NORTHROP GRUMMAN Collaboration Project (NGCP)

Final Design Review

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Statement of Disclaimer

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Abstract

The following paper details the final stage of the design process for the mechanical engineering senior project team (the Team) of the Northrop Grumman Collaboration Project club (NGCP) at California Polytechnic State University-San Luis Obispo (Cal Poly SLO). After receiving the design requirements from the Northrop contact, the Team set out designing the drone frame, payload system, fire suppression system, and electronics enclosures to meet the requested requirements. The design and early manufacturing plans can be found in the preliminary and critical design reviews—PDR and CDR, respectively, that accompany this document.

This document details the final design, manufacturing, assembly, and testing of the components designed by the Team. Since the feedback from CDR and presenting the designs to Northrop officials, the Team implemented a few design changes to better meet the customer’s needs. After these changes, the Team manufactured the composite frame material, and used 3D printing on each of the four systems (frame, payload, fire suppression, and electronics) to help keep costs and manufacturing time low. Once the components were completed and assembled, they were tested individually and in the full rescue mission sequence.

Of the four systems, three met the requirements set forth by Northrop (the frame, payload, and fire suppression systems). The composite frame withstood all flight and drop conditions, the payload mechanism was able to safely raise and lower the 2lb. payload, and the fire suppression systems was able to successfully deploy the suppressant on target. The electronics system, meant to keep the sensitive electronics components reasonably safe from water intrusion, did not meet the set requirement due to manufacturing inconsistencies and modifications made by the NGCP electronics team. These results help to bring the future of low cost, autonomous rescue drones closer to the present.
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1. Introduction

The Northrop Grumman Collaboration Project (NGCP) is a collaborative club project sponsored by Northrop Grumman for the students of Cal Poly San Luis Obispo (CPSLO) and Cal Poly Pomona (CPP) to create a fleet of vehicles to aid in the simulated rescue of a stranded hiker. The CPSLO club is responsible for delivering an autonomous flight vehicle that can suppress a fire and retrieve a payload. The four authors of these reports are the senior project members, who also are the lead engineers for the Mechanical Design Team of the CPSLO team. We, the Mechanical Design Team, are responsible for the design of the frame, electronics housing, payload, and fire suppression systems as their senior project.

As this is the last report for the project, it contains all previous reports, including the scope of work (SOW), preliminary design review (PDR), and critical design review (CDR), followed by the main content of this report, the final design review (FDR). The inclusion of the previous reports helps to show the design cycle of the project and illustrate how the design specifications and parameters were determined in the SOW, how the design selection process unfolded in the PDR, with the CDR report showing how the Mechanical design team planned to manufacture the designs, and the FDR showing the planned tests and results to verify the design specifications were met. Each report will be included as they are finished and will each have their own table of contents as well as appendices to help maintain report clarity.

Since the CDR report, the NGCP club presented our work to Northrop officials and received feedback on the design. The main point of concern for the Northrop employees was the off axis thrust imparted by the actuation of the fire extinguisher. To help mitigate the sudden thrust, the Team has designed a hose and bracket system to reroute the extinguisher thrust under the drone. More details of this design can be seen in the design overview section.

2. Design Overview

This section discusses the final iteration of the design developed over the last two quarters.

2.1. Design Description

The design scope includes the frame system, the fire suppression system, the payload retrieval system, and the electronics housing system. In Figure 1 below, the four sections of the design can be seen. Each of these four sections will be discussed in more detail in the following subsections.
2.1.1 Frame Subsystem

In Figure 2 below, the final design for the frame subsystem is shown. All the components of the subsystem are highlighted with text and arrows. The central structural parts of the frame are made from carbon fiber composites, while the motor cuffs are aluminum, and the legs are ABS plastic. The different components are fastened to each other with bolts.
2.1.2 Fire Suppression Subsystem

In Figure 3 below, the final design for the fire suppression subsystem is shown. All the components of the subsystem are highlighted with text and arrows. This subsystem consists of a stepper motor that pulls the fire extinguisher handle with a cord and a series of links. Furthermore, a hose (not shown) fits around the fire extinguisher nozzle and redirects the spray through the hose bracket. The hose bracket is located in the center of the frame, so that the fire extinguisher spray does not produce an offset thrust that might tip the drone.

![Figure 3: CAD model of the fire suppression subsystem.](image)

2.1.3 Payload Retrieval Subsystem

In Figure 4 below, the final design for the payload retrieval subsystem is shown. All the components of the subsystem are highlighted with text and arrows. The payload retrieval subsystem consists of a stepper motor that rotates a shaft that has cords wrapped around it. The cords go down to the truss, so when the shaft spins the truss is lowered or raised. The truss is connected with cord to the payload box, which folds outwards when it makes contact with the ground, designed for easy placement of a payload by a ground vehicle. Finally, the winch cage serves as a platform for mounting the motor and shaft. The winch cage is bolted to the carbon fiber frame.
2.1.4 Electronics Subsystem

In Figure 5 below, the final design for the electronics subsystem is shown. All the components of the subsystem are highlighted with text and arrows. The electronics subsystem comprises five boxes and their lids, all of which are 3D printed from PLA. The boxes have small legs at the bottom. These legs have holes for attaching the boxes to the carbon fiber frame with bolts. They also serve to raise the floor of the box up from the top carbon fiber plate. This allows for wires to be run under the boxes. The lids have extrusions that fit around the edge of the box, so that the lids stay put when they are pushed down onto the box.
2.2. Design Changes Since CDR

As mentioned in the introduction, the Team has added a hose and hose bracket to the fire suppression system to help mitigate off axis thrust. The concern with the off axis thrust imparted by the actuation of the fire extinguisher is that the flight controller on board the drone is not sophisticated enough to correct for such a large and sudden force. Additionally, the force would be placed between two of the motor arms which would likely cause the drone to tip or even flip, which would not be a recoverable flight orientation. By using the hose to route the suppressant agent below the drone’s center of mass and the hose bracket to hold it at the center of the small plate, the thrust will act at the center of the six motors and supply equal thrust to all motors, as seen in Figure 6. As a result, the drone may experience a brief increase in altitude but should be able to remain over the target.

Per the request of the Aero team, the Team designed a bridge for the Pixhawk and GPS unit to sit above the fire extinguisher, which allows the devices to sense more accurately. The design was printed out of PLA to be both lightweight and stiff.

Lastly, some of our 3D printed parts have been changed since the design phase with the goals of either being more ergonomic or facilitating printability.
3. Implementation
This section discusses how the final design was taken from CAD model to functional prototype. The final Team budget is available in Appendix C.

The CAD model of the drone used in-context design to ensure that different components did not interfere with each other and, if they were meant to be attached to each other, had matching bolt holes. Furthermore, parts were designed with procurement and manufacturing in mind. For example, the motor cuffs were designed to be cut from commercially available aluminum tube stock, and 3D printed parts were designed to fit into the maximum footprint allowed by Mustang 60’s 3D printers.

Once the design of the parts was finalized in CAD, the next steps were procurement, manufacturing, and assembly.

3.1. Procurement
The Team endeavored to purchase parts and materials that could be locally obtained to minimize delays due to shipping. For a detailed breakdown of the price and source of the materials, see Appendix C – Final Project Budget. From intentional design consideration in the beginning of this project, a significant portion of the drone parts were designed to be 3-D printed parts, which have minimal associated costs thanks to the free 3-D printing resources on campus, such as Innovation Sandbox.

For components such as the motors for the fire and payload subsystems, the Team placed orders online early in the manufacturing phase so that the components would arrive before they were needed for testing. For the fasteners, fire extinguisher, and hose the Team spent some time finding products readily available in the local hardware stores so that the components could be acquired in person. Similarly, the carbon fiber materials were acquired locally at The Craft, through the recommendation of the composite instructor.
3.2. Manufacturing
The manufacturing process can be broken down into three categories: carbon fiber process, 3-D printing, and shop work.

3.2.1 Carbon Fiber
The carbon fiber process began by working with the composites professor, Dr. Eltahry Elghandour, to determine the best method of producing the components in the design. As the Team was new to making carbon fiber parts, the professor helped the Team decide on the type and thickness of the carbon fiber fabric as well as the lay-up process.

There are two main types of carbon fiber fabric: plain carbon fiber fabric and pre-impregnated (prepreg) carbon fiber fabric. Prepreg carbon fiber comes from the manufacturer reinforced with a resin system [1] and is used in dry lay-ups. There are some advantages to prepreg material such as an even distribution of resin in the fibers and more predictable strength properties. However, they are much more expensive and require more curing time. As such, the composites professor recommended the use of plain carbon fiber, which requires wet lay-ups. A wet lay-up involves weighing the fiber to be used and mixing an appropriate amount of two-part epoxy to achieve the desired material characteristics. However, wet lay-ups do require more work prior to laying the fiber, there is more control in the process. The Team decided to follow the recommendation and use the wet lay-up process for both the plates and the arms. Figure 7 is a photo taken from the sandwich panel wet layup.

![Figure 7: The wet layup of the carbon fiber sandwich panel used for the arms.](image)

The Team started with making the bottom plate, which involved two sheets of the 0.04 in carbon fiber fabric, which weighed approximately 300 grams. With an equal amount of epoxy, the two sheets were wetted and stacked before being placed under vacuum (which helps to fuse the two sheets together). The top plate was created using the same process, although more fabric and epoxy was used due to the larger size of the top plate.

Once the Team finished the plates, several sandwich panel test pieces were made to help familiarize the Team with the sandwich panel lay-up process as well as provide different material types for load testing. With weight and strength in mind, the Team decided to use three 0.25 in thick foam layers, each separated
by a layer of carbon fiber, as the core material of the arms. Similar to the plates, the carbon fiber was weighed and the corresponding about of epoxy was mixed before stacking the three foam sheets between four sheets of carbon fiber and pulling a vacuum. Once the epoxy was cured (time varied due to quantity and whether heat was applied), the carbon fiber sheets were removed from the vacuum surfaces and were ready to be cut down to final dimensions in the shop. The sheets were cut into long strips and then, depending on their designated part function, cut into either shorter beams or a single longer beam.

3.2.2 3-D Printing

The process of 3-D printing involved creating the part in CAD and saving the part as an STL file which saves the part as a complex web of triangles. The STL files were then either sent to the Innovation Sandbox (the free 3-D printing resource on campus) or to one of the Team members to print on their personal 3-D printer. Prior to printing, the STL files must be processed by a slicer program which transforms the complex web of triangles into G-code that the printer can understand. That G-code is then loaded into the printer’s memory and then the printing will begin. Print time varies for each component as some have much more complex designs or were larger in size. Once the prints are finished and any support material has been removed, the parts are ready to be integrated into the design. The philosophy behind which parts were chosen to be 3D printed was dependent heavily on how complex their shape is and how much of a structural role did each of those parts played. Parts under a high structural load were opted to be carbon fiber or metal. Figure 8 is an example of one of the may complex parts printed on the 3D printers.

![Figure 8: A 3D printed fire extinguisher bracket, with the supports still attached.](image)

One lesson that the Team learned is that 3D printed parts for a project should begin to be printed as soon as possible. Although the Team had CAD files for the parts early in the manufacturing phase, the Team did not begin the 3D printing them until later in the manufacturing phase. The Team then encountered delays in 3D printing due to the availability of 3D printers.
3.2.3 Shop Work
The shop work for this project involved use of the tile saw, horizontal bandsaw, laser cutter, and drill press. The tile saw was used to cut the carbon fiber plates and sandwich panels down to their respective dimensions, and the drill press was used to drill the fastener holes in the sandwich panels that became arms. The laser printer was used to make a drill template for the hole of the top and bottom plates. The template was made of scrap plywood and the pattern was taken directly from the CAD model. This ensured the plates were drilled in the correct location for alignment with the other components. The horizontal bandsaw was used to cut down the aluminum bar stock which became the motor mounts for the six motors. The drill press was used to ensure the fastener holes in the arms were in the correct position as well as made in the correct orientation (vertical).

For cutting arms out of the composite panel, the Team marked straight lines and used a tile saw to cut along the lines. One lesson the Team learned is that once you line up the part and begin cutting, you should constantly watch that the tile saw blade does not deviate from the marked line. When the Team was cutting a spare arm, the composite panel shifted slightly, and the Team cut the arm too thin because the Team did not keep an eye on the blade to check if it was following the marked line.

3.3. Assembly
This section covers the assembly process for each subsystem.

3.2.1 Frame System
The frame assembly consisted of first aligning the fastener holes on the top plate, arms, and bottom plate and securing them with their associated fasteners. Next, the landing legs were bolted onto the frame using their fasteners. The Team found that the legs had a little too much space, which caused the legs to have some lateral play. The Team fixed this by using several small strips of duct tape on the legs to tighten the fit to the arms of the drone. Then, the motor mounts were bolted onto the ends of each arm. The Team also decided to make a small 3-D printed drill jig (Figure 9) for the motor mounting holes on the end of the motor brackets to ensure that the holes would align with the holes on the motor.
Figure 9: The drill jig was fixed to each motor cuff due to the extrusions that fit around the cuff and a ¼” bolt that was inserted through the previously drilled larger hole. This allowed accurate drilling of the smaller holes.

Finally, the rest of the subsystems could be bolted on or off the frame as needed for testing or for demonstration.

3.2.2 Fire Suppression System

The fire suppression system assembly began with collecting the printed components from their respective print locations. After collecting the printed components, the fire actuation motor was installed in the rear fire bracket, the fire extinguisher was secured into both fire brackets with tight tolerances and straps as an extra precaution. The hose to redirect the suppressant was secure to the nozzle of the fire extinguisher by a hose clamp, before being routed under the bottom plate and into the hose bracket. The short and long links of the fire actuation mechanism were connected by a zip tie before installed into the slot guide. The slot guide was friction-fit into the top of the fire brackets. The long link was connected to the actuation motor by the polyline cord and the short link was bolted to the lever of the fire extinguisher.

After testing if the new stepper motor could properly actuate the fire system, the Team found that the short link design needed to be modified and that the polyline cord frayed too easily despite its high tensile strength. The Team also found that the spool design needed to be modified to accommodate the new stepper motor shaft size. Figures 10 and 11 below show the design changes for the small link and the spool.
The updated model of the spool, featuring a D-shaped hole that fits around the motor shaft, as seen in Figure 11.

As for the replacement for the polyline cord, the Team chose to use paracord (95 lbs. tensile strength) as it provides a large margin of safety value of 10 (conservatively), as well as a thinner diameter that is less likely to fray.

3.2.3 Payload Retrieval System
The payload Retrieval system was constructed primarily from 3D printed parts. It is composed of its two subassemblies, the Winch and the Payload box. The winch is a single 3D printed component which has,
integrated into it, a stepper motor and a bearing block. The stepper motor and bearing drive and support a 5mm shaft joined to the stepper motor through a 5mm-to-5mm shaft coupling. The polycord to actuate the payload mechanism is wrapped around the shaft then glued on.

The payload box itself is composed of 2 groups of parts. The first is a large 3D printed truss superstructure which ensures the wires do not get tangled during flight or operation and it coordinates the tension. Several sets of wires are looped from the bottom payload box component to the bottom of the truss. The top of the truss has cords connecting it to the winch. The bottom grouping of parts is the payload box itself. It is composed of 5 flat 3D printed parts which have been stitched together to operate as discussed in the design description portion. Small holes were added to the design to make the stitching process relatively easy. The only modification to this system post design phase is that the design team realized that the original truss 3D model was too large to print so the design was altered slightly in order for it to fit standard print bed dimensions.

3.2.4 Electronics Containment System
The Electronics Containment System is a set of five 3D printed boxes on stilts that sit on the top platform of the drone. They function as containment units for batteries and electronics in order to provide them with some water resistance and convenient fastening points. During the design process the electronics boxes were designed to be too large to fit on a 3D printing print bed dimension. The boxes’ size had to be cut down during the manufacturing process to be printed at a size that fits print bed dimensions.

3.2.5 Software & Electronics
All the software and electronics needed to power and operate the drone were under the preview of the computer engineering/software (CPE) students. As such, the Team does not have the documentation for this aspect of the drone.

4. Design Verification
This section discusses how the prototype was tested against the engineering specifications developed in the SOW. To verify the design, tests of individual subsystems were performed. Furthermore, two test flights were performed. One was a test flight to test the strength of the frame and the thrust produced by the fire extinguisher, and the second was a full-system demo flight where all the subsystems were demonstrated. The tests proved that the design was able to meet all the specifications.

4.1. Specifications
Our specifications can be found in Appendix D, listed in our Design Verification Test Plan. Additional specifications and testing requirements have been added to the DVP due to feedback from Northrop Engineers and test requests from our other NGCP teams.

Each of the six specifications were selected to verify the design’s capacity to meet the design requirements from Northrop. The table below summarizes the design requirements and a description and brief explanation of how each test was designed to verify.
### Table 1: Design Requirement and Test Summary

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Test Description</th>
<th>Test Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quick access to electronics</td>
<td>Set a timer for 1 minute and attempt to remove electronics box lid</td>
<td>If it takes longer than 1 minute to remove a box lid, it is not a quick release design and would hinder any emergency access, creating a potentially dangerous electrical situation</td>
</tr>
<tr>
<td>Mission flight time of 15 minutes</td>
<td>Fly drone’s mission profile to assess approximate power needs</td>
<td>Need to ensure drone can meet the minimum flight time requirement as well as estimate the maximum flight time based on battery capacity</td>
</tr>
<tr>
<td>Payload weight of 1 lbs.</td>
<td>Load 2 lb. dumbbell onto payload platform and power winch</td>
<td>By successfully lifting and lowering a 2 lb. payload, the payload retrieval mechanism is fully capable of safely handling the mission payload (an injured person)</td>
</tr>
<tr>
<td>Fire suppression</td>
<td>Actuate fire suppression mechanism on ground and during test flight</td>
<td>Testing mechanism on the ground first allows for mechanism troubleshooting while testing in-flight allows for precision location troubleshooting</td>
</tr>
<tr>
<td>Structural multi-mission frame</td>
<td>Complete material property testing to assess composite properties</td>
<td>By completing inhouse composite layups, money was saved, however, the material properties are not known and therefore must be tested to ensure they are sufficient to support expected loads during mission</td>
</tr>
<tr>
<td>Mild inclement weather protection</td>
<td>Pour water over closed boxes to assess how much water enters the interior electronics area</td>
<td>Water mixing with electrical circuits and wire could lead to damaged circuits and shorts that would make the drone behave outside of its mission profile, which can lead to mission failure or damage to the payload</td>
</tr>
</tbody>
</table>

The following section provides further information on the completed tests as well as their results.

#### 4.2. Testing, Results, & Discussion

This subsection includes summaries of the test procedures (full procedures in Appendix E) and results for each of the tests conducted to ensure that the design specifications were met. Below is a summary table of the tests run on the design. Full DVP&R table is available in Appendix D.
<table>
<thead>
<tr>
<th>Specifications</th>
<th>Test Result</th>
<th>Quantity Pass</th>
<th>Quantity Fail</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Access Electronics</td>
<td>Pass</td>
<td>5</td>
<td>0</td>
<td>Able to access the electronics in the boxes in less than 1 minute. Did experience some resistance to lid removal. Recommend adjusting clip width.</td>
</tr>
<tr>
<td>Minimum Flight Time</td>
<td>Pass</td>
<td>3</td>
<td>0</td>
<td>PLA landing legs fractured on landing of test flight 1. ABS legs were fine (ABS is more impact-resistant). Recommend printing ABS legs in future.</td>
</tr>
<tr>
<td>Expected Payload Weight</td>
<td>Pass</td>
<td>1</td>
<td>0</td>
<td>Stepper motor controller warm after test. Could add heatsink.</td>
</tr>
<tr>
<td>Structural Prototype</td>
<td>Pass</td>
<td>1</td>
<td>0</td>
<td>Hole orientation in sliding link caused zip tie (connecting the link to extinguisher handle) to get twisted. New link was printed with hole orientation that prevented zip tie twisting.</td>
</tr>
</tbody>
</table>
| Composite Material Properties as Made | All Passed  | 3             | 0             | 1. $n_{safety} = 7.5 \pm 1.5$
2. $n_{safety} = 36.1 \pm 0.1742$
3. $f_{n1} = 6\,Hz, f_{n2} = 121\,Hz$ |
| Waterproof Electronics Box             | Fail        | 0             | 1             | A small amount of water did make its way into the boxes                                                                               |

4.2.1 Electronics access test
The electronics access test involved ensuring the electronics box lid was fully seated on the box. Then, a timer was set to 1 minute, and started when the Team member touched the box to remove the lid. The Team member was able to remove the lid in approximately 10 seconds. Therefore, the electronics access test was successful. All the electronics boxes had easily removable clip-on lids, and all of them could be opened in under 1 minute to access electronics.

4.2.2 Flight Test
The flight test procedure involved driving to the Educational Flight Range by Cuesta College. The Team arrived with the drone propellers not installed to ensure the motors would not experience damage during the car ride to the flight range. Once the propellers were installed and the flight computers calibrated, the aero team leads moved the drone out to the runway and proceeded to fly the drone for approximately 25 minutes.

According to the test criteria, the flight test was successful because the drone was able to fly for the specified amount of time (15 minutes) without needing to recharge. Furthermore, the drone did not crash at any instance and the carbon fiber frame stayed intact throughout the flight. However, some of the PLA landing legs broke during landing, but the ABS legs did not break. Following this incident, the drone was fitted with only ABS legs, which did not break in the following demo flight. An image of the drone during a flight test is shown below.
4.2.3 Payload capacity test

The payload capacity test involved loading a 2 lb. dumbbell onto the payload platform and actuating the winch motor and observing the platform get raised and lowered. Figure 13 is an image from the test off the drone.

The payload capacity test was successful. The payload retrieval subsystem was tested to ensure that it could lift the specified payload of 2 lbs. and to ensure that the payload platform securely contained the payload. To test this, the payload assembly was connected to the winch shaft with paracord, the payload platform with a 2-lb dumbbell on top was placed on the ground, the winch cage was manually held up at a constant height above the payload assembly, and the winch motor was given a signal to rotate. It was observed that the winch assembly was able to lift the payload assembly with the 2-lb dumbbell. Furthermore, the dumbbell did not fall out of the payload box; it was securely contained throughout the duration of the test.
4.2.4 Fire actuation test
The fire actuation test was successful. The fire actuation system was tested to ensure that it could pull the fire extinguisher handle all the way. First, the stepper motor and an empty fire extinguisher were secured onto the fire brackets. Then the fire extinguisher handle was connected to the sliding links with poly line, which were in turn connected to the stepper motor shaft with poly line. Then, the stepper motor was given a signal to rotate. It was observed that the stepper motor was able to pull the fire extinguisher handle through its full range of motion, meaning that the system can successfully actuate the fire extinguisher. However, during the demo flight, the drone was only able to spray the fire extinguisher in a couple of short bursts rather than a continuous stream (Figure 14). A possibility for the discrepancy in results is that a full fire extinguisher may require more force on the handle than an empty one. Nonetheless, the drone was still able to deploy its fire extinguishing fluid in the demo flight, even if in bursts, as shown in the image below.

![Image of drone actuating fire extinguisher](image1.jpg)

*Figure 14: The drone actuated the fire extinguisher after it reached its target.*

4.2.5 Tensile test of carbon fiber composite
The objective of this test was to determine the maximum tensile strength and Young's modulus of carbon fiber laminate plates. The test utilized a tensile testing machine to measure these properties, generating stress data points at specific strain percentages. The diagram of apparatus is shown in Figure 15.
The maximum strength of the laminate was identified as the stress level where a drop in stress occurred at a certain strain percentage, associated with laminate cracking.

The tensile strength was determined to be:

\[ \sigma_{T_{\text{max}}} = 73.29 \pm 14.78 \ [ksi] = 505 \pm 102 \ [MPa]. \]  

(1)

The safety factor to the maximum stress from simulation (67.7 MPa) was determined to be the following:

\[ n_{\text{safety}} = 7.5 \pm 1.5. \]  

(2)

Additionally, the Youngs modulus was determined to be:

\[ E = 3932.93 \pm 537.79 \ [ksi] = 27116.60 \pm 3707.93 \ [MPa]. \]  

(3)

It should be noted that the tested pieces were edge samples taken from the larger laminate sheet, which generally contain greater voids and exhibit lower strength. Given the nature of the edge pieces, it is reasonable to assume that the actual strength of the bulk laminate would be even higher.

Figure 16A shows the samples of the laminate used for the tensile strength test. Figure 16B shows the samples after failure. The observed failures aligned with predictions, exhibiting horizontal fractures and delamination.
The test results indicate that the carbon fiber laminate possesses significant tensile strength and stiffness, as evidenced by the obtained values for maximum strength and Young's modulus. The safety factors provide a measure of confidence in the material's performance, suggesting a substantial margin of safety. While the edge pieces used for the test exhibited lower strength due to voids, it is reasonable to expect even higher strength in the bulk laminate. The visual evidence of fractures and delamination in the test samples supports the understanding of the material's behavior under tensile loading conditions.

4.2.6 3-point bend test of sandwich-structured carbon fiber composites
A 3-point bend test was conducted to evaluate the flexural strength and load-deflection relationship of three different sandwich structures. These structures included a honeycomb core with carbon fiber/epoxy lamina on top and bottom, an aluminum honeycomb core with carbon fiber/epoxy lamina on top and bottom, and three layers of H80 foam with carbon fiber/epoxy lamina in between and on top and bottom. The diagram of apparatus is shown in Figure 17.
Figure 17: Diagram of 3-point bend test apparatus

Figure 18 shows one of the samples that is set up for a three-point bend test.

Figure 18: Example of three-point bend test setup

Finite element analysis (FEA) simulated results indicated that all samples had anticipated stresses lower than the maximum stress for failure.
The baseline test compared the Nomex honeycomb core design to the aluminum honeycomb core design, and based on the test results, the Nomex honeycomb was replaced by the aluminum honeycomb core due to its higher strength-to-weight ratio.

Comparing the H80 foam sandwich structure to the aluminum honeycomb core design, the foam sandwich structure demonstrated significantly lower weight while maintaining similar strength performance. The maximum flexural stress for the H80 foam sandwich structure was computed as:

$$\sigma_{f_{\text{max}}} = 2.44 \pm 0.0180 \text{ GPa}. \quad (4)$$

The maximum anticipated stress from simulation was 67.7 MPa. This yields a safety factor as the following:

$$n_{\text{safety}} = 36.1 \pm 0.1742. \quad (5)$$

Figure 19a showcased the samples used in the 3-point bend test with the H80 foam sandwich structure, while Figure 19B displayed the samples after failure.

In Figure 19B, the sample on the left represented specimen 1, which was subjected to a distributed load, while the two samples to its right (specimens 2 and 3) experienced a point load. The image clearly revealed differences in deformation among the specimens. It should be noted that in reality, the motor mount would make the load distribution more closely resemble the simulated distributed load. Although specimen 3 had a different length and a drill hole at the end, its strength was not significantly affected compared to specimen 2.

4.2.7 Dynamic test of sandwich-structured composite beam
A sine sweep test was performed to determine if any critical frequencies in the arms would pose concerns due to oscillations caused by the inertia resulting from a center of mass offset. Figure 20 shows the test diagram of apparatus.
Figure 20: Diagram of apparatus

Figure 21 shows the front view of the beam specimen with an accelerometer and a weight attached. The test revealed the presence of the first and second harmonics at frequencies of 6 Hz and 121 Hz, respectively. The operating frequency of the rotors was determined to be 60 Hz, indicating that the first and second harmonics of the drone arms would not be excited during normal operation. The accuracy of the test was confirmed through hand calculations using Euler beam theory, considering an end mass. However, it was surprising to discover that the first natural frequency of the drone arms was as low as 6 Hz. This can be attributed to the significant mass of the end mass (simulated rotor) relative to the mass of the beam.

To improve the test procedure, it is recommended to securely attach the end of the beam to the shaker table to better simulate a fixed end condition. In this regard, the current method utilizing bolts for attachment proved insufficient, as the beam could still be rotated with some force due to inadequate tightening. By enhancing the attachment mechanism, the test setup can more accurately represent the actual operating conditions, providing more reliable results.
4.2.8 Waterproofing electronics
To test for waterproofness of the electronics boxes, the Team executed the test procedure as listed in Appendix E8. A brief explanation of the test has been added here for the ease of the reader. One of the boxes was placed on a level surface with the lid fully seated, with the lid side up. Then three cups of water were poured over the top of the box before the exterior was wiped down with a paper towel to make sure no water would be brought inside while the lid was removed. Upon lid removal, the Team observed a small amount of water (~3-5 droplets) inside the box. As such, the boxes were proven to be lightly water resistant, but certainly not waterproof.

Figure 22: The electronics boxes mounted on the drone, after all the electronics had been installed.

5. Discussion & Recommendations
This section provides commentary on the project results and what future design iterations would consider.

5.1. Discussion
Over the course of this project, the Team learned that design implementation takes more time than one may initially allot, and that testing the software with the mechanical design should be done much sooner in the design cycle process. At the club demonstration day, the drone mechanically functioned as intended but experienced a few minor disruptions due to software quirks that were not discussed prior to the demo flight. Therefore, if continuing the design, the Team would work closely with the electrical/software club members to iron out the program profile.

Additionally, as mentioned above, the waterproofing of the electronics boxes was not successfully, so the Team would implement a new lid system that would securely fit the existing boxes, as well as implement flexible tubing between the side and rear boxes to better protect the cables from inclement weather. If building the drone again, the Team would spend more time ensuring the water tightness of the electronic boxes by testing different print settings.

5.2. Recommendations and Next Steps
Recommendations for future use of this platform would be to dial in the 3D printing settings and acquire a 3D printer designated for NGCP club use only, as the drone could have been assembled and tested much
earlier had the printing resources not been scarce. Additionally, it is highly recommended that the software and electronics team work more closely with the other teams as the Team experienced a few bugs in the fire and payload actuation code which were a direct result of miscommunication between teams.

As for use of the drone, the Team highly recommends working with the aero, software, and electronics teams to test fly the done early in the design cycle to test out design elements under consideration. This early flight testing will also provide some important flight characteristic data that may become useful if the same motors and propellers are used in the new design.

6. Conclusion
The goal of this project was to design and build drone components that could be used in a remote, autonomous rescue mission. As the mechanical leads in the NGCP club, the Team designed a modular composite frame, and modular 3D printed fire suppression, payload, and electronics housing systems. Due to careful planning, the assembly process of the drone went as smoothly as one could reasonably expect from students, with minor fitment issues between the drone arms and the motor mounts. To resolve this, 3D spacers were used. After the drone was assembled, the testing of the designs began.

Of the eight tests conducted on the Team’s design, seven tests were passed and only one was failed. The time to access the electronics was successfully less than the target time of one minute, which meets the design requirement of having accessible electronics.

The tensile test was used to find the ultimate tensile strength of the carbon fiber top and bottom plates, which was an important parameter for frame stress calculations. Although it was less than the tensile strength advertised by the carbon fiber manufacturer’s website, it was nonetheless determined that it was sufficiently strong.

The 3-point bend test was an important test to verify the strength of the drone arms. The bending stress caused in the 3-point bend test occurs in the same orientation in the arms as the stress produced by the propeller thrust, which is the highest load while in flight. The high safety factor obtained from the 3-point bend test supported the claim that the arms would not break during flight or landing.

The dynamic test, in which the drone arm was vibrated at a shake table, was important because it showed that the natural frequency of the drone arms was less than the usual operating frequency of the propellers. If they had been close to each other, the arms would be in resonance and thus would experience unexpectedly high vibrations and deformation. The dynamic test proved that this would not occur. The fire actuation test ensured that the fire suppression system worked as expected. As a result of this test, the design of the fire suppression system was improved by designing a better small link and spool.

The payload retrieval test verified that the winch motor was strong enough to lift the payload. Furthermore, it verified that the payload was secure in the payload retrieval box as it did not fall from the box while it was being raised.

The only test that failed, the waterproof test, was meant to show that water would not intrude into the boxes and damage the electronics. Although the boxes offered some protection from water, as only a small amount of water was able to enter, they were nonetheless not fully waterproof. A design suggestion to resolve this would be to add a gasket and a locking mechanism that presses the lid down onto the box.
The flight test proved that the drone was able to fly for the amount of time required by the specifications (15 minutes). If this had not been the case, modifications to the design would have been needed to reduce the weight, or extra batteries would need to be added.

Finally, the demo flight served as a conclusive demonstration of all subsystems working together to successfully complete the simulated search and rescue challenge presented by Northrop Grumman.

As for what would be done differently if the Team was to meet the design requirements again, the Team would begin prototype manufacturing as soon as possible with all 3D printed parts, communicate early and often with the other NGCP teams involved with the drone, and push to have the fully operational drone completed at least a month in advance of the demonstration deadline. Had these few key items been achieved, especially the month for testing and debugging, the resulting drone would have likely experienced little to no software quirks and would more fully meet Northrop’s design requirements.
References

Appendices

Appendix A – User Manual

This document provides the necessary information to safely operate and handle this product. Please, read and adhere to all the requirements listed in this document, as this product involves potentially harmful components which can be dangerous if the correct precautions are not taken.

Required Personal Protective Equipment (PPE)

- Safety glasses
- Hearing protection

Listed above are the required PPE for operating this drone. The safety glasses help prevent any loose material stirred up by the rotor wash from harming the eyes of the operator/observers. The hearing protection is used to dampen the loud noise of the six rotors during flight.

Safety Hazards

As with any drone, there is an inherent risk of objects coming into contact with the moving rotors, which may damage both the rotors and the object. For that reason, only operate the motor with rotors attached in open spaces and have any observers stand at least 3 ft away from any part of the drone. Also, only fly the drone in approved areas and ensure that the operator has the proper FAA credentials to do so, as this drone can reach an altitude of 300 ft.

Due to the mission parameters involving fire suppression, the drone is capable of flying loaded with a 2.5lbs fire extinguisher, which is pressurized to 100 psi. Be sure to securely load and strap the extinguisher into its specially designed brackets so that the extinguisher does not become loose during any flight-related operation (pre-flight, take-off, hover, landing, etc.). If the extinguisher is not properly secured, there is a chance that it could: come into contact with the rotors (which could break the rotors and/or puncture the pressurized canister); fall from the drone; or move enough to offset the center of mass of the drone, which could cause the drone to react to operator input in unexpected ways.

Assembly Instructions:

Before assembling the drone ensure that all necessary parts and fasteners are acquired as specified in Table 3.

Frame Assembly:

Place the small bottom plate on a flat surface, then place four of the drone’s short arms and one of the long arms on top of the small hexagon plate. Align the bolt holes as demonstrated in Figure 2323.
Then once aligned, place the large hexagon plate on top of the arms and use bolts to locate and fasten all the main frame components together. Ensure that washers are used for all the bolts on both sides to ensure a good fit. The bolt fit should be tight enough to simply thread the bolts through the holes and leave them for the purposes of aligning. Once the main frame body is together, add on the landing legs at an interval our prefer. The design team recommends at minimum 4 landing legs composed of two adjacent pairs as pictured in Figure 24. For the motor cuffs/mounts at the end of the arms, the order of operations to properly attach them is as follows:

1: Place the motor mount spacers/dampeners on the arm and align them with the holes,
2: Place the aluminum motor mounts on the arms and align them with the spacers and arms holes,
3: Bolt together the motor mounting grouping to the arm using washers.
Winch Mechanism and Payload Box Assembly:

To begin, fix the stepper motor onto the winch cage. This is done through 4 M3 screws to fasten the stepper motor to the cage. Once the motor is fastened add the 5mm-to-5mm shaft coupler and tighten it to the stepper motor shaft. Press the shaft bearing into the slot opposing the winch motor. Lastly Insert the winch shaft on the opposing end of the coupler and fasten it. It should resemble Figure 25.

The payload/folding box assembly is assembled in two phases. The first phase involves stitching the 4 walls of the payload box to the floor piece. This can be done through using a cut of canvas the size of the folding box and stitching all the folding box walls to the canvas through the small holes that dot their bottom edge. The unfolded box should look like Figure 26.
Once the folding box is completed a set of polychord runs from the corners of each of the folding box corners should match the ones demonstrated in Figure 27. These are then affixed to the bottom corners of the payload truss. The top corners of the payload truss are used to fix the entire payload box system to the winch.
Fire Extinguisher System Assembly:
The Fire Extinguishing system is assembled by first inserting the fire extinguisher through both fire extinguisher brackets with the nozzle of the fire extinguisher pointing down. Once the fire extinguisher is in place, the first part of the linkage mechanism, the slotted bracket, must then be fitted on top of the fire extinguisher brackets. The large linkage bar is then slid into the slotted bracket and the remaining linkage bars are bolted or zip-tied onto the large linkage bar as shown in Figure 28. Once the linkage mechanism is assembled, the system’s stepper motor is slotted into its appropriate spot at the end of the large fire extinguisher bracket along with the spool affixed to the end of the stepper motor. The length of the polychord used to actuate the linkage mechanism via the stepper motor is up to user description, but the string should be tight and tense.

Electronics Storage Assembly:
The electronics boxes are mounted by aligning the boxes sides with the corresponding hexagon sides and using the available mounting holes to bolt the boxes down to the top plate. The boxes can only fit washers on the nut side so ensure to use them there. The box orientations can be seen in Figure 29.
Many of the parts for this drone were 3D printed and as such, the files CAD files can be made available upon request. Additionally, as the frame was made of composite materials (carbon fiber, epoxy, and foam), the raw materials will be listed in the quantity used. Any of the purchased components will be listed in the quantity, price (as of purchase), source so that replacements can be acquired.

Table 3: Parts List

<table>
<thead>
<tr>
<th>Qty.</th>
<th>Name</th>
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<th>Price</th>
<th>Source</th>
</tr>
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<td>Top Plate</td>
<td>Frame</td>
<td>-</td>
<td>Manufactured by group</td>
</tr>
<tr>
<td>1</td>
<td>Bottom Plate</td>
<td>Frame</td>
<td>-</td>
<td>Manufactured by group</td>
</tr>
<tr>
<td>1</td>
<td>Long Arm</td>
<td>Frame</td>
<td>-</td>
<td>Manufactured by group</td>
</tr>
<tr>
<td>4</td>
<td>Short Arms</td>
<td>Frame</td>
<td>-</td>
<td>Manufactured by group</td>
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<td>6</td>
<td>Motor Mounts- Aluminum Rectangle Tube 1.5 x 2 x 0.125 Tube 6061 2 ft</td>
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<td>Online Metals</td>
</tr>
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<td>Qty.</td>
<td>Name</td>
<td>Assembly/Subassembly</td>
<td>Price</td>
<td>Source</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------------------</td>
<td>----------------------</td>
<td>--------</td>
<td>-----------------</td>
</tr>
<tr>
<td>6</td>
<td>Motor Bracket Spacers</td>
<td>Frame</td>
<td>-</td>
<td>3D Printer</td>
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<tr>
<td>1</td>
<td>Camera Mount</td>
<td>Frame</td>
<td>-</td>
<td>3D Printer</td>
</tr>
<tr>
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<td>Landing Leg</td>
<td>Frame</td>
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<tr>
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</tr>
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<td>Platform Bottom</td>
<td>Payload</td>
<td>-</td>
<td>3D Printer</td>
</tr>
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<td>Long Walls</td>
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<td>-</td>
<td>3D Printer</td>
</tr>
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</tr>
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<td>Nylon Fabric</td>
<td>Payload</td>
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<td>Washers</td>
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<td>NGCP Workroom</td>
</tr>
<tr>
<td>1</td>
<td>Nuts- ¼ 50 pack</td>
<td>Electronics</td>
<td>$13.49</td>
<td>Ace Hardware</td>
</tr>
</tbody>
</table>
Repair Actions
The repair actions for this drone fall into four categories: carbon fiber, 3D print, electronics, miscellaneous.

Carbon Fiber
If any of the arms acquire a crack or delaminate, do not fly/operate the drone! If any spare arm material is available, cut it to the necessary size, and drill the appropriate holes accordingly. To switch out the old arm, simply unbolt all bolts holding the arm in place and gently pull the arm out (gloves are highly recommended if any carbon fibers are exposed) and discard it safely. Then, slide the new arm into place, taking care to align the holes in the arm with the holes in the plates. Proceed to fasten the bolts and replace any components that were removed.

3D Print
For 3D printed parts that are damaged or suffer from wear, they can simply be replaced with a new part printed from PLA or stronger material. As most parts are bolted on the procedure is to unbolt and remove the worn part and bolt on the new part.

Aluminum Parts
The six aluminum parts on the drone are all identical and therefore can be replaced with an identical spare if they are damaged. The process to replace is to unbolt them and pull off both the aluminum mount and 3D printed spacer and replace both as it is likely that if the aluminum is damaged in some way, the spacer beneath it is also damaged.

Maintenance
The structural components of this drone are composed of non-corrodible or corrosion resistant material and far exceed the foreseen lifespan of the drone, which is one official full-scale test flight. Maintenance is to be foreseen in the event of damage during test flight or transportation and will most likely involve the replacement of various types of parts as mentioned above. The general guidelines for maintenance are very simple due to the modular nature of the drone with the easy bolt-on-bolt-off design.

Travel and Transportation Recommendations:
Due to the unwieldy size of the drone, the design team’s recommendation for transportation is to either transport the drone completely disassembled in boxes or to have someone monitor the drone during its transportation to ensure it does not suffer inadvertent collisions.

Device Operation Disclaimer
Due to the design team’s focus on structural design, repair and structural maintenance, this document should not inform or suggest any information concerning the piloting or aeronautical setup of the drone.

Miscellaneous
Due to the scope of this design team’s authority being exclusive to the main structural design, there is not much feedback in this user manual about aeronautical debugging or repair information.
Part Replacement Information

Due to the prototypic nature of this design and its unique goal there are no OEM (original equipment manufacturer) parts aside from wholesale components such as the stepper motors, bolts, and fire extinguishers provided in the bill of materials. All structural components such as the arms, plates, 3D printed parts and motor mounts were developed in house. Detailed information on how to manufacture these parts has been provided in the drones manufacturing guide along with specification drawings and material recommendations. If this user manual came with the full Med Evac Aircraft Final Design Review Report, then the manufacturing section can be found in Appendices F-G of the CDR.
Appendix B – Risk Assessment

<table>
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<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Risk Reduction Methods /Control System</th>
<th>Final Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Status / Responsible /Comments /Reference</th>
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</thead>
<tbody>
<tr>
<td>1-1-1</td>
<td>operator Common tasks</td>
<td>mechanical / cutting / severing Spinning Rotor</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Stay away from operating area</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Complete [2/21/2023] Ben E</td>
</tr>
<tr>
<td>1-1-2</td>
<td>operator Common tasks</td>
<td>mechanical : drawing-in / trapping / entanglement Cables</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Stay away from operating area</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Complete [2/21/2023] Nikkia P</td>
</tr>
<tr>
<td>1-1-3</td>
<td>operator Common tasks</td>
<td>mechanical : unexpected start Misc Electrical Issues</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Stay Away from operating area</td>
<td>Serious Remote</td>
<td>Low</td>
<td>Complete [2/21/2023] Santiago R</td>
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<tr>
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<td>operator Common tasks</td>
<td>electrical / electronic : lack of grounding (earthing or neutral) Composite Body</td>
<td>Moderate Remote</td>
<td>Negligible</td>
<td>Do not Touch the drone</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Complete [2/21/2023] Santiago R</td>
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<td>1-1-5</td>
<td>operator Common tasks</td>
<td>slips / trips / falls : falling material / object Drone Falling From Sky</td>
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<td>Medium</td>
<td>Stay away from operating area</td>
<td>Catastrophic Remote</td>
<td>Low</td>
<td>Complete [2/21/2023] Ben U</td>
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<td>operator Common tasks</td>
<td>noise / vibration : noise / sound levels &gt; 80 dBA Loud Rotors</td>
<td>Moderate Very Likely</td>
<td>High</td>
<td>Wear ear protection or stay away</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Complete [2/21/2023] Ben U</td>
</tr>
<tr>
<td>1-1-7</td>
<td>operator Common tasks</td>
<td>chemical : chemical emissions Fire Suppressant</td>
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<td>Negligible</td>
<td>Stay away from operating area</td>
<td>Minor Remote</td>
<td>Negligible</td>
<td>Complete [2/21/2023] Nikkia P</td>
</tr>
</tbody>
</table>

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].
<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Risk Reduction Methods / Control System</th>
<th>Final Assessment Severity Probability</th>
<th>Risk Level</th>
<th>Status / Responsible / Comments / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1-8</td>
<td>operator Common tasks</td>
<td>fluid / pressure : high pressure 100 PSI</td>
<td>Moderate</td>
<td>Remote</td>
<td>Negligible</td>
<td>Do not damage the fire extinguisher</td>
<td>Moderate</td>
<td>Negligible</td>
</tr>
<tr>
<td>2-1-1</td>
<td>maintenance technician parts replacement</td>
<td>mechanical : cutting / severing Rotor</td>
<td>Serious</td>
<td>Remote</td>
<td>Low</td>
<td>Be cautious of accidental startup</td>
<td>Serious</td>
<td>Low</td>
</tr>
<tr>
<td>2-1-2</td>
<td>maintenance technician parts replacement</td>
<td>mechanical : unexpected start Misc Electrical Issues</td>
<td>Serious</td>
<td>Remote</td>
<td>Low</td>
<td>Be cautious of accidental startup</td>
<td>Serious</td>
<td>Low</td>
</tr>
<tr>
<td>2-1-3</td>
<td>maintenance technician parts replacement</td>
<td>electrical / electronic : lack of grounding (earthing or neutral) Composite Body</td>
<td>Moderate</td>
<td>Remote</td>
<td>Negligible</td>
<td>Be cautious of live/non discharged parts</td>
<td>Moderate</td>
<td>Negligible</td>
</tr>
<tr>
<td>2-1-4</td>
<td>maintenance technician parts replacement</td>
<td>electrical / electronic : shorts / arcing / sparking Swapping Electronics</td>
<td>Moderate</td>
<td>Remote</td>
<td>Negligible</td>
<td>Be cautious of live/non discharged parts</td>
<td>Moderate</td>
<td>Negligible</td>
</tr>
<tr>
<td>2-1-5</td>
<td>maintenance technician parts replacement</td>
<td>ergonomics / human factors : posture Bending Over</td>
<td>Minor</td>
<td>Likely</td>
<td>Low</td>
<td>Take breaks as necessary</td>
<td>Minor</td>
<td>Remote</td>
</tr>
<tr>
<td>2-1-6</td>
<td>maintenance technician parts replacement</td>
<td>fluid / pressure : fluid leakage / ejection Residue Fire Suppressor</td>
<td>Minor</td>
<td>Likely</td>
<td>Low</td>
<td>Be mindful of the residue material</td>
<td>Minor</td>
<td>Remote</td>
</tr>
<tr>
<td>2-2-1</td>
<td>maintenance technician trouble-solving / problem solving</td>
<td>mechanical : cutting / severing Rotor Start Up</td>
<td>Serious</td>
<td>Likely</td>
<td>High</td>
<td>Have a proper arming procedure</td>
<td>Serious</td>
<td>Unlikely</td>
</tr>
</tbody>
</table>

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Privileged and Confidential Information
<table>
<thead>
<tr>
<th>Item Id</th>
<th>User / Task</th>
<th>Hazard / Failure Mode</th>
<th>Initial Assessment Severity Probability</th>
<th>Initial Assessment Risk Level</th>
<th>Risk Reduction Methods / Control System</th>
<th>Final Assessment Severity Probability</th>
<th>Final Assessment Risk Level</th>
<th>Status / Responsible / Comments / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-2-2</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>mechanical : drawing-in / trapping / entanglement Cables</td>
<td>Serious</td>
<td>Unlikely</td>
<td>Medium</td>
<td>Lay all cables away from technician</td>
<td>Serious</td>
<td>Unlikely</td>
</tr>
<tr>
<td>2-2-3</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>mechanical : pinch point Fire Actuation System</td>
<td>Moderate</td>
<td>Likely</td>
<td>Medium</td>
<td>Utilize cover for actuation system</td>
<td>Moderate</td>
<td>Remote</td>
</tr>
<tr>
<td>2-2-4</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>mechanical : unexpected start Misc Electronic issues</td>
<td>Moderate</td>
<td>Likely</td>
<td>Medium</td>
<td>Have a kill switch for drone</td>
<td>Moderate</td>
<td>Unlikely</td>
</tr>
<tr>
<td>2-2-5</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>electrical / electronic : energized equipment / live parts Live Parts</td>
<td>Moderate</td>
<td>Likely</td>
<td>Medium</td>
<td>Be cautious of live/non discharged parts and have a kill switch</td>
<td>Moderate</td>
<td>Unlikely</td>
</tr>
<tr>
<td>2-2-6</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>electrical / electronic : lack of grounding (earthing or neutral) Composite Body</td>
<td>Moderate</td>
<td>Likely</td>
<td>Medium</td>
<td>Be cautious of live/non discharged parts</td>
<td>Moderate</td>
<td>Unlikely</td>
</tr>
<tr>
<td>2-2-8</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>ergonomics / human factors : Minor Likely</td>
<td>Medium</td>
<td>Low</td>
<td>Take breaks as necessary posture Bending Over</td>
<td>Minor</td>
<td>Likely</td>
<td>Low</td>
</tr>
<tr>
<td>2-2-10</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>fluid / pressure : high pressure High Pressure Fire Extinguisher</td>
<td>Moderate</td>
<td>Remote</td>
<td>Negligible</td>
<td>Do not damage or pull the pin on the fire extinguisher</td>
<td>Moderate</td>
<td>Remote</td>
</tr>
<tr>
<td>Item Id</td>
<td>User / Task</td>
<td>Hazard / Failure Mode</td>
<td>Initial Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Risk Reduction Methods / Control System</td>
<td>Final Assessment Severity Probability</td>
<td>Risk Level</td>
<td>Status / Responsible / Comments / Reference</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>-----------------------</td>
<td>------------------------------------------</td>
<td>------------</td>
<td>------------------------------------------</td>
<td>--------------------------------------</td>
<td>------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>2-2-11</td>
<td>maintenance technician trouble-shooting / problem solving</td>
<td>fluid / pressure : fluid leakage / ejection Fire Suppresant</td>
<td>Moderate Unlikely</td>
<td>Low</td>
<td>Point nozzle away at all times Moderate Unlikely</td>
<td>Low</td>
<td>Complete [2/21/2023] Nikkia P</td>
<td></td>
</tr>
<tr>
<td>3-1-1</td>
<td>passer by / non-user walk near machinery</td>
<td>slips / trips / falls : falling material / object Drone Falling</td>
<td>Catastrophic Remote</td>
<td>Low</td>
<td>It should only be operated on when grounded Catastrophic Remote</td>
<td>Low</td>
<td>Complete [2/21/2023] Ben E</td>
<td></td>
</tr>
</tbody>
</table>

Page 4 Privileged and Confidential Information
## Appendix C – Final Project Budget

### NGCP BUDGET

<table>
<thead>
<tr>
<th>ITEM</th>
<th>QUANTY</th>
<th>COST/PERS</th>
<th>LINK</th>
<th>REASON</th>
<th>NOTES</th>
<th>PAID BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fiber Materials</td>
<td>1</td>
<td>$2,200.00</td>
<td>N/A</td>
<td>Structural Material for drone</td>
<td>Cost will be handled at end by paying professor Elgandor. Estimation is based on a $30/sqft</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>1/4&quot; x 4&quot; x 8&quot; H80 Foam Sheet</td>
<td>2</td>
<td>$97.00</td>
<td>N/A</td>
<td>Structural Material for drone</td>
<td>Picking Up from local vendor 2/11/2023</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>Aluminum Rectangle Tube 1.5 x 2 x 0.125 Tube 6061 2 ft</td>
<td>2</td>
<td>$44.81</td>
<td><a href="https://www.onlinemetals.com/en/buy/aluminum/1-5-x-2-x-0-125-aluminum-rectangle-tube-6061-t6-extruded/pid/19660">Link</a></td>
<td>Metal Motors Cuffs</td>
<td>Must be cut and machined</td>
<td>NGCP CPE FUND</td>
</tr>
</tbody>
</table>

**Total Project (including Club) Sum:** $10,566.47

**Senior Project Only:** $2,531.62
<table>
<thead>
<tr>
<th>ITEM</th>
<th>QUANTITY</th>
<th>COST/PER</th>
<th>LINK</th>
<th>Reason</th>
<th>Notes</th>
<th>Paid By:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 - 20 Nyloc Insert Zinc Plated Nuts: 100 pack</td>
<td>1</td>
<td>$13.58</td>
<td>N/A</td>
<td>Fasteners</td>
<td>Picking Up from local vendor</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>1/4 - 20 Hex Head Bolts: 100 pack</td>
<td>1</td>
<td>$32.99</td>
<td>N/A</td>
<td>Fasteners</td>
<td>Picking Up from local vendor</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>Nylon Strap 1 In thick. 150 Ft</td>
<td>1</td>
<td>$38.00</td>
<td>N/A</td>
<td>Strapping Down Electronics and Extinguisher</td>
<td>Picking Up from local vendor</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>3Mx 18 Bolts</td>
<td>10</td>
<td>$0.24</td>
<td>N/A</td>
<td>Used to hold stepper motors to design</td>
<td>Ace Hardware</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>ITEM</td>
<td>QUANTITY</td>
<td>COST/PER</td>
<td>LINK</td>
<td>Reason</td>
<td>Notes</td>
<td>Paid By</td>
</tr>
<tr>
<td>------</td>
<td>----------</td>
<td>----------</td>
<td>------</td>
<td>--------</td>
<td>-------</td>
<td>---------</td>
</tr>
<tr>
<td>1/4 - 20 Hex head Shouldered 2.25 inch bolts</td>
<td>20</td>
<td>$0.36</td>
<td>N/A</td>
<td>Used to bolt down electrical boxes and shorter components</td>
<td>Ace Hardware</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>Polywire 25 Feet</td>
<td>1</td>
<td>$25.00</td>
<td>N/A</td>
<td>Used for payload retrieval bay over polyline due to its smaller diameter.</td>
<td>Bought from Home Depot</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>Travel Expenses</td>
<td>1</td>
<td>$7,000.00</td>
<td>N/A</td>
<td>SLO Safe rides Approximate pricing for all trips</td>
<td>N/A</td>
<td>NGCP CPE FUND</td>
</tr>
<tr>
<td>NGCP Bulk Order T-shirts</td>
<td>40</td>
<td>$20.00</td>
<td>N/A</td>
<td>Club ordered T-shirts Shirt producer in town</td>
<td>N/A</td>
<td>NGCP CPE FUND</td>
</tr>
</tbody>
</table>

*Shaded cells are expenses associated with the club side of this senior project*
<table>
<thead>
<tr>
<th>Item No.</th>
<th>Specification</th>
<th>Test Description</th>
<th>Acceptance Criteria</th>
<th>Test Responsibility</th>
<th>Test Stage</th>
<th>SAMPLES TESTED</th>
<th>TIMING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Composite Material Properties as Made</strong></td>
<td>Carbon Fiber tests</td>
<td>1. Safety factor of 2.  2. Safety factor of 2.  3. Natural frequency harmonics within 30 Hz and 90 Hz.</td>
<td>Ben U</td>
<td>SP</td>
<td>C</td>
<td>2/17/2023</td>
</tr>
<tr>
<td></td>
<td>*<strong>Waterproof Electronics Box</strong></td>
<td>Waterproofing Electronics</td>
<td>Pass/Fail</td>
<td>Santiago</td>
<td>FP</td>
<td>1</td>
<td>Sub</td>
</tr>
<tr>
<td>1</td>
<td>*#4: Time to Access Electronics</td>
<td>Test ability to quickly access any electronic component</td>
<td>Under 1 Minute</td>
<td>Ben E</td>
<td>FP</td>
<td>1</td>
<td>Sub</td>
</tr>
<tr>
<td>2</td>
<td>*#6: Minimum Flight Time</td>
<td>Flight Time</td>
<td>15 Minutes Minimum</td>
<td>Aero Team (Ben E)</td>
<td>FP</td>
<td>1</td>
<td>Sys</td>
</tr>
<tr>
<td>4</td>
<td>Structural Prototype</td>
<td>Fire Extinguisher Actuation</td>
<td>Pass/Fail</td>
<td>Nikkia</td>
<td>SP</td>
<td>1</td>
<td>Sub</td>
</tr>
</tbody>
</table>

*Indicates that this specification was taken from the NGCP Drone Engineering Design Specifications

**Indicates that this specification was added due to feedback from other engineers or discovery from analysis and testing

*** Indicates that this specification was taken from the NGCP Drone House of Quality document developed for PDR
<table>
<thead>
<tr>
<th>Item No.</th>
<th>Test Result</th>
<th>Quantity Pass</th>
<th>Quantity Fail</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pass</td>
<td>5</td>
<td>0</td>
<td>Able to access the electronics in the boxes in less than 1 minute</td>
</tr>
<tr>
<td>2</td>
<td>Pass</td>
<td>3</td>
<td>0</td>
<td>PLA landing legs fractured on landing. ABS legs were fine (ABS is more impact-resistant). Recommend printing ABS legs in future.</td>
</tr>
<tr>
<td>3</td>
<td>Pass</td>
<td>1</td>
<td>0</td>
<td>Stepper motor controller warm after test. Could add heatsink.</td>
</tr>
<tr>
<td>4</td>
<td>Pass</td>
<td>1</td>
<td>0</td>
<td>Hole orientation in sliding link caused zip tie (connecting the link to extinguisher handle) to get twisted. New link was printed with hole orientation that prevented zip tie twisting.</td>
</tr>
</tbody>
</table>
| 5       | All Passed  | 3             | 0             | 1. $n_{safety} = 7.5 \pm 1.5$
2. $n_{safety} = 36.1 \pm 0.1742$
3. $f_{n1} = 6 \text{ Hz}, f_{n2} = 121 \text{ Hz}$ |
| 6       | Fail        | 0             | 1             | A small amount of water did make its way into the boxes |
Appendix E – Test Procedures
E1: Electronics Access Test

Test Name: Electronics Access Test
Purpose: To determine ease of access of electronics as per Northrop’s request for an easily accessible electronics box.
Scope: This test confirms our specification # 4 from our house of quality which requires that users are able to access any electronic component in under 1 minute.
Equipment: Stop watch and ¼ in wrenches.
Hazards: Possible minor pinching and crushing of hands while removing lids or bolts.
PPE Requirements: Safety Goggles always necessary around drone.
Facility: Outdoors or Indoors on a stable surface
Procedure:
1) Lay drone out on stable surface
2) Start the stopwatch and time yourself reaching and removing random electronic component located within the drone’s electrical boxes.
3) Repeat this test 3 to 5 times to ensure that removing various electronic elements still falls within specifications
Results:
Pass criteria: The electronic component can be removed in under 60 seconds.
Number of samples: 3
Test Date(s): 5/2/2023
Test Results:
Trial 1 [Battery]: Pass
Trial 2 [ECS]: Pass
Trial 3 [MCM]: Pass
Trial 4 [Camera]: Pass
Trial 5 [An Entire Electronics Box]: Pass
Performed By: Ben Elkayam
E2: Flight Test

Test Name: Flight Test
Purpose: To confirm the ability of the drone to fly while loaded with mission critical components.
Scope: This test is primarily for the frame of the drone, but tangentially involves the winch, fire, and electronics components.
Equipment: Drone/components, RC drone receiver, stopwatch.
Hazards: Noise from rotors; minor electric shock risk while connecting motor to power source; drone falling from flight altitude; rotors getting tangled in long hair/dangling material.
PPE Requirements: Safety glasses, hearing protection recommended. Otherwise, stay clear of drone while rotors are spinning.
Facility: RC Flight Field
Procedure:
1) Arrive at flight field
2) Assemble the desired mission configuration
3) Connect primary batteries
4) Calibrate flight controls via laptop
5) Check all fasteners are secure
6) Move drone to take-off area
7) Arm drone (rotors are now spinning slowly)
8) Operator maintains at least 6 ft of space from grounded drone
9) Operator initiates flight sequence
10) Stopwatch operator begins time when drone ~1 ft off ground
11) Operator flies drone through mission profile
12) Stopwatch operator ends time when drone ~1 ft off ground
13) Drone is disarmed, and batteries are removed

Results:
Pass Criteria: Drone flies for more than 15 minutes.
Fail Criteria: Drone flies for less than 15 minutes.
Number of samples to test: 3.
Test Date(s): 5/25
Test Results: Pass
Performed By: Ben Elkayam and the club Aero team
E3: Payload Capacity Test

**Test Name:** Payload Capacity Test  
**Purpose:** To confirm the ability of winch motor to function as designed for the expected payload weight of ~2lbs.  
**Scope:** This test is for the payload retrieval system of the drone. The winch motor will need to raise, hold, and lower the payload on the payload platform during the mission operation.  
**Equipment:** Power source, motor, payload retrieval system, 2lbs weight.  
**Hazards:** Minor electric shock risk while connecting motor to power source. Risk of sudden loss of support and falling weight.  
**PPE Requirements:** Safety glasses  
**Facility:** NGCP Club work room  
**Procedure:**  
1) Ensure connections between payload platform, truss, and winch shaft are secure  
2) Connect motor to power source  
3) Run associated motor code profile (lower, hold, raise, hold, lower)  
4) Adjust code as necessary  
5) Adjust cables between payload platform, truss, and winch as necessary  
6) Repeat procedure steps 1-5 twice more with the dumbbell loaded on the payload platform  

**Results:**  
**Pass Criteria:** Winch motor can smoothly operate with the dumbbell loaded on the payload platform  
**Fail Criteria:** Winch motor cannot smoothly operate with the dumbbell loaded on the payload platform.  

**Test Date(s):** 5/6/2023  
**Test Results:** Stepper motor was able to raise and lower the payload retrieval mechanism with the 2lb. dumbbell on the platform. Noticed the strings began to wrap unevenly, so would recommend installing separators to keep the four strings separated.  
**Performed By:** Nikkia Psomas-Sheridan & NGCP CPE Team
**E4: Fire Actuation Test**

**Test Name:** Fire Actuation Test  
**Purpose:** To confirm the ability of fire actuation motor to function as designed.  
**Scope:** This test is for the fire suppression system of the drone. The motor will need to apply ~7 lbs. of force on the linkage system and hold for approximately 10 seconds.  
**Equipment:** Power source, motor, fire suppression system (3-d components), empty fire extinguisher  
**Hazards:** Minor electric shock risk while connecting motor to power source. Risk of sudden loss of support and falling weight. Trace amounts of suppression residue released during actuation.  
**PPE Requirements:** Safety glasses  
**Facility:** NGCP Club work room  
**Procedure:**  
1) Ensure connections between fire actuation linkage, spool, and motor are secure  
2) Connect motor to power source  
3) Run associated motor code profile (apply load, hold, release)  
4) Adjust code as necessary  
5) Adjust cables between fire actuation linkage and spool as necessary  
6) Repeat procedure steps 1-5 twice more to ensure repeatability  
**Results:**  
Pass Criteria: Motor can smoothly apply the minimum required load of 7lbs. and hold for a minimum of 10 seconds.  
Fail Criteria: Motor cannot smoothly apply the minimum required load of 7lbs. and hold for a minimum of 10 seconds.  
**Test Date(s):** 5/6/2023  
**Test Results:** Stepper motor was able to fully depress the fire extinguisher handle. Old spool did not fit larger shaft of stepper motor, so must re-design and reprint.  
**Performed By:** Nikkia Psomas-Sheridan & NGCP CPE Team
E5: Tensile test of carbon fiber composite

**Test Name:** Tensile test of carbon fiber composite  
**Purpose:** Determine in-plane tensile properties of carbon fiber composite  
**Scope:** The scope is to determine the maximum tensile strength of the carbon fiber composite used on the top and bottom plate of the drone, as well as determining tensile properties for further analysis. The in-plane poisons ratio cannot be determined without strain gauges, which will not be done in this test because of lack of experience and supervision during the procedure. This test procedure assumes that the samples are already made.  
**Equipment:**  
Diagram of apparatus is shown in Figure 30.

![Diagram of apparatus](image)

**Figure 30: Diagram of apparatus**

![Diagram of apparatus](image)

**Figure 1: Diagram of apparatus**

Equipment is shown in Table 4.

<table>
<thead>
<tr>
<th>Table 4: Equipment needed for test.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile testing machine</td>
</tr>
<tr>
<td>Micrometers</td>
</tr>
<tr>
<td>Force indicator</td>
</tr>
<tr>
<td>Strain-indicating device</td>
</tr>
<tr>
<td>Wedge grips</td>
</tr>
<tr>
<td>Rectangular specimen with dimensions as follows: thickness = 0.1 in, width = 1 in and length = 6 in.</td>
</tr>
</tbody>
</table>

**Hazards:**  
- Fingers in tensile test machine.
• Shattered material when specimen breaks.

**PPE Requirements:** N/A

**Facility:** Composites laboratory.

**Procedure:**
1) Measure specimen dimension
2) Confirm the calibration of the tensile test machine with Dr E.
3) Setup test procedure as in the diagram of the apparatus.
4) Tensile force is applied, and stress/strain is measured until failure.
5) Test procedure is repeated with all specimens.

**Results:**
Pass criteria: a safety factor of 2 or more to approximate maximum stress as estimated through analysis during maximum thrust from motors.

Fail criteria: safety factor under 2.

**Test Date(s):** 2/17/2023

**Test Results:**

Figure 31 shows the stress strain plot generated during the tensile test.

![Stress Strain plot](#)

*Figure 31: Stress-Strain relationship for tensile strength test*

Table 5 shows the all the data generated from the tensile strength test.
The tensile strength was determined to be:

$$\sigma_{Tmax} = 73.29 \pm 14.78 [ksi] = 505 \pm 102 [MPa].$$

(6)

The safety factor to the maximum stress from simulation (67.7 MPa) was determined to be the following:

$$n_{safety} = 7.5 \pm 1.5.$$  

(7)

Additionally, the Youngs modulus was determined to be:

$$E = 3932.93 \pm 537.79 [ksi] = 27116.60 \pm 3707.93 [MPa].$$

(8)

**Performed By:** Benjamin Ulfhake
E6: 3-Point Bend Test of Composite

Test Procedure Template for Uncertainty Analysis

**Test Name:** 3-Point Bend Test of Composites  
**Purpose:** To assess the material properties of sandwich-structured composites.  
**Scope:** The scope of this test procedure is to assess the ultimate flexural strength and the load-deflection relationship of a sandwich-structured composite. The test will also involve a comparison of three different designs, namely: a honeycomb core with carbon fiber/epoxy lamina on top and bottom; an aluminum honeycomb core with carbon fiber/epoxy lamina on top and bottom; and three layers of H80 foam with carbon fiber/epoxy lamina in between and on top and bottom. The Nomex honeycomb core design and the aluminum honeycomb core design will serve as the baseline designs for comparison.  
**Equipment:** The diagram of apparatus is shown in Figure 32 for the three-point bend test.

![Figure 32: Diagram of apparatus](image)

A list of equipment is presented in Table 6.

<table>
<thead>
<tr>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing machine</td>
</tr>
<tr>
<td>Support pins and loading pin</td>
</tr>
<tr>
<td>Micrometers for width and thickness measurements</td>
</tr>
<tr>
<td>Deflection measurement device</td>
</tr>
<tr>
<td>Equipment for the layup process: carbon fiber, Nomex honeycomb, Aluminum honeycomb, H80 foam, epoxy, release film, breather material, vacuum bag and other.</td>
</tr>
<tr>
<td>Tile saw to cut specimen.</td>
</tr>
</tbody>
</table>

**Hazards:**  
- Fingers in the tensile test machine.  
- Shattered material when specimen breaks.
PPE Requirements:
- Safety glasses when cutting specimen with tile saw.
- N95 mask when cutting specimen with tile saw.
- Plastic gloves when doing layups.

Facility: Composites Laboratory.

Procedure:
1) Layup composites with the different designs described in the scope.
2) Cut the specimen (minimum length is 6 in).
3) Measure specimen the dimensions (i.e., width and thickness) and weigh the specimen.
4) Confirm the calibration of the tensile test machine with Dr E.
5) Setup test procedure as in the diagram of the apparatus. The specimen rests on two support pins and is loaded on the loading nose at an equal distance from the support pins.
6) Force is applied at the loading nose, and the deflection is measured until failure.
7) The procedure is repeated with all specimens.
8) After baseline tests are performed, the remaining specimens are tested with the same procedure and compared with the baseline.

Results:
Pass criteria: a safety factor of 2 or more to approximate maximum stress as estimated through analysis during maximum thrust from motors.
Fail criteria: a safety factor under 2.
Design analysis: the software used will provide applied force and displacement.
Uncertainty analysis: the software used will provide applied force and displacement.

Uncertainty analysis: Error propagation will be used to determine the uncertainty in flexural stress, $\sigma_f$, where $\sigma_f$ is approximated as the function of the moment, $M$, the vertical distance to from the midplane, $z$, and the area moment of inertia, $I$, as shown in the equation below:

$$\sigma_f = f(M, z, I) = \frac{Mz}{I}. \quad (9)$$

The propagated uncertainty can therefore be written as,

$$u_{\sigma_f} = \sqrt{\left(\frac{\partial \sigma_f}{\partial M} u_M \right)^2 + \left(\frac{\partial \sigma_f}{\partial z} u_z \right)^2 + \left(\frac{\partial \sigma_f}{\partial I} u_I \right)^2}, \quad (10)$$

where $u_M$, $u_z$, and $u_I$ are the reading uncertainties for each variable. The area moment of inertia can be derived from Steiner's formula and using an equivalent moment of inertia for the core. This would be derived by using the following transformation factor,

$$n_{fc} = \frac{E_f}{E_c}. \quad (11)$$

Where $E_c$ is the young’s modulus of carbon fiber laminate, and $E_f$ is the youngs modulus of the foam. The equivalent area for the foam would be,

$$A_{feq} = A_f * n_{fc}. \quad (12)$$
Where $A_f$ is the original area of the foam. When considering bending about $e_y$ the length in y for the foam is transformed as,

$$b_{feq} = b \cdot n_{fc},$$ \hfill (13)

Where $b$, is the length in the y direction for the carbon fiber laminate. The transformed cross-section will therefore be as shown in Figure 33.

![Figure 33: Equivalent Foam Dimension](image)

The resulting area moment of inertia about $e_y$ can be written as,

$$I_y = \int x^2 dA = b(3 + 2n_{fc}) \cdot \frac{h^3}{12}.$$ \hfill (14)

Including all the variables in equation 14, it can be written as,

$$\sigma_f = \frac{Px}{b \left(3 + 2 \frac{E_f}{E_c}\right) \cdot \frac{h^3}{12}} \cdot z = f(P, x, b, E_f, E_c, h, z).$$ \hfill (15)

Where $P$ is the applied force, $L$ is the length of beam and $h$ is the length of the beam in the z direction. Note that maximum flexural stress would occur when $x$ and $z$ is at their maximum.

The resulting propagated uncertainty is therefore written as,

$$u_{\sigma_f} = \sqrt{\left(\frac{\partial \sigma_f}{\partial P} u_P\right)^2 + \left(\frac{\partial \sigma_f}{\partial x} u_x\right)^2 + \left(\frac{\partial \sigma_f}{\partial b} u_b\right)^2 + \left(\frac{\partial \sigma_f}{\partial E_f} u_{E_f}\right)^2 + \left(\frac{\partial \sigma_f}{\partial E_c} u_{E_c}\right)^2 + \left(\frac{\partial \sigma_f}{\partial h} u_h\right)^2 + \left(\frac{\partial \sigma_f}{\partial z} u_z\right)^2}. $$ \hfill (3)

**Test Date(s):** 3/9/27, 3/17/23 and 21/4/23

**Test Results:**
The test results are divided into two sections. One for the baseline test contains the Nomex Honeycomb core and the Aluminum Honeycomb core sandwich structures and another one with the H80 Foam sandwich structure.

**Baseline tests:**
Table 7 shows the specimen dimensions for the Nomex Honeycomb core and the Aluminum Honeycomb core sandwich structures.

**Table 7: Specimen Dimensions for the Nomex Honeycomb core and the Aluminum Honeycomb core sandwich structures**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Nomex Honeycomb</th>
<th>Aluminum Honeycomb</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Length [in.]</strong></td>
<td>9+11/16</td>
<td>7+14/16</td>
<td>8</td>
</tr>
<tr>
<td><strong>Thickness [in.]</strong></td>
<td>1.049</td>
<td>0.745</td>
<td>0.745</td>
</tr>
<tr>
<td><strong>Width [in.]</strong></td>
<td>1.395</td>
<td>1.624</td>
<td>1.834</td>
</tr>
<tr>
<td><strong>Mass [g]</strong></td>
<td>61</td>
<td>52</td>
<td>62</td>
</tr>
</tbody>
</table>

Figure 34 shows the force-displacement relationship for specimen 1-3 for the baseline tests.

![Figure 34: Force-Displacement Relationship for specimen 1-3](image)

Figure 35 shows one of the samples that is set up for a three-point bend test.
From the baseline tests the aluminum honeycomb was considered the better candidate.

**Foam test**

Table 8 shows the specimen dimensions for the H80 foam sandwich structure specimens.

Table 8: Specimen dimensions for the H80 Foam sandwich structures

<table>
<thead>
<tr>
<th>Sample #</th>
<th>H80 Foam</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [in.]</td>
<td>7+14/16</td>
<td>8+1/16</td>
</tr>
<tr>
<td>Thickness [in]</td>
<td>0.824</td>
<td>0.825</td>
</tr>
<tr>
<td>Width [in.]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mass [g]</td>
<td>32</td>
<td>33</td>
</tr>
</tbody>
</table>

In Figure 36 and 37 the results for the three-point bend test are shown as Force vs Displacement. Figure 36 shows the force as a distributed load and Figure 37 shows the force as a point load.
Figure 36: Force-Displacement Relationship for distributed load

Figure 37: Force-Displacement Relationship for point load

Figure 38 shows the specimen after the three-point bend test was conducted.

Figure 38: H80 Foam specimen after load test. The first specimen to the left shows the distributed load. The two specimens to the right were

Figure 39 shows one sample that is set up for a three-point bend test with a distributed load.
Figure 39: Setup for distributed load. The distributed load was approximated using a 1 in. wide fiber glass laminate.

Figure 40 shows one sample that is set up for a three-point bend test with a point load.

Maximum stress for the distributed load was calculated with the following MATLAB code with the parameters shown in Table 7 and Table 8.

\[
\begin{align*}
    dfdx &= \frac{P}{b^*(3+2*(E_f/E_c))*h^{3/12}} \\
    dfdb &= -\frac{P*x}{(b^*(3+2*(E_f/E_c))*h^{3/12}} \\
    dfdh &= -\frac{3*P*x}{(b^*(3+2*(E_f/E_c))*h^{4/12}} \\
    dfdP &= \frac{x}{(b^*(3+2*(E_f/E_c))*h^{3})} \\
    dfdEf &= \frac{P*x}{(b^*(3+2*(E_f/E_c))*h^{3/12})^2*2*b*h^3/(12*E_c)} \\
    dfdEc &= \frac{P*x}{(b^*(3+2*(E_f/E_c))*h^{3/12})^2*2*b*E_f*h^3/(12*E_c^2)}
\end{align*}
\]
\[ \sigma_{fmax} = 2.44 \pm 0.0180 \text{ GPa.} \]  

(16)

The maximum flexural stress was computed as:

The maximum anticipated stress from simulation was 67.7 MPa. This yields a safety factor as the following:

\[ n_{safety} = 36.1 \pm 0.1742. \]  

(17)

Performed By: Benjamin Ulfhake
E7: Dynamic test of sandwich-structured composite beam

**Test Name:** Sine sweep test of sandwich-structured composite beam

**Purpose:** The purpose of this test is to find the first harmonic modes of the drone beams that are within the operation frequencies of the rotors.

**Scope:** The scope is to identify any critical frequencies that may pose a risk to the structural integrity of the drone arms due to inertia caused by an offset of the center of mass. To achieve this, a sine sweep test will be performed using an identical arm of the drone prototype. During the test, the center plate of the drone will be considered the fixed end. To simulate the weight of the motor, a weight will be attached to the end of the beam.

**Equipment:**
Table 9 shows the equipment necessary to perform this test.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP 35665A Dynamic Signal Analyzer</td>
<td>1</td>
</tr>
<tr>
<td>Power amplifier</td>
<td>1</td>
</tr>
<tr>
<td>Shake table</td>
<td>1</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>2</td>
</tr>
<tr>
<td>0.6 lbs. weight</td>
<td>1</td>
</tr>
<tr>
<td>Measurement tape</td>
<td>1</td>
</tr>
<tr>
<td>Caliper</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 9: Equipment

Figure 41 shows the test diagram of apparatus.

Figure 41: Diagram of apparatus
Figure 42 shows the front view of the beam specimen with an accelerometer and a weight attached.

Hazards: N/A
PPE Requirements: N/A
Facility: Vibrations laboratory.
Procedure:
1) Measure the specimen’s length, width, and thickness. The length is from the end of the beam to the fixed end. Take note of the serial number of the accelerometers.
2) Setup the test apparatus as shown in Figure 1 without the weight shown in Figure 2.
3) Connect BNC cables from the accelerometers and the amplifier to the signal analyzer.
4) Perform an automated sine sweep on the dynamic signal analyzer with a start frequency of 1Hz and stop frequency of 1kHz.
5) Perform steps 2-4 again but now with the weight attached to the end of the beam as shown in Figure 2.

Results:
Pass criteria: No natural frequency modes within 50% to 150% of the operating frequency of the drone rotors.
Fail criteria: Natural frequency within 50% of the operating frequency of the drone rotors.
Test Date(s): 3/23/23
Test Results:
Figure 43 shows the Bode plot from the Sine Sweep showing the first frequency harmonic at 5.955 Hz.
Figure 43: Bode plot showing first natural frequency mode at 6 Hz (X-marker).

Figure 44 shows the second frequency harmonic at 120.88 Hz.

The operating frequency of the rotors is around 60 Hz. Therefore, there are no frequency harmonics within 50% to 150% of the operating frequency.
Performed By: Benjamin Ulfhake, Santiago Robles, Ben Elkayam