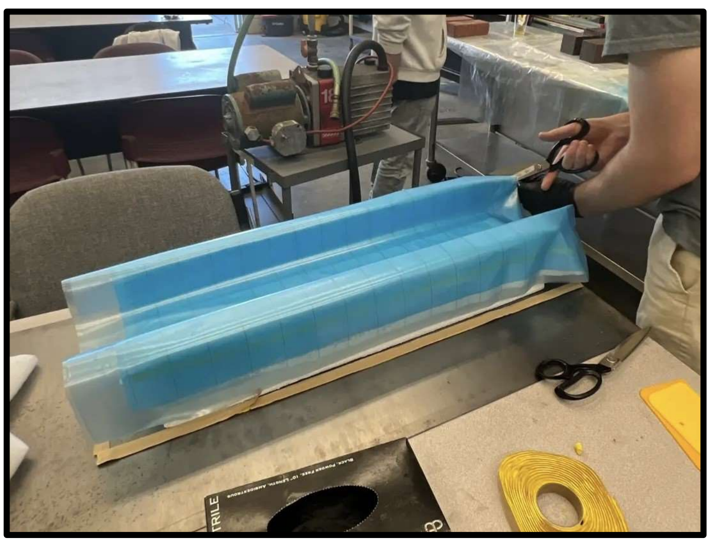


Figure 10. Preparing Fiberglass in the Fuselage Mold

Internal structures for the wings consisted of 3D printed ribs made of PETG and stringers laser cut from birch plywood. Similarly, the ailerons are also 3D printed using PETG. The ribs and stringers were designed with slots to interlock with each other for locating purposes and to aid with assembly of subcomponent. Once assembled, ribs, stringers, ailerons, and carbon fiber wing spars are glued together using Loctite super glue. Internal structures and the composite skin are then mated together (Figure 11) using *West Systems* Six10 epoxy.

Figure 11. Partially Completed Wings After the Top and Bottom Carbon Fiber Skin Sections were Adhered to the Internal Structure of the Wings

Like before, the fuselage consists of 3D printed ribs and birch wood laser cut stingers (Figure 12). On the other hand, the fuselage includes integrated mounting plates for the landing gear which were manufactured out of 1/8-inch 6061 aluminum using the water jet. The mounting plates where the wing interfaces with the fuselage are also made from ½ inch aluminum stock and are machined using the manual mill. Just like the wings, the internal structures are glued together before being permanently bonded to the composite skin.

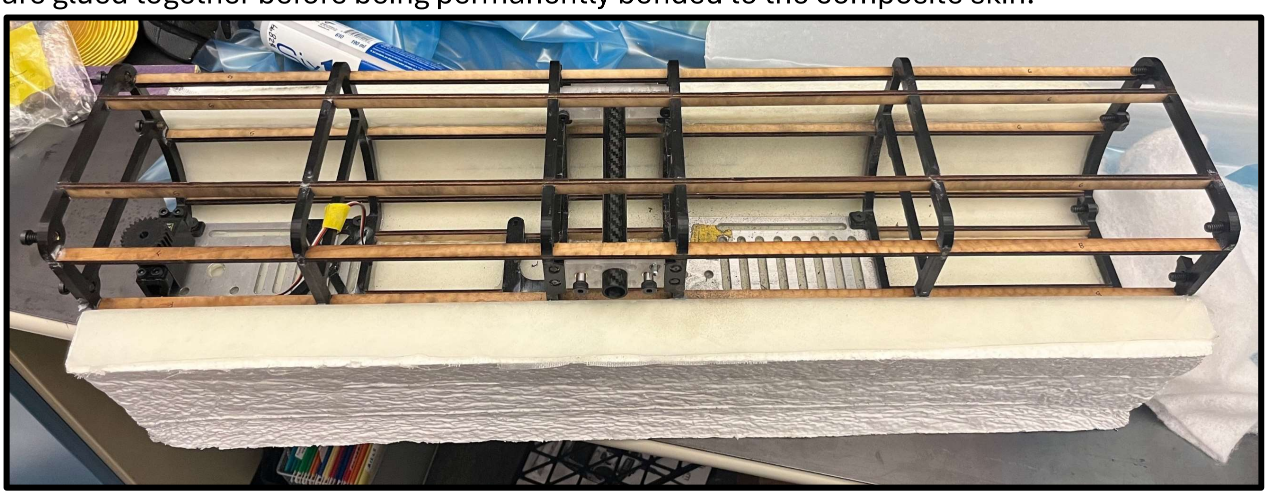


Figure 12. Internal Structure of the Fuselage After it was Adhered to the Bottom Skin Section

The electronics payload tray (Figure 13), tail section, nose, and empennage are 3D printed. The tray is made of PLA while the tail, nose, and empennage are all made of PETG for durability. These components are printed with three walls and utilize the honeycomb infill pattern at 10% density.

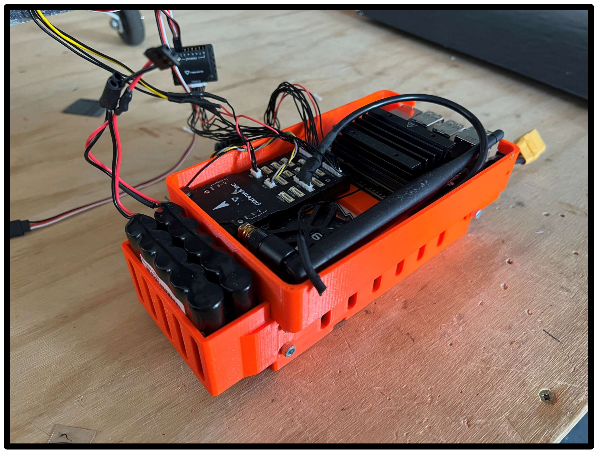


Figure 13. Assembled Payload with Embedded Electronics

Lastly, the main landing gear 2D profile is water jet from 1/8-inch 6061 aluminum stock. Eventually, the part is bent in the finger brake to achieve the specified angles design in CAD (Figure 14b). All water jet parts require the reaming of the holes to me for post processing to ensure correct tolerances. For the nose gear, a water jet aluminum piece is bent in a U-shape to where it is then welded to a ½ in aluminum tube (Figure 14a). Added to the subcomponent are two collar clamps along with a small spring for the suspension.

Figure 14a. Front Landing Gear

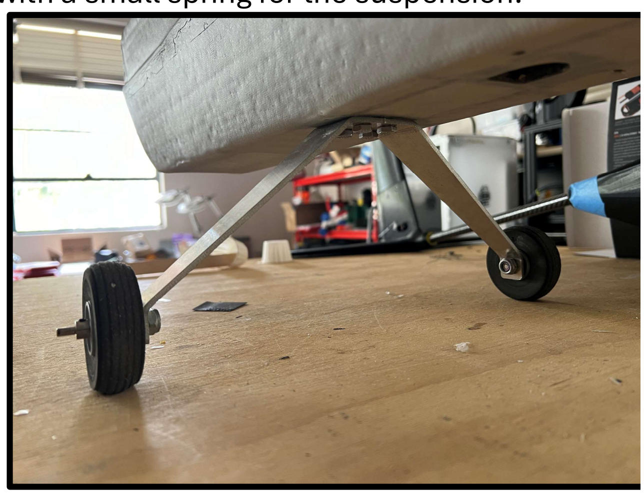


Figure 14b. Rear Landing Gear

3.3 Assembly

Final assembly was designed to be quick and easy considering one of the requirements from RFP is to be able to ready the aircraft in ten minutes or less. Both the nose and main landing gear are bolted to the aluminum mounting plates located at the underside of the fuselage. With all the electronics mounted inside of the payload, try, the entire tray is inserted at the rear of the aircraft and through the fuselage until it aligns with the mounting holes. From the exterior of the fuselage, four bolts are installed to secure the electronics payload tray. The main propulsion unit is mounted at the front of the nose cone. All cables from the motor are connected to the electronics and the nose is bolted to the fuselage. The tail section consists of four major pieces and are bolted together. An embedded nut inside of the central hub for the tail allows for the boom to securely screw into position. A similar action occurs where the boom connects with the empennage. With the entire rear end of the aircraft assembled, the empennage is bolted to the main fuselage just like the nose cone. Finally, the wings are installed by inserting each wing spar through the central carbon fiber tube housed in the fuselage. By lining the holes of the wings with the protruding bolts from the fuselage, the wings can twist-lock into place, completely the full assembly of the FRA (Figure 15).

Figure 15. Fully Assembled Fire Response Aircraft

3.4 Software & Electronics

As mentioned before, the Northrop Grumman Collaboration Project is a multidisciplinary project that includes an embedded systems team. The Mechanical Engineering Senior Design team's responsibility was to design the aircraft's mechanical structures. For this reason, the Computer Programming Engineers of the embedded systems team took responsibility for selecting and acquiring the required electronics and developing the autonomous flight system.

4 Design Verification

4.1 Specifications

Seen below in Table 1 are the design specifications established by the Northrop Grumman Request for Proposal (RFP) and the Mechanical Senior Design Team. Included within the table are the most important specifications relevant to the design and operation of the aircraft.

Table 1. Design Specifications

No.	Specification	Description	Target	Tolerance	Risk	Compliance
1	Flight Time	Operation time during flight	40 Minutes	Min	M	Analysis, Inspection
2	Trim	Aircraft stability can control	Good	Max	H	Analysis, Inspection
3	Weight	Total assembly weight	10 lb_m	Max	M	Analysis, Inspection
4	Assembly Time	Time it takes for aircraft to become operational	10 Minutes	Max	M	Testing
5	Cost	Total cost	$3750	Max	L	Analysis
6	Landing Gear Loading	Maximum applied force	30 lb_f	Max	H	Analysis, Testing
7	Manual Control	User input, non-autonomous	Yes	Max	M	Testing
8	Use Survey	Operation and capabilities	Good	Max	M	Inspection
9	FFA Requirements	Must meet guidelines	Yes	Max	L	Inspection
10	Operating Conditions	Maximum wind conditions	5 mph	Max	M	Analysis
11	Aircraft Speed	Expected flight speed during operation	35 mph	± 10 mph	M	Analysis, Inspection

To maintain an overall aircraft weight of 30 lb_m or less, it was highly considered from the start to use composites for the wing and fuselage skins. Based on the mechanical and material properties of both carbon fiber and fiberglass, it was deemed more than sufficient for withstanding the expected loads without sacrificing weight.

The weight of the aircraft directly affects the flight time specification of 40 minutes. Usually, increasing flight time suggests using either more or larger capacity batteries to satisfy the electronics power requirements; however, doing so results in further increasing the weight of the aircraft which ultimately reduces the flight time. Instead, optimizing the airfoils to fully utilize aerodynamic lift helps maintain flight characteristics while reducing the need for extra batteries. For this parameter, it is the responsibility of the aerodynamic team to select the optimal airfoil given the light parameters.

The specification for trim conditions relates heavily to the aerodynamics and control surface mechanisms. Determining the stability of the aircraft is analysis performed by the aerodynamics team. However, the control surfaces are used to maneuver the aircraft and maintain state equilibrium during cruise. Off-the-shelf radio-controlled servo motors were selected to drive the ailerons, rudder, and elevator since they are lightweight, easily integrated, and can deliver the required torque.

Regarding the challenge to assemble the aircraft in 10 minutes, the rotating studs and spring latch design was chosen for simple and easy collapsibility of the wings. The electronics payload is enclosed inside of a tray that can be inserted through the fuselage and secured to the bottom. Both the nose and empennage are non-permanently bolted to the fuselage to allow easy access to the aircraft's interior.

Cost specifications are less of a concern than others presented in Table X. Although some of the selected building materials like carbon fiber are expensive, the project has received sufficient funds from Northrop Grumman.

To withstand the anticipated 60 lb_f load during a rough landing or crash, it was thought to use a stiff, yet spring-like material for the main landing gear. Not only would it resist the external loading, but it would also act as suspension aid in dispersing the energy.

For the remainder of the specifications listed in Table 1, they are less significant regarding the design of the mechanical structures of the aircraft. Manual controlling is not within the scope of Mechanical Engineering Senior Design team and is handled by an experienced remote-controlled pilot. As the final design for the FRA developed, FAA requirements for Unmanned Arieal Vehicles were referred to ensure the aircraft is in full compliance. The use survey, operation conditions, and speed were verified during the testing of the FRA.

4.2 Testing and Results

Unfortunately, due to various setbacks and conflicts, the Mechanical Engineering Senior Design team was unable to perform any tests to verify the final prototype. Located in Appendix F are the test procedure that would have been performed had there been more time. Further discussion can be found in section 5.2 and 6 of this report.

5 Discussion & Recommendations

5.1 Discussion

For the 2024 Demo Day for the Northrop Grumman Collaboration Project, all members gathered at the Cal Poly Educational Flight Range near Cuesta College to demonstrate the capabilities of the four autonomous vehicles. Unfortunately, the FRA was unable to fly due to various reasons. With wind gusts upwards of 20 mph, it was advised by the Northrop Grumman mentors to cancel the flight to prevent the almost certain crash of the vehicle. Additionally, while inspecting the final assembly of the FRA, the Northrop Grumman mentors voiced concerns about the size and deflection of the control surfaces, explaining that the design would be insufficient in controlling the aircraft in any winding conditions. Lastly, it was discovered that the center of gravity (CG) of the FRA was slightly off compared to the calculated location. More specifically, the CG was too far behind the root quarter chord's leading edge, meaning the aircraft could not stand on its own and had reduced pitch authority from the elevators.

5.2 Recommendations and Next Steps

Given the feedback from Northrop Grumman and the failures mentioned in the previous section, members have already begun making the changes to the FRA. A selection of members from the Cal Poly SLO team have agreed to continue working on the first iteration of the FRA with the hopes of test flying in the beginning weeks of the summer. After all is completed, the aircraft will be handed off to the Cal Poly SLO team to continue working on for the 2024-2025 Northrop Grumman Collaboration Project.

Since the project's conclusion, some design recommendations for future iterations of the FRA were noted. It was initially decided to change the fuselage to a square shape purely for manufacturing and assembly purposes. Minor issues arose due to this decision in which it is believed that reverting the shape back to one with a more circular cross-section would increase the strength and stiffness of the fuselage. It was also thought that the current tail boom would be stiff enough for the application. Although it was true for bending, torsional stiffness was neglected, resulting in an unstable tail end and rising concerns of unwanted vibrations. Increasing the outer diameter of the tail boom should mitigate the rotational motion. It was also observed from Cal Poly Pomona's aircraft that connecting cables from the tail stabilizers to the fuselage should also increase the rigidity of the tail section.

6 Conclusion

Although the Fire Response Aircraft did not take flight, the Mechanical Engineering Senior Design team was successful in designing, analyzing, and manufacturing the structure of an autonomous drone. The team was fortunate enough to present the work in front of a panel of Northrop Grumman engineers and receive valuable feedback. Additionally, the team gained valuable experience with working and communicating with members of different disciplines. Especially since the project was not advertised to be a "club," the Senior Design team was able to overcome any challenges and deliver a fully assembled aircraft.

Unfortunately, conflicts during the early stages of the project caused major delays and prevented progress, reducing the overall time needed to complete the project. As a result, verification testing for aerodynamic flight, electronics, and mechanical structures were unable to be performed.

However, the Northrop Grumman Collaboration Project and the development of the FRA will continue after this year. Considering the Cal Poly SLO team has no prior experience designing and building a fixed wing autonomous drone, the Mechanical Engineering Senior Design team can leave the first historical data for future project members to learn from and continue developing.

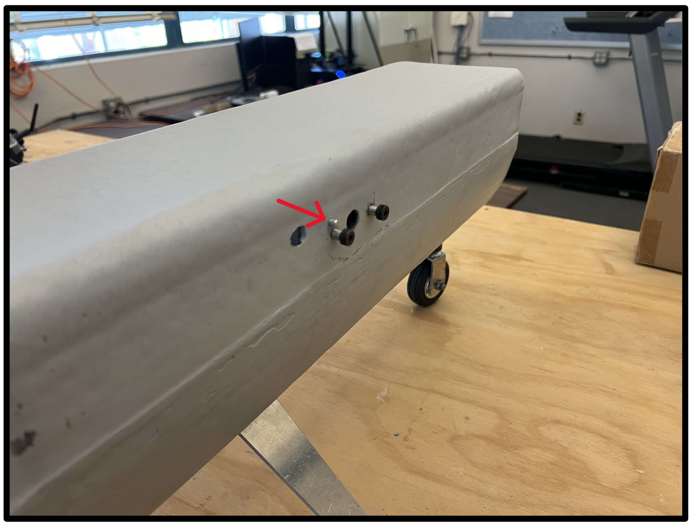
Appendices

Appendix A – User Manual

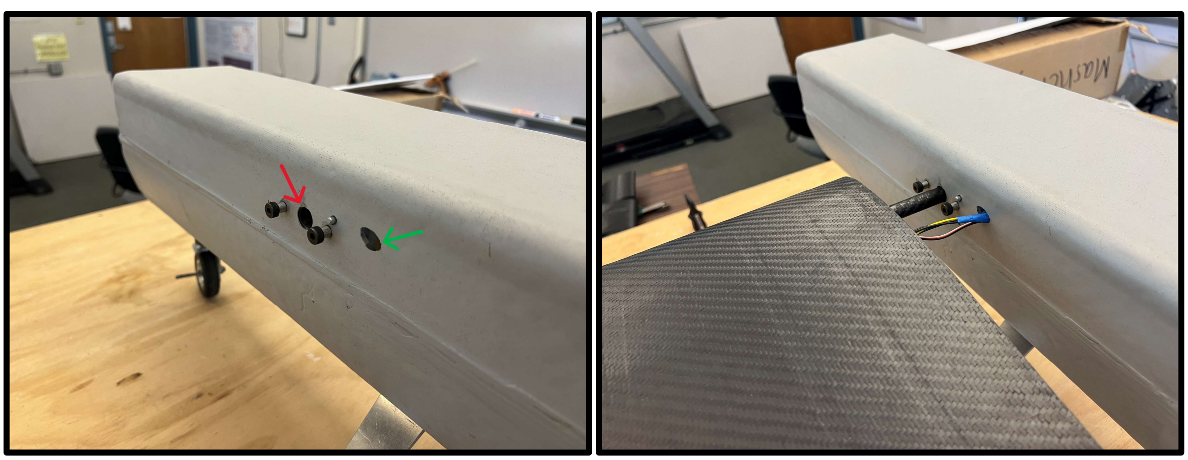
Per Northrop Grumman's requirements, the FRA should be assembled in under 10 minutes. The wings and tail can be removed to make the aircraft more compact and transportable. Additionally, the payload tray is removable, so the electronics are easily accessible. While safety precautions should be taken when operating the aircraft, no PPE is required for assembly.

Fire Response Aircraft (FRA) Assembly Instructions:

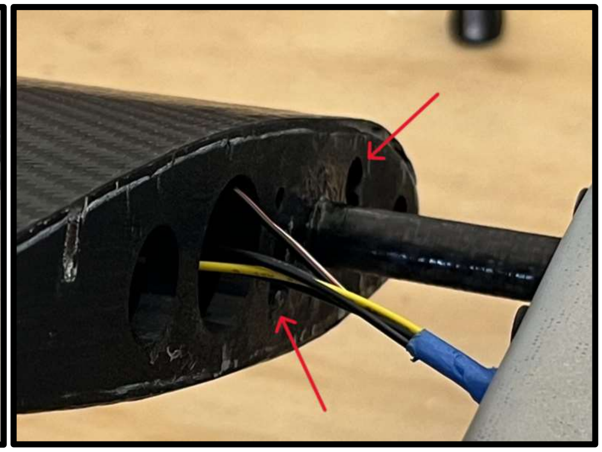
1. Ensure that the silver pins are poking out of the sides of the fuselage



2. Slide the wing spar tube for one of the wings into the spar hole and the wire feed hole located on the corresponding side of the fuselage.

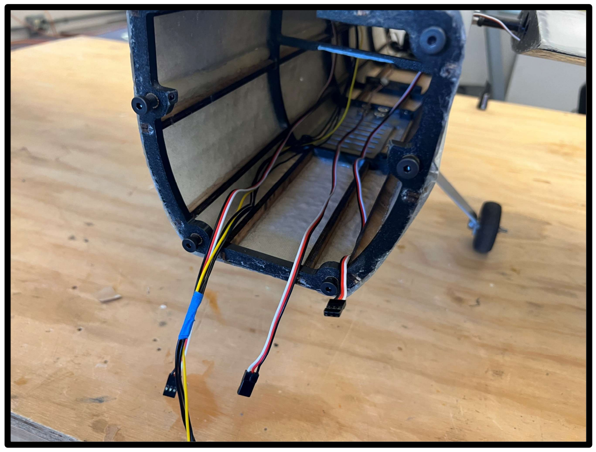


3. Rotate the wing slightly forward to align the largest portion of the slots in the wing root with the two bolts protruding from the fuselage. Then slide the wing up to the side of the fuselage.

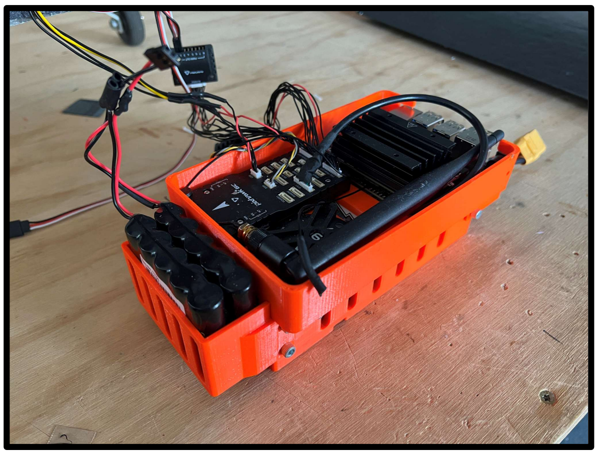


4. Rotate the wing downwards to engage the wing and lock it into place. (Optionally, place an object under the wing to prevent the wing and fuselage from tipping over).

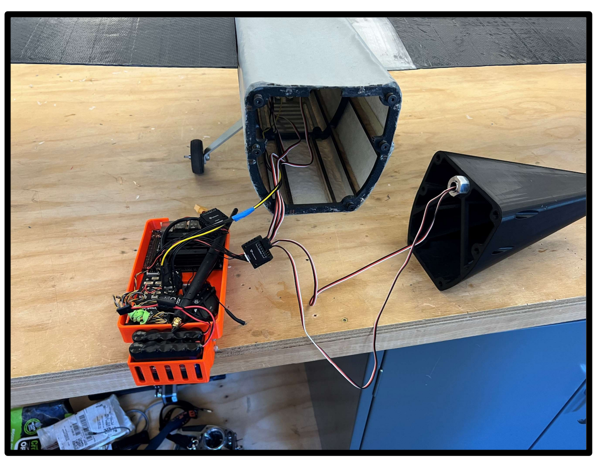
5. Repeat steps 1 and 5 with the other wing.
6. Prep for the payload by ensuring that all wires for the wings and servos are pulled through the back of the fuselage.



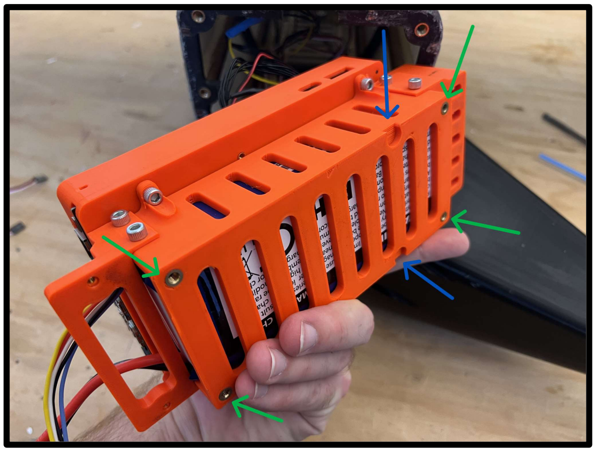
7. Ensure that the Payload contains all necessary components.

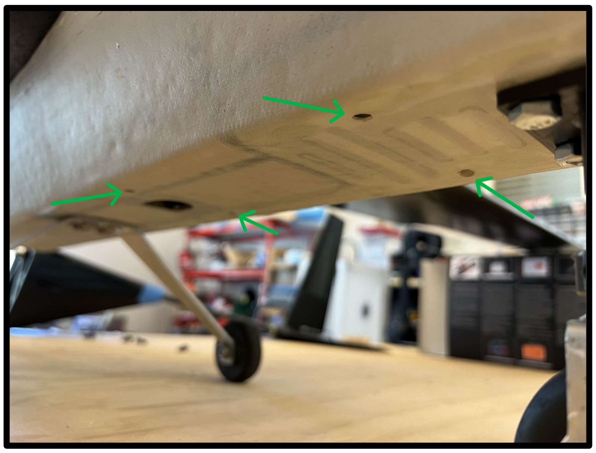


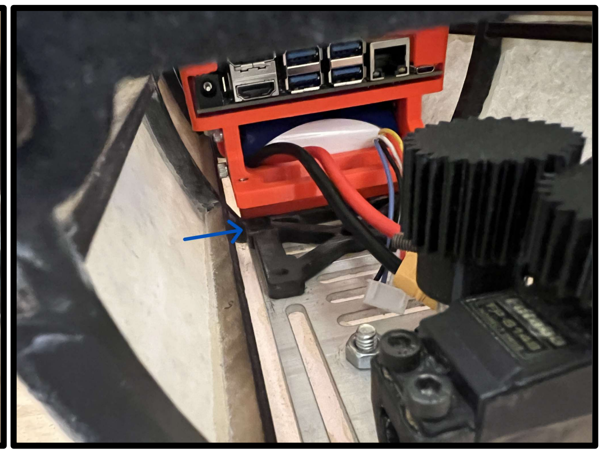
8. Connect the servo and sensor wires to the payload access points according to the layout found in the electronics manual written by the embedded systems team.



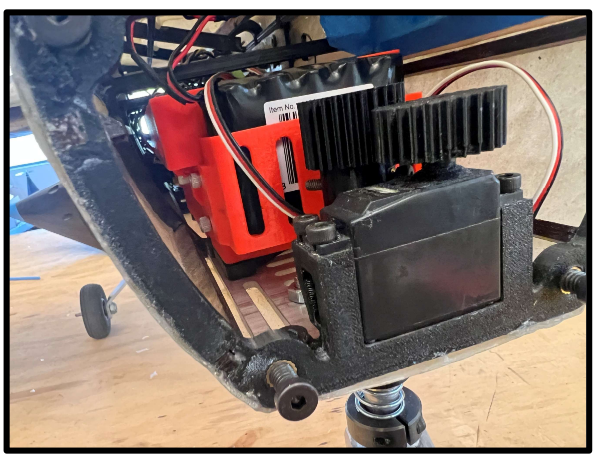
9. Slide the payload tray into the fuselage from the back. Align the two mounting slots and the four tapped holes with the lugs and holes in the fuselage.





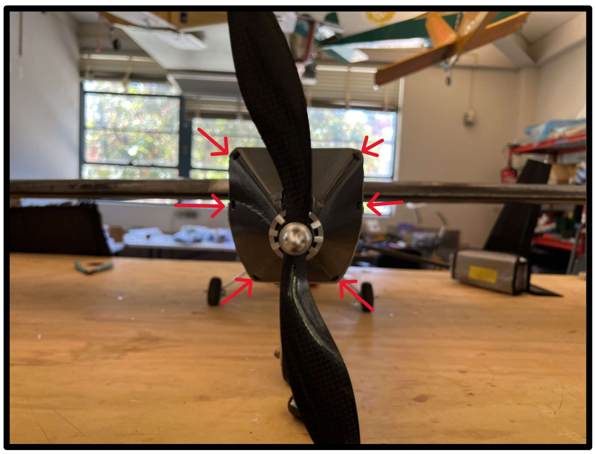


10. Ensure that the payload is seated and screw it in place

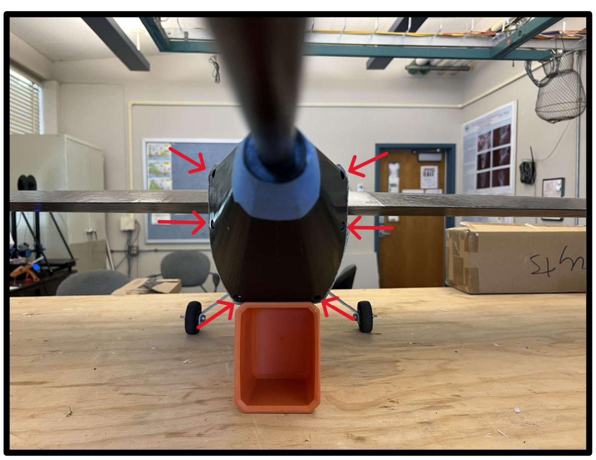


11. Connect the wires from the motor on the nose cone to the payload.

12. Secure the nose cone to the front of the fuselage by screwing hex key fasteners through the six counterbore holes in the nose cone to the threads in the fuselage.

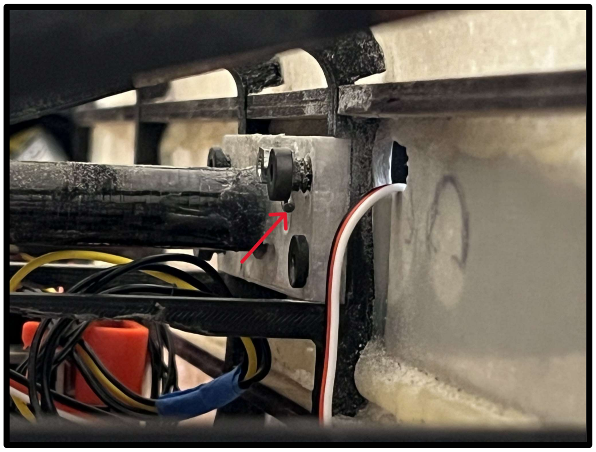


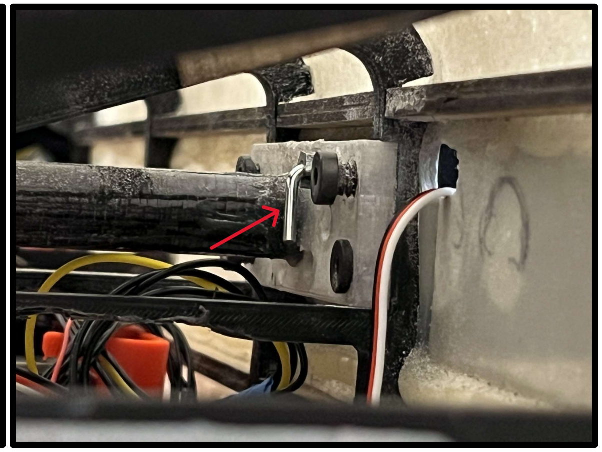
13. Secure the empennage (which should have the tail boom and tail surfaces already attached) to the rear of the fuselage by threading six hex fasteners through the empennage counterbore holes to the fuselage threads. (Optionally, place an object under the empennage to ensure that the aircraft does not tip backwards)



Fire Response Aircraft (FRA) Disassembly Instructions:

1. Complete the steps 6 through 14 in reverse order.
2. When removing the wings ensure that the pins are retracted. Pull the pin bars out and rotating them to lock them in the retracted position.



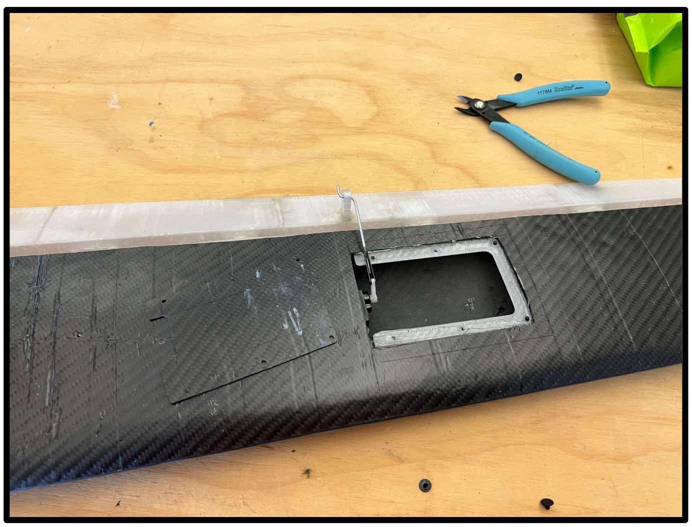


3. Then complete steps 2 through 4 in reverse order.
4. Repeat step 3 for the other wing.

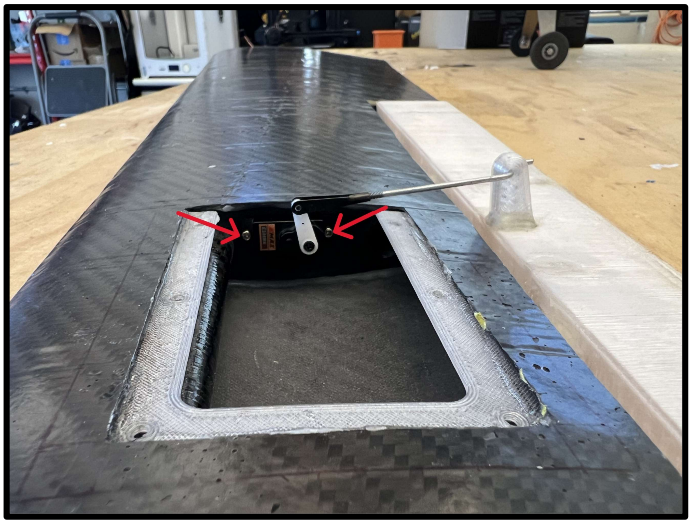
Access Panel Instructions:

1. Using a pair of flush cutters, cut the tops off the six plastic rivets securing the access panel to the wing.

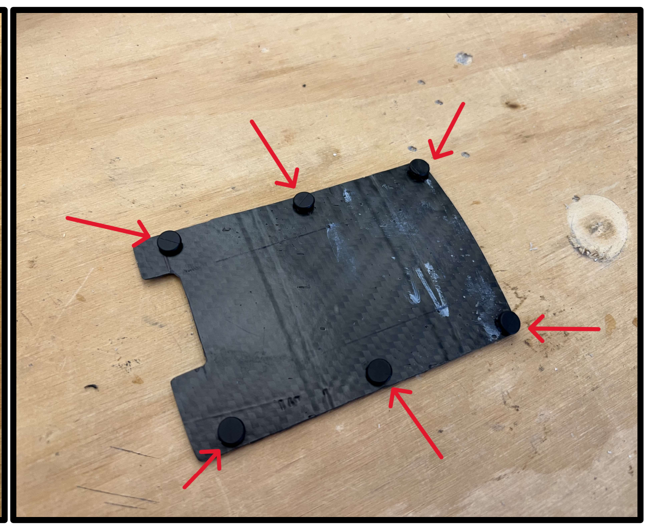
2. Remove the panel and push the remaining sections of the plastic rivets through the mounting holes.



3. The internally mounted servos can now be accessed. Remove the two mounting screws to remove servo.



4. Once internal repairs are completed, push six new plastic rivets through the six holes in the access panel.



5. Push each of the six plastic rivets through the holes in the wing to reattach the access panel

Appendix B – Risk Assessment

designsafe Report

Application: FRA

Description:

Product Identifier:

Assessment Type: Detailed

Limits:

Sources:

Risk Scoring System: ANSI B11.0 Two Factor

Analyst Name(s):

Company:

Facility Location:

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	RC Operator Flight	mechanical : cutting / severing	Serious Unlikely	Medium	standard procedures, instruction manuals, supervision	Serious Remote	Low	Action Item
1-1-2	RC Operator Flight	mechanical : unexpected start	Serious Unlikely	Medium	standard procedures, instruction manuals, supervision	Serious Remote	Low	Action Item
1-1-3	RC Operator Flight	mechanical : break up during operation	Moderate Unlikely	Low	standard procedures, instruction manuals, supervision	Moderate Remote	Negligible	
1-1-4	RC Operator Flight	mechanical : machine instability	Moderate Unlikely	Low	standard procedures, on-the-job training (OJT), supervision, instruction manuals	Moderate Remote	Negligible	
1-1-5	RC Operator Flight	slips / trips / falls : falling material / object	Minor Unlikely	Negligible		Minor		
1-1-6	RC Operator Flight	ergonomics / human factors : duration	Minor Remote	Negligible		Minor		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-7	RC Operator Flight	material handling : motor vehicle movement	Minor Remote	Negligible		Minor		
1-2-1	RC Operator Basic Trouble Shooting	mechanical : cutting / severing	Serious Unlikely	Medium	standard procedures, instruction manuals, supervision, gloves, footwear, warning label(s)	Serious Remote	Low	Action Item
1-2-2	RC Operator Basic Trouble Shooting	mechanical : pinch point	Minor Unlikely	Negligible		Minor		
1-2-3	RC Operator Basic Trouble Shooting	mechanical : break up during operation	Minor Unlikely	Negligible		Minor		
1-2-4	RC Operator Basic Trouble Shooting	slips / trips / falls : falling material / object	Minor Unlikely	Negligible		Minor		
1-2-5	RC Operator Basic Trouble Shooting	ergonomics / human factors : posture	Minor Unlikely	Negligible		Minor		
1-2-6	RC Operator Basic Trouble Shooting	ergonomics / human factors : lifting / bending / twisting	Minor Unlikely	Negligible		Minor		
2-1-1	Maintenance Technician Assembly/Disassembly	mechanical : pinch point	Minor Unlikely	Negligible		Minor		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-1-2	Maintenance Technician Assembly/Disassembly	mechanical : unexpected start	Moderate Unlikely	Low	standard procedures, instruction manuals, supervision, gloves, footwear, warning label(s)	Moderate Remote	Negligible	
2-1-3	Maintenance Technician Assembly/Disassembly	mechanical : break up during operation	Minor Unlikely	Negligible		Minor		
2-1-4	Maintenance Technician Assembly/Disassembly	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low	standard procedures, warning label(s), supervision	Moderate Remote	Negligible	
2-1-5	Maintenance Technician Assembly/Disassembly	electrical / electronic : unexpected start up / motion	Moderate Unlikely	Low	standard procedures, supervision, gloves, footwear, warning label(s)	Moderate Remote	Negligible	
2-1-6	Maintenance Technician Assembly/Disassembly	slips / trips / falls : falling material / object	Minor Unlikely	Negligible		Minor		
2-1-7	Maintenance Technician Assembly/Disassembly	ergonomics / human factors : posture	Minor Unlikely	Negligible		Minor		
2-1-8	Maintenance Technician Assembly/Disassembly	ergonomics / human factors : lifting / bending / twisting	Minor Unlikely	Negligible		Minor		
2-2-1	Maintenance Technician Set-Up	mechanical : cutting / severing	Serious Unlikely	Medium		Serious		
2-2-2	Maintenance Technician Set-Up	mechanical : unexpected start	Moderate Unlikely	Low		Moderate		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-2-3	Maintenance Technician Set-Up	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low		Moderate		
2-2-4	Maintenance Technician Set-Up	electrical / electronic : unexpected start up / motion	Moderate Unlikely	Low		Moderate		
2-2-5	Maintenance Technician Set-Up	slips / trips / falls : falling material / object	Minor Unlikely	Negligible		Minor		
2-2-6	Maintenance Technician Set-Up	ergonomics / human factors : excessive force / exertion	Minor Unlikely	Negligible		Minor		
2-2-7	Maintenance Technician Set-Up	ergonomics / human factors : posture	Minor Unlikely	Negligible		Minor		
2-2-8	Maintenance Technician Set-Up	ergonomics / human factors : repetition	Minor Unlikely	Negligible		Minor		
2-2-9	Maintenance Technician Set-Up	ergonomics / human factors : lifting / bending / twisting	Minor Unlikely	Negligible		Minor		
2-3-1	Maintenance Technician Start Machine	mechanical : cutting / severing	Serious Unlikely	Medium	standard procedures, supervision, warning label(s), gloves, footwear	Serious Remote	Low	Action Item
2-3-2	Maintenance Technician Start Machine	mechanical : unexpected start	Moderate Unlikely	Low	standard procedures, supervision, footwear	Moderate Remote	Negligible	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-3-3	Maintenance Technician Start Machine	electrical / electronic : unexpected start up / motion	Moderate Unlikely	Low	standard procedures, supervision, footwear	Moderate Remote	Negligible	
2-4-1	Maintenance Technician Parts Replacement	mechanical : pinch point	Minor Unlikely	Negligible		Minor		
2-4-2	Maintenance Technician Parts Replacement	mechanical : break up during operation	Minor Unlikely	Negligible		Minor		
2-4-3	Maintenance Technician Parts Replacement	electrical / electronic : unexpected start up / motion	Moderate Unlikely	Low	standard procedures, supervision, warning label(s), gloves, footwear	Moderate Remote	Negligible	
2-4-4	Maintenance Technician Parts Replacement	slips / trips / falls : falling material / object	Minor Unlikely	Negligible		Minor		
2-4-5	Maintenance Technician Parts Replacement	ergonomics / human factors : posture	Minor Unlikely	Negligible		Minor		
2-4-6	Maintenance Technician Parts Replacement	ergonomics / human factors : lifting / bending / twisting	Minor Unlikely	Negligible		Minor		
2-5-1	Maintenance Technician Trouble-shooting	mechanical : cutting / severing	Serious Unlikely	Medium	standard procedures, instruction manuals, supervision, footwear, gloves, warning label(s)	Serious Remote	Low	Action Item
2-5-2	Maintenance Technician Trouble-shooting	mechanical : pinch point	Minor Unlikely	Negligible		Minor		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-5-3	Maintenance Technician Trouble-shooting	mechanical : unexpected start	Moderate Unlikely	Low	standard procedures, instruction manuals, supervision, gloves, footwear	Moderate Remote	Negligible	
2-5-4	Maintenance Technician Trouble-shooting	mechanical : break up during operation	Minor Unlikely	Negligible		Minor		
2-5-5	Maintenance Technician Trouble-shooting	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low	standard procedures, instruction manuals, supervision, warning label(s)	Moderate Remote	Negligible	
2-5-6	Maintenance Technician Trouble-shooting	electrical / electronic : unexpected start up / motion	Moderate Unlikely	Low	standard procedures, instruction manuals, supervision, warning label(s)	Moderate Remote	Negligible	
2-5-7	Maintenance Technician Trouble-shooting	electrical / electronic : power supply interruption	Minor Unlikely	Negligible		Minor		
2-5-8	Maintenance Technician Trouble-shooting	slips / trips / falls : falling material / object	Minor Unlikely	Negligible		Minor		
2-5-9	Maintenance Technician Trouble-shooting	ergonomics / human factors : excessive force / exertion	Minor Unlikely	Negligible		Minor		
2-5-10	Maintenance Technician Trouble-shooting	ergonomics / human factors : posture	Minor Unlikely	Negligible		Minor		
2-5-11	Maintenance Technician Trouble-shooting	ergonomics / human factors : lifting / bending / twisting	Minor Unlikely	Negligible		Minor		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-5-12	Maintenance Technician Trouble-shooting	material handling : instability	Minor Unlikely	Negligible		Minor		
2-5-13	Maintenance Technician Trouble-shooting	material handling : motor vehicle movement	Minor Unlikely	Negligible		Minor		
3-1-1	Non-User Work Next to / Near Machinery	mechanical : cutting / severing	Serious Unlikely	Medium	standard procedures, instruction manuals, supervision, gloves, footwear, warning label(s)	Serious Remote	Low	Action Item
3-1-2	Non-User Work Next to / Near Machinery	mechanical : unexpected start	Moderate Unlikely	Low	standard procedures, supervision, footwear	Moderate Remote	Negligible	
3-1-3	Non-User Work Next to / Near Machinery	electrical / electronic : unexpected start up / motion	Moderate Unlikely	Low	standard procedures, supervision, warning label(s)	Moderate Remote	Negligible	
3-2-1	Non-User Walk Near Machinery	mechanical : cutting / severing	Serious Unlikely	Medium	standard procedures, supervision, footwear, warning label(s)	Serious Remote	Low	Action Item
3-2-2	Non-User Walk Near Machinery	mechanical : machine instability	Minor Unlikely	Negligible		Minor		
3-2-3	Non-User Walk Near Machinery	electrical / electronic : unexpected start up / motion	Minor Unlikely	Negligible		Minor		

Appendix C – Final Project Budget

*Complete project budget was withheld by the project manager and sponsor.

Appendix E – Design Verification Plan & Report (DVPR)

DVP&R - Design Verification Plan (& Report)											
Project:	Northrop Grumman Collaboration Project		Sponsor:	Dr. Lynne Slivovsky					Edit Date:	2/7/2024	
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipmen	Parts Needed	Responsibility	TIMING Start date	Finish date	Numerical Results	Notes on Testing
1	#3 Weight	Overall weight of the aircraft when fully assembled	Weight	10 pounds	Scale	n/a	Seamus				
2	#4 Assembly Time	Total time from unloading disassembled plane to plane being fully operational	Time	10 minutes	Human assemblers	n/a	Allison				
3	#6 Impact/Crash Force	Maximum force the aircraft should be able to withstand during a crash	lbf	900 lbf			Michael				
4	#7 Landing Gear Load Rating	Maximum force that can be applied to the landing gear during landing	lbf	60 lbf			Dominic				
5	#12 Wind Resistance	Maximum wind speeds the aircraft can safely and properly operate	mph	5 mph	Wind tunnel		Chase				
6	Wing Spar Testing						Michael				

Appendix F – Test Procedures

WING STRUCTURES

MODAL ANALYSIS

Objective

To determine the natural frequencies of the wing structures and compare them to critical frequencies that contribute to aerodynamic flutter.

Description of Test

The completed wing structures subassembly will be mounted to a shake table with an accelerometer which will measure the vibrations of the structure during a Sine Sweep test. The results will be displayed on the Spectrum Analyzer in the form of a Bode Plot. Two tests will be performed: The first will determine frequency range for multiple modes. The second test will more accurately determine the first natural frequency of the system as it is of most concern within the context of aerodynamic flutter.

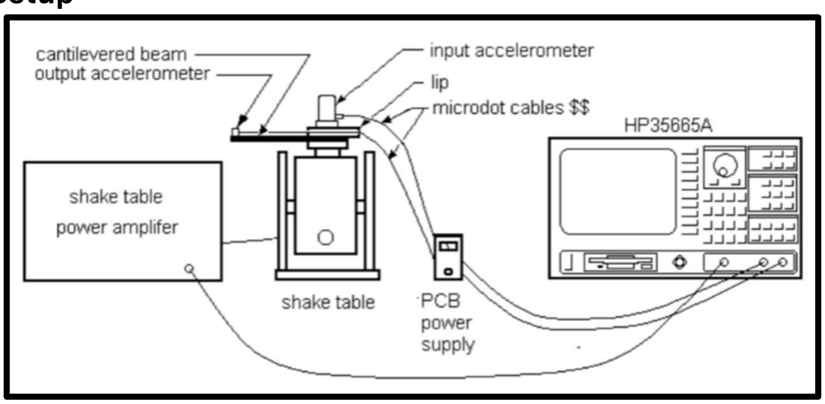
Location

Building 13: Engineering
Room: 102 – Mechanical Vibrations Laboratory

Personal Protective Equipment

1. No specific PPE is required to run this test.

Experimental Setup



Testing Equipment

- Input Accelerometer
- Output Accelerometer
- Shake Table
- Power Amplifier
- PCB Power Supply
- HP35665A Spectrum Analyzer
- Microdot Cables

- Mounting Adapter

Setup for Spectrum Analyzer

System Menu	
Preset	Do Preset
Measurement Menu	
Inst Mode	2 Channel Swept Sine
Input	Channel 1 Range: 1 V_{rms} Channel 2 Range: 1 V_{rms}
Frequency	Resolution: 400 points/sweep Auto Resolution: ON Sweep: Linear → Up → Auto *Test 1:* Start (10 Hz) – Stop (500 Hz) *Test 2:* Start (10 Hz) – Stop (100 Hz)
Source	Level: 0.5 V_{rms} Auto Level: OFF
Average	Fast Average: OFF *Test 1*: Settle Time & Integrate Time (50 Cycles) *Test 2*: Settle Time & Integrate Time (25 Cycles)
Display Menu	
Measure Data	Frequency Response
Display Format	Bode Diagram
Trave Coord	Linear Magnitude
Scale Active Trace Scale Active Trace	Auto Scale: ON N/A Auto Scale: ON N/A

NOTE: The left column represents the physical button on the Spectrum Analyzer. The right column represents the action needed on the digital display screen of the Spectrum Analyzer.

Test 1: Multiple Natural Frequencies

1. Set up the Spectrum Analyzer according to Table 1.
2. Mount the wing structure on the shake table via the adapter.
3. Connect all wires as shown in ***Experimental Setup***.
   NOTE: The wing structure is estimated to be a cantilever beam. Mount the accelerator in a similar fashion as shown in the figure.
4. Turn on the Power Amplifier, PCB Power Supply, and Spectrum Analyzer.
5. Perform a Sine Sweep test between the values of 10-500 Hz to capture multiple natural frequencies by pressing the orange START button.

6. The Bode plot will be display peaks of various heights which indicates the natural frequency. Record the x-position of the peak to obtain the natural frequency.

Table 2: Test 1 Results

Natural Frequency	***Value***	***Units***
ω_{n1}		Hz
ω_{n2}		Hz

Test 2: First Natural Frequency

1. Repeat the steps from **Test 1**; however, perform a Sine Sweep test between the values of 10-500 Hz to capture multiple natural frequencies.

Table 3: Test 2 Results

Natural Frequency	***Value***	***Units***
ω_{n1}		

End Procedure

After the sweep test has finished, the shake table will stop vibrating. Turn off all electronics and return all equipment.

Results

The results of the Sine Sweep test are in the form of a Bode Plot which can be transferred into a MATLAB file but is not necessary. A photo with the addition of the values recorded above will be sufficient in conveying the results.
Uncertainty analysis will be performed after the tests have been completed. Parameters of interest regarding uncertainty analysis are shown below.

Table 4. Uncertainty Analysis

Parameters	***Uncertainty***	***Units***
Spectrum Analyzer		
Weight of Wing Structure		
Accelerometers		
Function Generator		

NOTE: See official reports document for results with calculations and final uncertainty.

Performed By: ________________________ **Test Date:** ____________________________

Reference

California Polytechnic State University: Mechanical Engineering
ME 318: Mechanical Vibrations – Lab Manual for Cantilever Beam (Lab 6)

BONDING ADHESIVE
TENSILE AND SHEAR STRENGTH

Objective
To determine the maximum strength in both shear and axial loads that can be applied to the bonding adhesive before failure. The bonding adhesives bond the ribs and the wing to each other and need to be strong to withstand external forces during flight. This test will also identify if the shear or axial stresses are of higher concern.

Description of Test
Failure of the adhesive bonding is noted when the two adjoined parts start to detach from each other. Two metal pieces will be joined using the chosen bonding adhesive in a single lap shear joint. Each end will be placed in the jaws of the wedge grip attachment of an Instron Universal Testing Machine. A tensile load will be applied to the system until the adhesive fails. The load at which it fails is the maximum strength of the bonding adhesive.

Location
Building: 41B – Aerospace Laboratories
Room: 136 – Structures/Composites Laboratory

Personal Protective Equipment
1. Safety Glasses
2. Long Pants
3. Closed-Toe Shoes

SAFETY WARNING: Always be sure to lower the protective plexiglass cover before conducting each sample.

Testing Equipment
- Instron Universal Testing Machine
- Metal Sheets
- Bonding Adhesive

Procedure
1. Cut two pieces of metal to be 1” wide and 6” long.
2. Overlap the pieces by 1” and join them using the bonding adhesive.
3. Place each end of the joined piece into the upper and lower jaws of the wedge grip attachment on the Instron machine so that at least 1” is gripped on each side.
4. Follow operation procedures for the Instron Universal Testing Machine. This will not be covered in this test procedure. Begin operating the Instron until the adhesive fails. Note the load at which the adhesive fails in Table 1.
5. Repeat 2-4 to test for shear strength as well.

Table 1. Example Data Collection

Sample	Tensile Failure Load (psi)	Shear Failure Load (psi)
1	2500	5000

Performed By: ______________________________**Test Date:** ______________________________

Reference
California Polytechnic State University: Mechanical Engineering

WING LOADING

ULTIMATE STRESS TEST

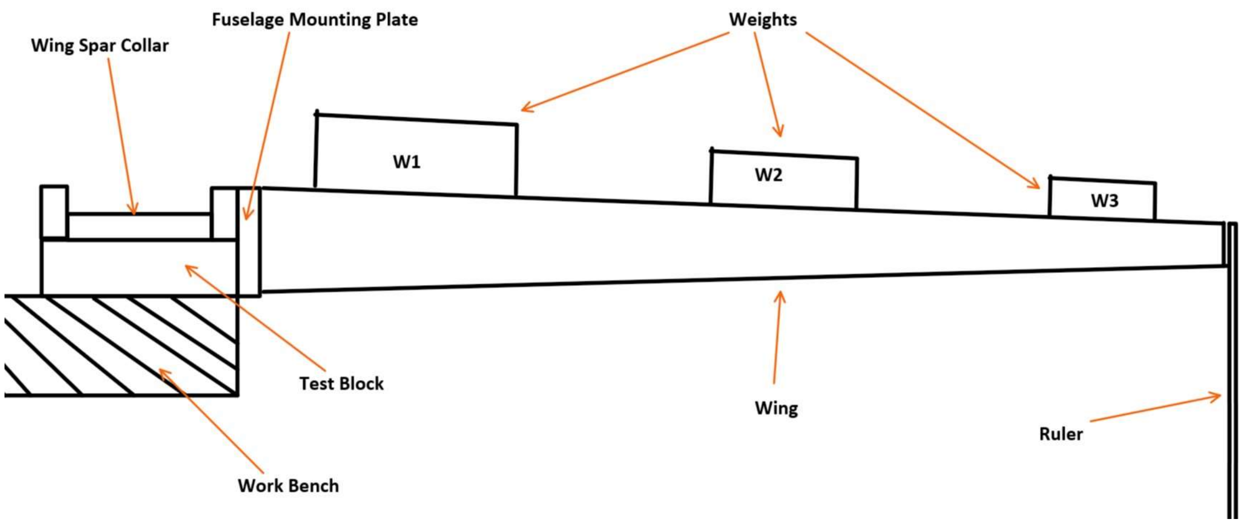
Objective
To determine if the constructed wing design will fail under maximum expected loading conditions during normal operation.

Description of Test
A test block that is complete with the fuselage mounting plate and internal collar will be affixed to a working bench. The wing will be attached to the test block upside down, so that added weights will load the wing in the same direction as the lifting force. Measured weights will be placed on the wing to match desired distributed loads across the wing. The two load distributions will be an elliptical profile to simulate the non-uniform lifting force on the wing, and a uniform distributed force to obtain a conservative estimate of performance.

Location
Building: Aero Hangar

Personal Protective Equipment
1. Eye Protection
2. Closed Toe Shoes
3. Pants
4. Gloves

Experimental Setup



Testing Equipment

- Test Mounting Block
- Ruler
- Measured Weights
- Wing
- Work Bench
- Clamps

Test 1: Non-Uniform Lift

1. Assemble the Test Block with the Wing Spar Collar and Fuselage Mounting Plate a Ensure that the Fuselage Mounting Plate is mounted such that the wing will be inverted once it is attached
2. Clamp the test block to a work bench
3. Attach the wing to the Test Block
4. Measure the distance from the ground to the tail end of the airfoil at the tip of the wing a Record this value as the Starting Height in Table 1
5. Add the three weights to the wing
6. Record the Ruler Measurement
7. Determine the Wing Deflection by subtracting the Ruler Measurement from the Starting Height
8. Note if the wing experiences a visual failure (skin cracks, or irreversibly deforms)
9. Repeat steps 1-8 for all weight distributions

Table 1: Test 1 (Non-Uniform Lift) Results

Starting Height [in]			
Weights (1,2,3) [lbs]	**Ruler Measurement [in]**	**Wing Deflection [in]**	**Failure**
W1, W2, W3			
W1, W2, W3			
:	:	:	:

Test 2: Uniform Conservative Lift

1. Repeat steps 1-4a, if the experimental setup is not still assembled
2. Evenly distribute the conservative weight load uniformly across the wing
3. Repeat step 6-8 and record in Table 2

Table 2: Test 2 (Uniform Lift) Results

Starting Height [in]			
Weight [lbs]	**Ruler Reading [in]**	**Deflection[in]**	**Failure**
W			

End Procedure

Disassemble the experimental setup. Remove the wing from the test block and remove the clamps from the test block. Return the test block, wing, and clamps to their sources.

Results

Uncertainty analysis will be performed after the tests have been completed. Parameters of interest regarding uncertainty analysis are shown below.

Table 3. Uncertainty Analysis

Parameters	Uncertainty	Units
Wing Weight		
Weights		
Ruler		

Performed By: ______________________________ **Test Date:** ________________________________

Test Name:
Control surface deflection test

Purpose: *(This is the purpose of the test)*
Test the actuation of the control surfaces by the servo motors

Scope: (Defines what feature or function the test is for)
Control surfaces

Equipment: (List of equipment necessary, diagram of apparatus from Experimental Design Planning Form)
This test requires a servo tester that connects to the servos to actuate the control surfaces. It also requires a protractor to verify the angles. **Hazards:** (list hazards associated with the test)
The servos and tester will be electrically wired to a 6 volt battery. There is an electrical shock hazard associated with this test.

PPE Requirements: (e.g. safety goggles, respirators)
None

Facility: (Where the test should occur)
Test will occur in the club workroom.

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) Connect the servo tester to the battery and servo.
2) Actuate the servo to its maximum upward and downward deflections.
3) Measure and record the angle at the maximum deflections.

Results: Pass Criteria, Fail Criteria, Number of samples to test, Design analysis equations/spreadsheet with uncertainty. Comment on how Uncertainty Analysis will be completed.
Control surfaces must deflect 20+5 degrees. Five samples will be taken for each direction for each control surface. Any samples below 20 degrees will result in a failed test.

Test Date(s):
Test Results:
Performed By: Seamus Robinson