WESTERN MICHIGAN UNIVERSITY AIAA
ADVANCED ROCKETRY CLUB

2019-2020 NASA USLI CDR

January 10, 2020

CONTENTS

1 ACRONYMS

AGL	Above Ground Level
AIAA	American Institute of Aeronautics and Astronautics
APCP	Ammonium Perchlorate Composite Propellant
ARC	Advanced Rocketry Club
CAD	Computer Aided Design
CDR	Critical Design Review
CEAS	College of Engineering and Applied Sciences
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CG	Center of Gravity
CP	Center of Pressure
CT	Communications/Telemetry
DAP	Design Analysis Plan
DBF	Design-Build-Fly
DDM	Design Decision Matrix
DFMEA	Design Failure Mode and Effect Analysis
DVP	Design Verification Plan
E/P	Electronics/Payload Bay
ESC	Electronic Speed Controller
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FPV	First Person View
FRR	Flight Readiness Review
GPS	Global Positioning System
HPR	High Power Rocketry
HS	High School
IMU	Internal Measurement Unit
LV	Launch Vehicle
LVT	Launch Vehicle Team
MAB	Main Avionics Bay
MSDS	Material Safety Data Sheet
MV	Mission Vehicle
MTB	Main Telemetry Bay
NAR	National Association of Rocketry
NFPA	National Fire Protection Association
PDR	Preliminary Design Review
PLA PLAR	Post Launch Assessment Review
PPE	Personal Protection Equipment
RSO	Range Safety Officer
SET	Student Engagement Team
SLI	Student Launch Initiative
SMT	Social Media Team

STEM	Science, Technology, Engineering, and Math
TALL	Tilt Adjustment Landing Leg
TOF	Time of Flight
TOLS	Three Oaks Launch Site
TRA	Tripoli Rocketry Association
UAV	Unmanned Aerial Vehicle
WMU	Western Michigan University

2 GENERAL INFORMATION

2.1 ADVISORS / STUDENT LEADERS

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2.2 ORGANIZATION OUTLINE

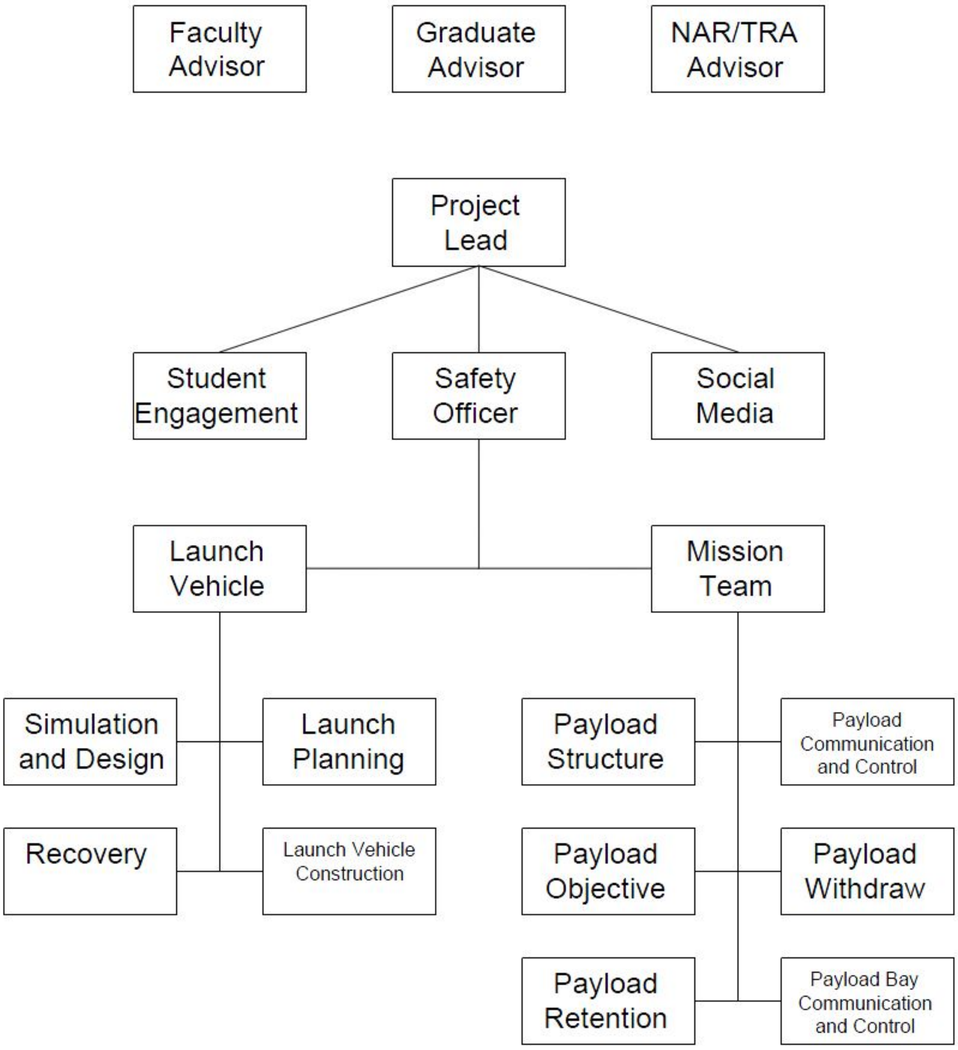

Figure 2.1: Flowchart Depicting Organization of the Teams and Sub-teams

2.2.1 LAUNCH VEHICLE TEAM

The Launch Vehicle Team (LVT) is responsible for the design, construction, testing, and delivery of the launch system. This includes material considerations, propulsion system decisions, flight simulation, mission deployment systems, and vehicle recovery systems. Simulations and vehicle evaluations will be conducted throughout the build process to ensure a successful flight. Additional focus will be given to in-flight stability in order to account for payload shifts throughout all flight modes. Simulations will also be used to predict the altitude of flight in accordance with Student Launch Initiative (SLI) Handbook Vehicle Requirement 2.1. This subgroup will handle most of the hazardous materials during the build process. As a proactive safety measure, only senior members that are Tripoli Rocketry Association (TRA) Level 2 certified will handle the construction of the propulsion and ejection systems. Any additional hazardous materials will be handled with the close supervision of the Safety Officer. This team is comprised of eighteen student members and one student team lead.

2.2.2 MISSION TEAM

The key responsibility of the Mission Team is to design, construct, and test the payload that will execute the lunar ice recovery mission. Additional responsibilities include the creation of the payload control systems, communication and launch vehicle telemetry, and the execution of the mission. To ensure each of the team's responsibilities are achieved, this team will be further divided into sub-teams. These sub-teams can be seen in Figure 2.1. Some of these sub-teams' responsibilities overlap; therefore, close communication will be required. These teams either work on components that will remain in the rocket body after the payload is ejected or are part of the payload itself. The first payload team is Payload Structures. This team is responsible for the design, testing, and implementation of the mission vehicle's structural components. The next payload team is the Payload Objective Team. This team is responsible for all aspects of the system that will be mounted to the mission vehicle for the recovery of simulated lunar ice. Another payload team is the Payload Communication and Control. The key responsibilities of this group are ensuring the mission vehicle has a working communication system and enabling the control of the mission vehicle at all necessary points throughout the mission. The remaining sub-teams will work on components that will remain in the rocket body after the mission vehicle exits. These sub-teams are Payload Retention, Payload Withdrawal, Terrain Risk Mitigation, and Payload Bay Communication and Control. These sub-teams deal with all factors necessary to prepare the mission while it is inside of the Launch Vehicle (LV), such as monitoring battery levels and keeping the mission vehicle restrained throughout the LV's flight. The Mission Team's structure has significantly changed since the submission of the proposal. The main reason for the changes is the projected number of members being higher than the actual number of members. This resulted in a restructuring of the team to include increased area specialization. Members of the new sub-teams handle the design, simulation, construction, and testing of each subsystem. This team is comprised of ten student members and one team lead.

2.2.3 SAFETY OFFICER

The Advanced Rocketry Club (ARC) Safety Officer is responsible for ensuring that all team members abide by all safety regulations. Furthermore, the Safety Officer will ensure that hazardous materials are handled properly and all operations are conducted in a safe manner. To accomplish this, the Safety Officer will maintain current versions of all safety documents, create safety procedures for the build and launch of the vehicle in conjunction with the team leads, and create checklists to be followed by the team during ground tests and flights of the sub-scale and full-scale vehicles. The Safety Officer will create a safety contract to be followed by all members and conduct risk assessments of both build and flight hazards. Additionally, the Safety Officer will conduct regular reviews of construction, launch, and design decisions to ensure they abide by all regulations and procedures. The Safety Officer will be the primary point of contact for the Range Safety Officers at the launch sites utilized by ARC during the competition season. In addition, the Safety Officer will ensure that Science, Technology, Engineering, and Math (STEM) engagement events are conducted in a safe manner.

2.2.4 SOCIAL MEDIA TEAM

The Social Media Team (SMT) will enable public outreach by creating an open line of communication between NASA, the public, and ARC. ARC will establish a consistent social media presence to help communicate the progress of the rocket and payload to the public and SLI officials. The club will document construction milestones, safety efforts, launches, periodic tests, and team member involvement. This team fulfills SLI communication requirements and facilitates long-term team sustainability. Advertising the club's activities to current and prospective students will facilitate continuing interest in ARC. This team is comprised of one student team member and one student team lead.

2.2.5 STUDENT ENGAGEMENT TEAM

The Student Engagement Team (SET) is responsible for organizing and engaging local K-12 students in STEM experiences and rocketry-focused activities. Per SLI requirements, ARC must reach 200 students through educational events that promote STEM or rocketry. In prior years, the Western Michigan University (WMU) American Institute of Aeronautics and Astronautics (AIAA) Pegasus Chapter (which includes ARC) has been active in educational activities within southwestern Michigan. The College of Engineering and Applied Sciences (CEAS) encourages involvement with local students. As a result, WMU AIAA has ongoing educational activities that will be expanded throughout the coming year. The SET is tasked with planning and enacting additional educational opportunities as well as continuing legacy activities. These activities will be documented and compiled to establish the scope of students reached through the SET's efforts. This is further discussed in Section 5. This team is comprised of four student team members and one student team lead.

3 CRITICAL DESIGN REVIEW SUMMARY

3.1 TEAM SUMMARY

Team Summary	
Team Name	WMU Advanced Rocketry Club (ARC)
Mailing Address	4601 Campus Dr. Kalamazoo, MI 49008
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3.2 LAUNCH VEHICLE SUMMARY

The LV will be made from 128 inches of uniform 7.5 inch diameter BlueTube™. The upper body is an 18 inch section of BlueTube™and nose cone that houses the round canopy drogue parachute. The lower body consists of the lower air frame, payload bay, fins, main recovery system, and propulsive system. The body fins are a 4 split fin configuration constructed of fiberglass. The rocket will launch on a L1420R-P Aerotech motor in a 75mm reloadable motor casing. The LV is intended to reach target apogee of 4635 feet. Upon apogee, there will be a single ejection charge separating the nose cone from the upper air frame (while maintaining connection through a tethered shock chord) and ejecting the drogue parachute. At 550 feet, a second ejection charge will ignite, ejecting to MAB from the lower body, pulling the main parachute from the body. The main parachute mounts externally at the bottom of the LV to allow it to descend perpendicularly to the ground and land on its fins. Additional vehicle characteristics are shown in Table 5.1 of Section 5.

3.3 PAYLOAD SUMMARY

The final version of the payload design is a custom 3-D printed chassis optimized using a generative design process. This iteration of the drone design is internally referred to as "Droney". This drone will be comprised of a main chassis, rotor boom arms, legs, a collection system, motors, rotors, and accompanying aluminum hardware. The components will be primarily made of nylon, but PL, and carbon fiber rods will also be used. Unique features of this design include stowing boom arms, a generative designed chassis, and a brush sample collection method. The generative design process will be further discussed in subsequent sections. The payload will be controlled by a Raspberry Pi and a Raspberry Pi flight controller hat. This system will communicate telemetry information to the ground station using 2.4GHz WiFi directly to the Raspberry Pi and a 915MHz LoRa connection to the flight controller. This redundant system will ensure that telemetry information is available to the ground station at all times. In addition to these connections, a 2.4GHz controller will be connected to the on-board flight controller for mission capabilities. This system is design for mass objective gathering.

4 CHANGES MADE

4.1 LAUNCH VEHICLE CHANGES

As the entire LV and mission system design matures, the physical parameters of the system change. These changes maybe propagate through the entire system, requiring dramatic changes to remain compliant. With PDR feedback and design changes in mind, the LV and recovery systems experienced large shifts since the preliminary design. Specifically in the recovery system components and propulsion system. The following summarizes the LV changes since PDR, with the subsequent sections providing details on the current designs.

4.1.1 AIRFRAME/LAUNCH VEHICLE CHANGES

The weight and size of the mission systems have crept above the preliminary estimates. This has pushed the launch vehicle CG further aft, impacting the vehicle stability. To combat this, the team removed the tail cone. While this eliminates a drag reducing feature, it dramatically decreases aft weight and raises the LV stability above that of the PDR model. The team decided it could afford eliminating ballasting weight in the nosecone, decreasing overall weight and stability to values that were deemed acceptable.

4.1.2 PROPULSION SYSTEM CHANGES

The team's PDR including flight simulations that were non-compliant with KE regulations. One instigator of the excessive KE was the descending vehicle weight, and one component that contributed a large amount of weight was the motor. The L1420 proved to be decrease the LV weight after burnout,and when coupled with new recovery systems lowered landing KE to below the competition maximum. Making this configuration's KE compliant.

4.1.3 RECOVERY SYSTEM CHANGES

The PDR parachute configuration relied on the team's ability to utilize already produced parachutes. As previously discussed, this resulted in the KE being non-compliant. This was solved by using commercially available parachutes for the main deployment system that were much large than the PDR parachutes.

The current recovery process does not involved upper body and lower body separation. This is more reliable and safer in terms of deployment consistency. Simulations and KE calculations take the entire LV weight into account.

4.2 Payload Changes

4.2.1 Payload Objective

The payload objective system has proceeded in the direction previously outlined. There have been no major modifications from the previous primary system.

4.2.2 Payload Communication and Control

Personnel changes in ARC since PDR submission have led to design modifications in the paylaod communication and control system. The payload will be powered by a single Li-Po battery that will be initialized during launch preparations rather than a primary and idle battery. The increased amount of battery drain has been taken into consideration for the choice of this Li-Po system.

4.2.3 Payload Structure

Further analysis of the payload's structures identified issues with the system's weight and strength. To combat these shortcomings, a generative design process was employed to both lighten and strengthen the structure. It was also determined that nylon would be over 80 times stronger than the previous material without increasing weight. As a result, the payload structure will be primarily composed of 3-D printed nylon.

4.2.4 Payload Withdrawal System

Ejection System: During initial testing of the constant force spring ejection system, it became apparent that the system would not operate in the manner intended. Instead, the spring expanded to keep a nearly constant outer diameter. The lack of transfer of energy to the radial damper resulted in the total energy being converted into linear velocity. It was determined that the carriage would move too fast for a safe deployment. The belt winch alternative system was chosen over the linear servo alternative system because linear servos of the correct length and strength could not be found.

4.2.5 Payload Retention System

Retention Hook Material: During various tests of the retention system hooks, it was demonstrated that the plywood used for the hooks could only withstand 1.198 lbs of sudden applied force before breaking. Since forces during flight are expected to be greater than this value, other materials were considered. Aluminum alloy 6061 was chosen as the material to replace the wood due to its strength-to-weight ratio.

4.3 PROJECT PLAN CHANGES

The overall content of the team project plan remains the same as what was previously presented and explained in the proposal. However, subscale flight failures have shifted flight data collection and design iteration back three weeks. Initial flight was planned for December 16th 2019, current project plan places this at January 18th 2020. While initial plans had this as a critical milestone, the granting of extension has decoupled all following critical events from the subscale flight. That is to say that full scale construction and CDR completion are occurring concurrently. At this time we have secured funding that is available for use. In PDR, the project plan showed plan slippage due to funding delay. These have since been alleviated as additional funding has been acquired ahead of the preliminary schedule. At this time it is not expected that these delays will have a dramatic affect on our project.

5 LAUNCH VEHICLE

5.1 MISSION STATEMENT AND SUCCESS CRITERIA

The launch vehicle will reach an apogee between 3,500 and 5,500 feet, safely return to the ground, and activate payload deployment systems. During flight and landing, loads will be limited to maintain the functionality of all components. Upon landing in the appropriate orientation, the payload drawer will extend to allow the payload to begin its ice retrieval mission. The mission will be considered a success when the following requirements are met:

Launch Vehicle Success Criteria

1. LV reaches a minimum of 3,500 feet AGL while remaining below 5,500 feet AGL.
2. Initial recovery system deploys and maintains connection to lower body
3. Main recovery system ejects and deploys succesfully without harming mission systems or LV
4. LV lands in the predetermined orientation.
5. Payload deployment system is intact and actuates successfully.

5.2 LAUNCH VEHICLE SYSTEMS

Since PDR, the launch vehicle system have undergone iterative designs to remain competition compliant while addressing changes in other systems. The following sections will describe the final choices made in the LV designs. Table 5.2, Figure 5.1, and Figure 5.2 can be used as a reference as each subsystem is explained to help understand how the systems combine and/or interact.

General LV Characteristics	
Stability	2.23
Weight (Loaded)	40.5 lbf
Weight (Burnt)	34.86 lbf
Length	128 in
Diameter	7.5 in
Number of Fins	8 (Split 4)
Predicted Apogee	4972 ft
Flight Time	~135 sec

Table 5.1: General Launch Vehicle Characteristics

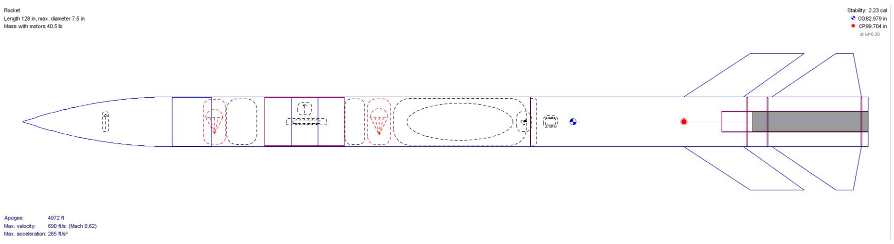


Figure 5.1: Oberon Mk1 Simulation Model

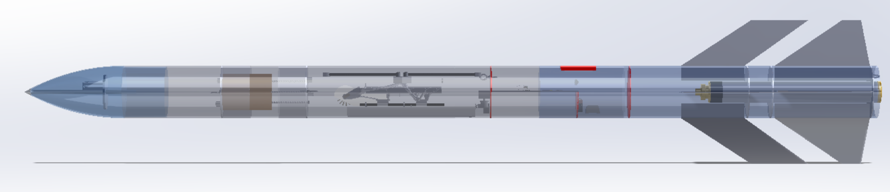


Figure 5.2: Oberon Mk1 3D Model

5.2.1 AIRFRAME SUBSYSTEM

The launch vehicle airframe will be constructed of BlueTube 2.0™in two main sections. The lower section houses the payload, main recovery system, TALL, and launch vehicle telemetry systems, and it will be constructed with 85 inches of 7.5 inch constant diameter BlueTube 2.0™. The upper section will be 18 inches of 7.5 inch constant diameter BlueTube 2.0™and will house the apogee recovery system and launch vehicle avionics. The two sections will be coupled using 12 inches of coupler. The sections will be purchased from Always Ready Rocketry, and the fin slots will be cut through the ARR CNC services. The construction of the subscale launch vehicle yielded small errors in certain machined sections. These errors were within acceptable range given the test setting. For the full scale construction, the team is more comfortable outsourcing the precision machining processes of the BlueTube 2.0™. The lower body telemetry section will have a removable access panel. The area around the panel will experience large stress concentration during flight and recovery. This will be mitigated by the use of smaller diameter coupler sections along the access hole. Certain interior sections of the airframe will also have additional coupler lengths to strengthen areas that will benefit from the added support. At the recovery mounting points, the added interior strength will decrease the risk of an airframe zipper on deployment or a yielding of the parachute mounting point.

5.2.2 NOSECONE

Given time restrictions, budgetary constraints, and team experience, it is most reasonable for the team to purchase a nosecone that fits the launch vehicle's operating conditions. HPR retailers provide a variety of options in this regard. These included several material and shape options, with specific attention paid to performance characteristics in the subsonic regime. Additionally, the material of the nosecone must provide RF transparency and enough weight to induce adequate static stability of the launch vehicle.

Given these concerns, a fiberglass Ogive nosecone has been selected. The Ogive has excellent drag characteristics in the subsonic regime. While the Von Karmann geometry provides better aerodynamic characteristics in the expected flight regime, it is not commercially available at the required diameter. The nosecone will have an aluminum tip to increase the compressive strength of the nosecone, and it will serve as a structural anchor point for interior construction.

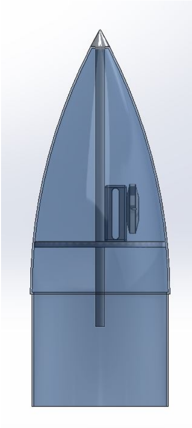


Figure 5.3: Nosecone Assembly

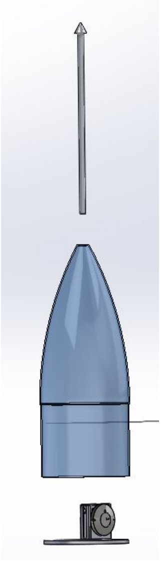


Figure 5.4: Nosecone Assembly

5.2.3 Fins

The launch vehicle uses a four fin split configuration. This configuration is the result of the center-of-gravity of the fully loaded vehicle. The mid-airframe housing of the payload shifts the CG further aft. The static stability of a three or four fin configuration was lower than the competition requirements. A split fin design allowed the team to raise the stability margin to a value that fulfilled team design standards and competition requirements.

The lower fin geometry was chosen due to its aerodynamic properties and its ease of manufacturing. The fin is a tapered trapezoid, which exhibits aerodynamic benefits and is shaped such that landing damage is minimized, which is important when considering that the launch vehicle is designed to land on two of the fins. The fore fins were chosen with similar concerns in mind, but additional consideration was given to profile interaction with the lower fins. The swept tapered trapezoidal shape minimizes negative interaction between the fin sets. This shape is also optimized for material usage, as other geometries used enough material to negate the CP changes decrease the LV stability. The span of each fin set is identical to ensure a uniform landing face across both fin sets.

For ease of manufacturing, each fin set has a rectangular cross section with no taper along its cord length. The fins will be cut from G10 fiberglass sheets with fin tabs extending to the outer diameter of the motor mount for increased strength. Once properly filleted internally and externally, the fins will be able to withstand all expected flight forces, including landing forces. The following figures show the dimensioned drawings of the fins.

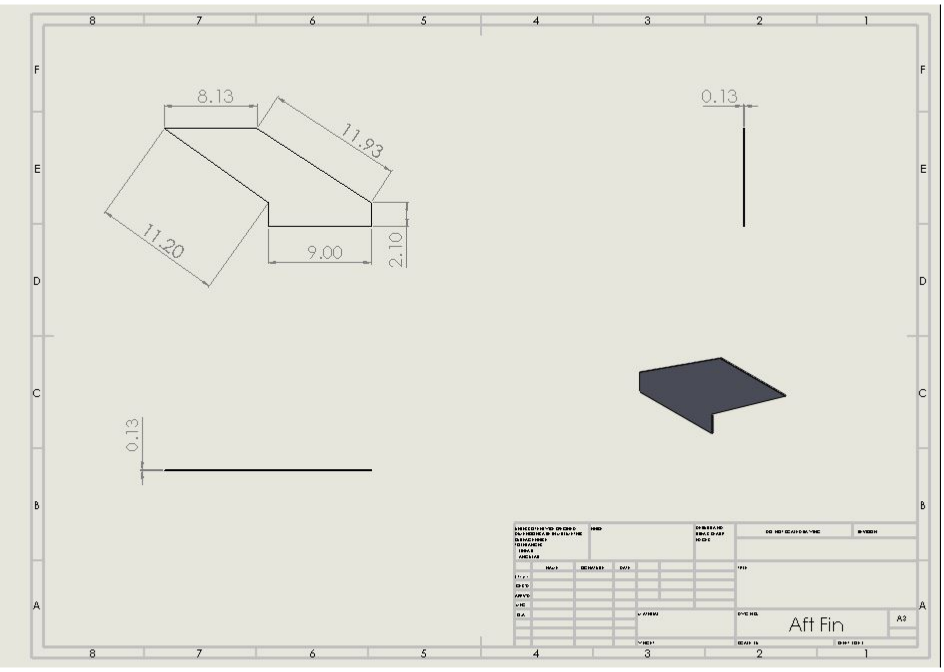


Figure 5.5: Aft Fin Drawing

5.2.4 PROPULSION SYSTEMS

The vehicle's motor is the Aerotech L1420R-P. Simulations with this motor place the apogee well within the required range. The thrust to weight ratio of 8.05 will aid in-flight stability and allow the launch vehicle to reach 66.3 ft\s at rail exit. Through analysis of many simulation parameters, the team expects the launch vehicle to reach an apogee of 4970 feet. This is higher than the predicted apogee at PDR, but design changes necessitated a new propulsion system. The motor is housed in an Aerotech 75mm/5120 motor casing. The launch vehicle will no longer use a tail cone, as flight stability is not a concern in the current configuration. In addition, the weight added by the tail cone negatively impacted static stability. The changes to the payload systems since PDR yielded a different weight distribution in the launch vehicle,

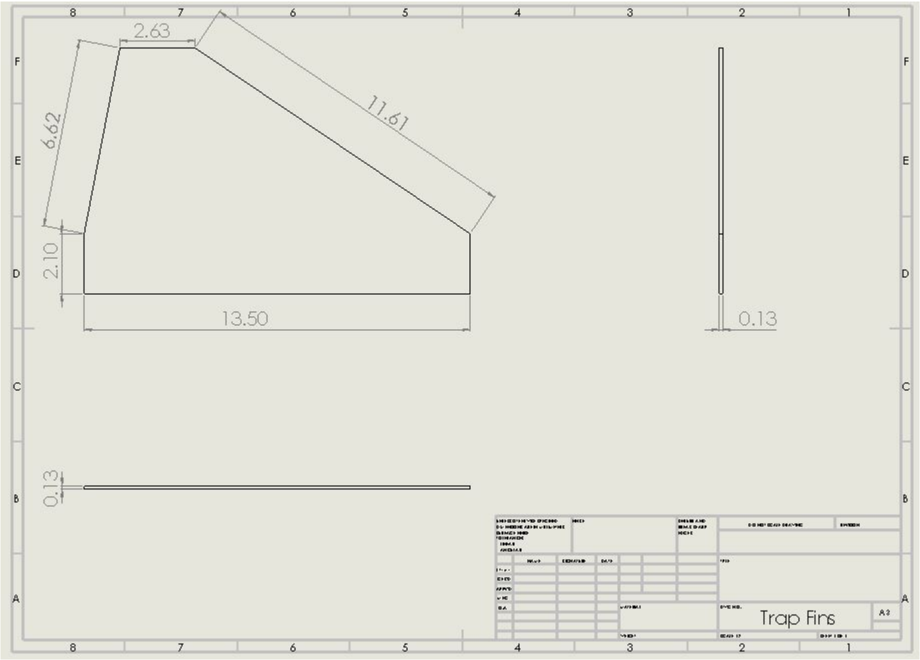


Figure 5.6: Trapezoidal Fin Technical Drawing

which necessitated balance adjustments to maintain a static stability of 2.23 calibers. Motor retention will instead come from a 75 millimeter motor retention system. This has a marginal effect on static stability while fulfilling the retention capability of the tail cone.

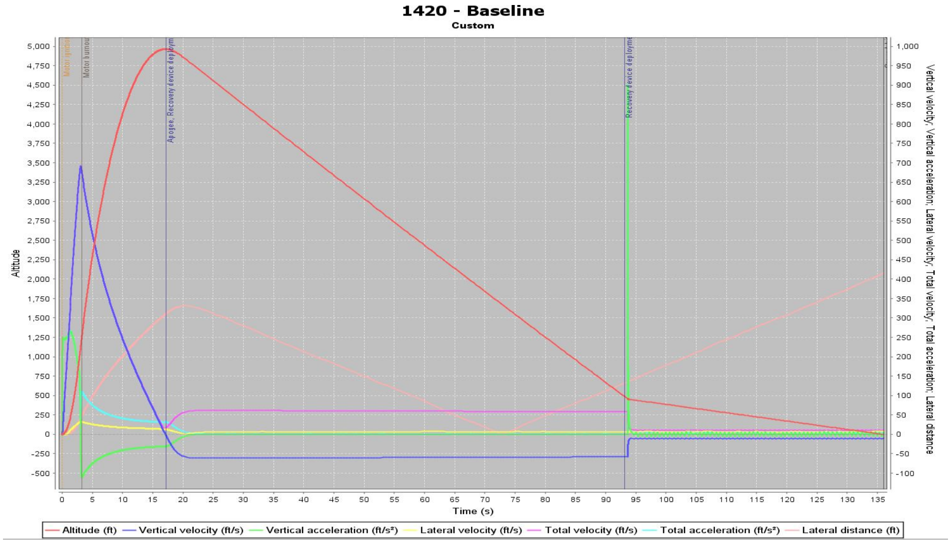


Figure 5.7: LV Flight Simulation on L1420

Simulations of a variety of conditions on the current configuration suggest that LV will exceed the predicted PDR apogee. The team has accepted this fact as the LV and propulsion system combination is required to remain compliant. Ideal condition simulations place the vehicle ground-hit velocity at 10.1 ft/s, and high wind conditions topping the ground-hit ve-

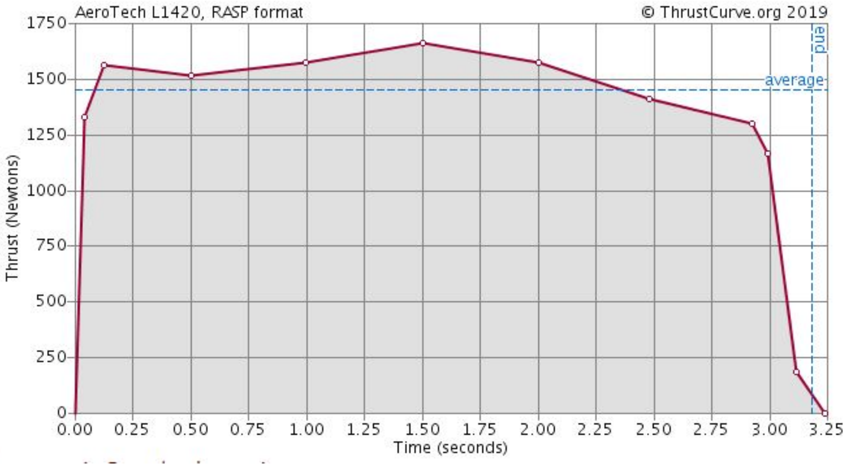


Figure 5.8: L1420 Thrust Curve

locity at 11.4 ft/s. The entire range of ground-hit velocities place the LV KE under the required limit. This is discussed in further detail in Section 5.4.2. Similarly, high-wind conditions place lateral drift at 2125 feet. Below the competition maximum of 2500 feet. This data has confirmed this propulsion configuration to be adequate for ARC and NASA requirements.

Wind Speed (mph)	Apogee (ft)	Lateral Drift (ft)	Ground-Hit Velocity (ft/s)	Flight Time (sec)
0	4963	438	9.82	138
5	4961	448	9.97	137
10	4933	1028	10.1	136
15	4856	1682	10.4	136
20	4813	2135	10.7	134

Table 5.2: Wind Speed Variation Simulations

5.2.5 AUXILIARY TELEMETRY BAY

The nosecone will house the redundant telemetry systems of the launch vehicle. These systems will provide backup location data for the launch vehicle throughout its entire flight. Due to the fact that the launch vehicle will no longer separate during the descent, this data will serve as the competition required redundant system.

The equipment in this section does not need to interact with any other components of the launch vehicle, and as such is contained in the nose. The balsa wood bulkhead is mounted to the nose tip bolt, and the PLA housing is mounted on the bulkhead. A SPOT Trace is mounted on the housing to serve as the redundant tracking system. The SPOT Trace is a self-contained off-the-shelf tracking unit, requiring no auxiliary power. This assembly is shown in Figure 5.3 and Figure 5.4. The balsa wood bulkhead was chosen because it is cheap to manufacture and will not experience any direct loads throughout the flight. The PLA housing will be 3D printed to allow for a specific fit to the team's GPS board without sacrificing weight or price.

5.2.6 MAIN AVIONICS BAY

The main avionics bay (MAB) will house redundant altimeters. There will be one PerfectFlite StratologgerCF and one Altus Metrum EasyMini. Each altimeter will have an independent power system attached to an independent ejection charge system. Each power system utilizes external screw-PCB switches as a launch safety mechanism. This allows for the MAB to be off prior to manual arming once the LV is ready for launch. These The EasyMini will be the altimeter attached to the main deployment charges. The StratologgerCF will be set to deploy 1 second after apogee and attached to deployment charges with 10% more black powder. The delay and added black powder will ideally prevent deployment failure due to inadequate pressurization or power failure of the main altimeter. The MAB acts as the control center for all recovery systems. It couples the upper and lower bodies and is therefore able to interact with both the main and apogee deployment systems. Since the PDR, the team has changed the deployment process. The upper body and lower body sections will remain attached and the entire launch vehicle will descend together. The details of this process are discussed in section 5.4.1. In this arrangement, the MAB is physically connected to the main deployment systems and will trigger them with the redundant altimeters.

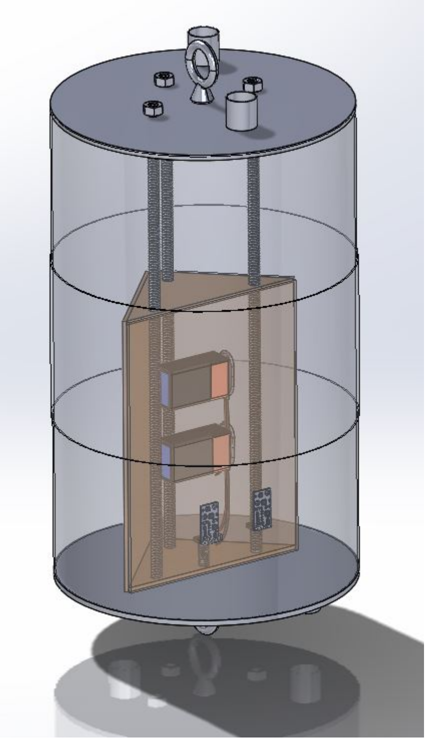


Figure 5.9: Main Avionics Bay

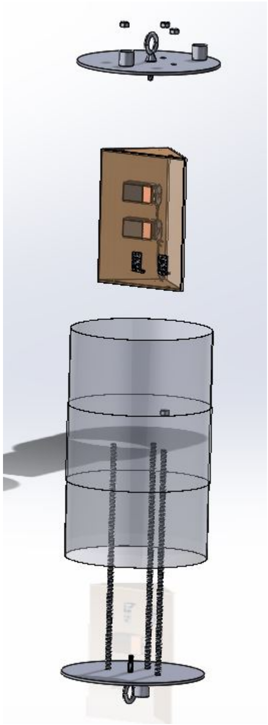


Figure 5.10: Main Avionics Bay Exploded View

5.3 MAIN TELEMETRY BAY

The Main Telemetry Bay (MTB) will house the main tracking and communication units of the launch vehicle. This section will also hold the control systems for payload deployment and serve as a secondary communication base for the drone in flight. The MTB will be located behind the payload bay and separated from the payload bay by a fiberglass bulkhead. Fiberglass has been chosen because this bulkhead will experience deployment pressurization loads. This bulkhead is also where the main deployment eye bolt will be mounted. The MTB will be accessible by an external panel on the airframe. The panel will be secured using two screws and pressure sealed with a gasket on the panel perimeter. The panel is shown in the airframe assembly in Figure 5.12. The MTB can be found between the red bulkheads in Figure 5.11. The main telemetry system will be the NEO-M8N. More information on the specifications of this GPS unit can be found in Section 5.6. The MTB will also house the communication system for the launch vehicle and mission systems as well as their power sources. The control system hardware will be wired through the payload bay bulkhead, allowing for control of the mission systems while protecting the controls from deployment charges and moving mission systems. The specific systems and their hardware are further discussed in Section 6.

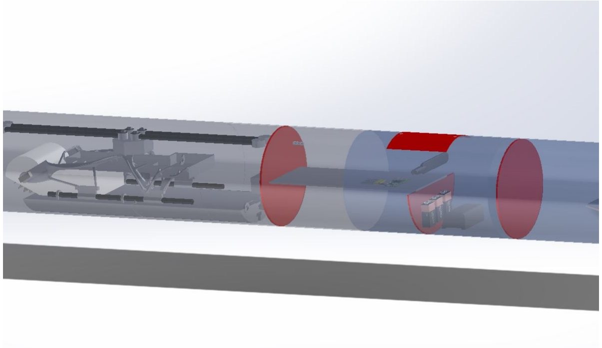


Figure 5.11: Telemetry Bay

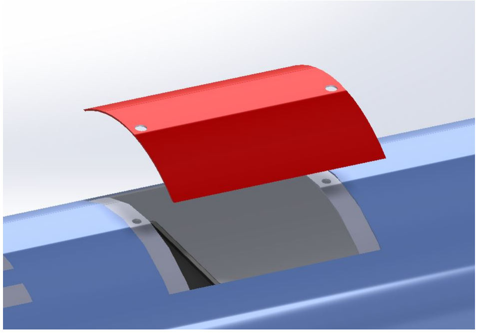


Figure 5.12: Telemetry Bay Access Panel

5.4 RECOVERY SYSTEMS

Since PDR, the team has made significant changes to the recovery system design. While the core functionality of landing the launch vehicle in a predetermined orientation remains, the process involved in achieving this state has been streamlined for increased feasibility and safety. The following sections describe the recovery procedures at all pertinent stages of flight and the justification for these decisions.

5.4.1 RECOVERY DEPLOYMENT PROCESS

The recovery system deploys in stages during the flight to minimize drift distance, protect the integrity of mission systems, and limit the dangers of the descending launch vehicle. All recovery decisions consider these three factors. The three recovery stages are **Apogee**,**Main**,and **Landing**.

Apogee

Upon reaching apogee, the MAB will detect that the LV has stopped ascending. This will trigger the staggered ignition of both deployment blasts on the foremost section of the MAB. This will eject the drogue parachute and nosecone assembly. Both of these components will be tethered to the launch vehicle, attaching to the eyebolt of the MAB. One end of the body length shock cord will be tethered to the bottom of a swivel bolt, with the other end tethered to the drogue chute lines. This will prevent tangling of the shock cords from preventing full unfurling of the drogue chute. This configuration can be seen in Figure **??**. The launch vehicle will descend under the drogue until the MAB recognizes that the LV has reached approximately 600 feet. At this point, the main deployment stage begins.

Main

Once the MAB has recognized that it has reached main deployment altitude, it will ignite the two deployment blasts located on the aft end of the MAB. This will eject the avionics bay (which remains tethered to the LV) and pull the main parachute from the lower body. Unlike the PDR configuration, the shock cord tethering the main chute to the lower body will also tether the main chute to the avionics bay, drogue chute, and nosecone assembly. This configuration is similar to that of most HPR recovery systems. However, the main chute will be mounted both internally at the forward end of the lower body, and externally at the aftmost section of the lower body. These mounting points are shown in Figure 5.14 and Figure 5.13. The main chute shock cord will also utilize a swivel bolt to alleviate tangling. The tether to the avionics bay will be 2.5 body lengths. Allowing the drogue chute, avionics bay, and nosecone assembly to hang far below the lower body inhibit their ability to spin on descent and potentially tangle the main recovery system. Keeping the upper and lower body connected throughout descent increases the overall weight of the descending body when compared to the team's PDR configuration. Larger main parachutes have been chosen to lower the descent speed and KE.

Landing

The launch vehicle does not have any active recovery systems after the main stage and prior to reaching the ground. However, the launch vehicle must right itself once touched down to ensure a successful payload deployment. Assuming the LV has landed in the correct orientation, the TALL will be activated. Unlike the previous two stages, the TALL activation will be a manual procedure. Once the TALL has been fully extended, the recovery process is complete and the mission team takes mission controls.

5.4.2 PARACHUTES AND SHOCK CORD

As previously mentioned, the current configuration requires new parachutes to lower the total KE. Given the team's experience with constructing parachutes it solely became a matter of what canopy size would slow the descent enough. However, it is important to know the coefficient of drag of the parachute when determining its ability to slow descent. The team utilized empirical data from parachute retailers and simulated the LV on the commercial parachutes. After simulating a selection of parachutes it was clear that at least 200 inches of parachute diameter was required to lower the KE below 75 ft-lbf. As previously mentioned, the team previously constructed parachutes that were effectively para-sheets. Retailers with dome or cruciform canopies were first considered. Parasheets are typically considered to have a coefficient of drag of 0.75, purchasing enough material to create the same diameter canopy in either cruciform of dome would be more expensive. Ultimately the team found an 18 foot (216 inches) cruciform parachute that was the most cost effective option while meeting the KE requirements. The simulations in Section 5.2.4 were conducted utilizing this parachute. As shown in the flight simulations, the ground-hit velocities ranged from 9.82 f/s to 10.7 ft/s. The loaded weight of the LV is 40.5 lbf, with a burnout weight of 34.81 lbf. As the entire LV remains together throughout the flight, the landing weight would be the burnout weight. KE is calculated using ground-hit velocity and mass of the LV. However, it is important to convert the weight of LV in mass (lbm or slugs).

Velocity (ground-hit velocity): $v = ft/s$
Acceleration due to Gravity: $g = 32.2 ft/s^2$
Mass: $m = (lbf/g) slugs$

$$KE = (0.5)(m)(v^2) ft - lbf \tag{5.1}$$

Using Equation (5.1), the landing KE is at its lowest 52.124 ft-lbf and its highest 61.885 ft-lbf. Both values are compliant.

Tubular nylon is the standard shock cord material used in HPR. The specific width of the tubular nylon affects the tensile strength and therefore its ability to withstand ejection loads. Tensile strength would logically be the most important parameter of the shock cord. Tensile strength must be coupled with elastic properties to not only minimize ejection loads on cord, but loads on the rest of the launch vehicle and payloads due to large deceleration. Another consideration is heat resistance, as the shock cord is the most exposed to ejection gases. Materials like Kevlar address that concern. However, the team was able to determine from subscale testing that the aft mounted shock cord is not exposed to enough heat to jeopardize the cords strength. Therefore half-inch tubular nylon will be used for parachute shock cord and component tethering.

A similar method was used to determine the new drogue parachute sizing. However, in this case in house production is cost effective up to around 80 inches diameter. Iterative simulations showed that a deployment velocity of <40ft/s would limit descent KE and allow for safe main deployment. Utilizing Equation (5.1) with a descent velocity of 40 ft/s the KE was 8.87 ft-lb. This is achieved through at least 54 inches of a parasheet system. The team plans on constructing a 56 inch parasheet to increase safety margin. This lowers main deployment velocity to 37.7 ft/s and descent KE to 769.35 ft-lb.

5.4.3 MAIN RECOVERY SYSTEM MOUNTING

The recovery system employed by the Oberon is unconventional in nature. Rather than mounting the shock cord axially on a structural piece like the motor mount, there needs to be two mounting points that will support both axial and bending loads. Each mounting point utilizes the same general mounting procedure: 3/8" galvanized shouldered lifting eye-bolt mounted in a fiberglass bulkhead. These bolts are rated for up to 1300 pounds of lifting forces, far above the maximum expected loads at main deployment. The bulkhead will be flanked by coupler section, in a similar manner as mentioned in section 5.2.1. This is shown in the fore section in Figure 5.13 and the aft section in Figure 5.14. The red components represent the main chute mounting parts. Of course this concentrates shock loads at points where the shock cord wraps around the airframe edge. To prevent airframe zippering, coupler lengths will be placed on these edges, doubling the airframe thickness at the points of highest stress. In the aft configuration the coupler support section is also red.

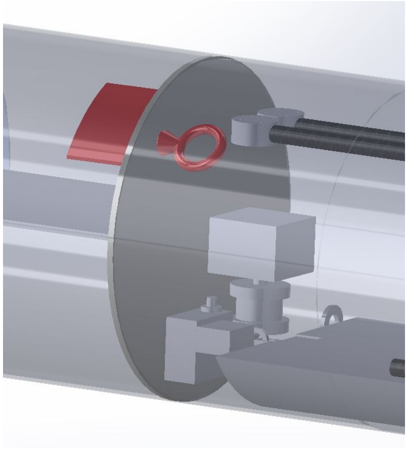


Figure 5.13: Fore Chute Mount

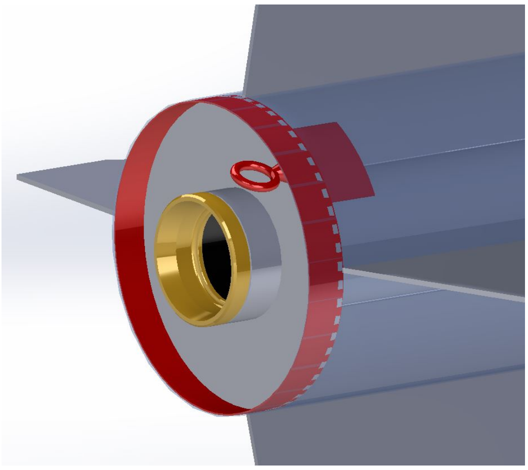


Figure 5.14: Aft Chute Mount

5.4.4 APOGEE RECOVERY SYSTEM MOUNTING

The apogee recovery system matches that of most standard high power rockets. The drogue chute will only separate the nosecone from the launch vehicle. Shock cord will be attached to the Main Avionics Bay and the nose tip bolt. Both the Main Avionics Bay and nose tip will hold the shock cord with the same 3/8" galvanized shouldered lifting eye-bolt (with the nose tip eye bolt being female threaded). The shock cords attached to the nose tip and Main Avionics Bay will then attach to Petzl P58s small bearing swivel bolt. This bolt is rated for working loads of 1124 pounds, this will withstand deployment forces and prevent tangling of the shock or parachute cords during descent or deployment.

5.4.5 TERRAIN RISK MITIGATION

In order to assure that payload deployment remains unobstructed, the Oberon is designed to land on its side and adjust its body angle to be level with the horizon. When the recovery system deploys, the main chute will reorient the rocket body so that TALL and two of the Oberon's tail fins will point towards the ground. In order to protect it from damage, TALL will not be deployed until the rocket has come to a complete stop. The ground station will manually send the command to activate TALL, before the PCA9685 servo controller extends TALL's linear actuators to the correct length. TALL is located between the electronics bay and the rear payload bulkhead, and will deploy from a cutout in the side of the rocket body that is $1inch$ long and 1/3 circumference wide. the Once deployed, TALL and the two tail fins will act as a modified tripod in order to support the weight of the rocket and keep it steady for payload deployment.

Tilt Adjustment Landing Leg (TALL):

No major changes to TALL have occurred since the PDR. The Tilt Adjustment Landing Leg is comprised of 2 major parts: a printed PLA foot and two linear actuators.

In order to successfully lift the nose of the Oberon, TALL must provide at least $16.05lbf$ (at least $8.25lbf$ per linear actuator). It must also have a stroke of at least 3.437 in order to get the rocket body to a level horizon. This proved to be a difficult task, since most linear actuator with the required thrust could not fit within the 7 in diameter body tube. The Actuonix L12 linear actuator was chosen because it was the only design capable of meeting these requirements. In order to attach TALL to the rocket body, each linear actuator will be mounted using epoxy and PLA spacers.

Maximum Force (per Actuator): $17.98lbf$
Stroke: $3.937in$
Closed Length (hole to hole): $5.984in$
Operating Voltage (per Actuator): $6V$

As discussed in the PDR, TALL will use a rounded, printed PLA foot to distribute the weight of the rocket body across the ground. Due to the complexity of the design and the accessibility of 3d printers near ARC's lab, the foot will be 3d printed using PLA plastic at 100% infill. The updated foot design has been narrowed externally and hollowed out internally in order to save space, reduce weight, and provide more clearance for the linear actuators. The circular base of the foot is 1/3 of the circumference of the rocket body wide. This will help to evenly distribute the load of the rocket body, and will keep the foot from sinking too far in to the soil beneath it upon deployment. When retracted into the Oberon, the foot is also designed to sit flush with the outer surface of the rocket body.

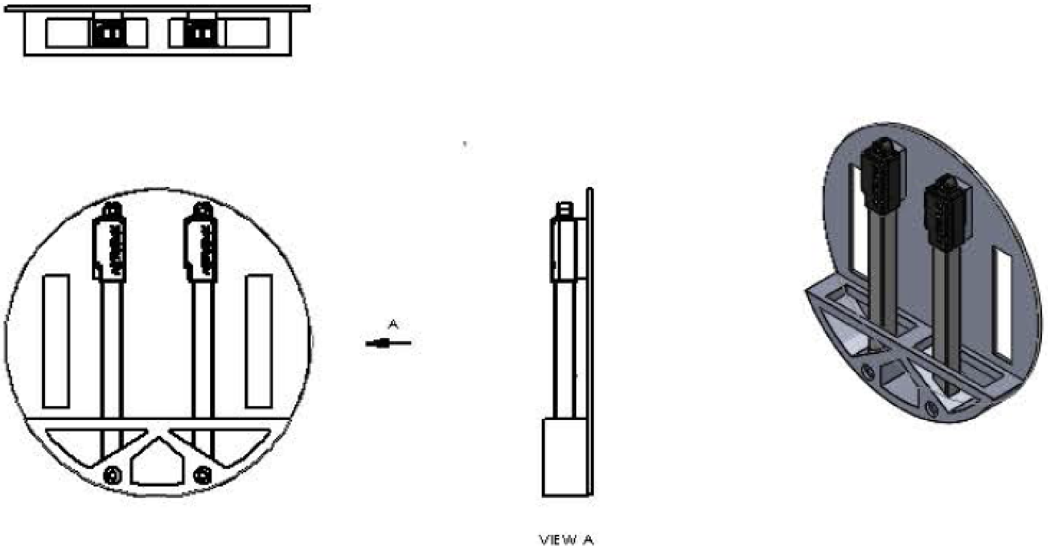


Figure 5.15: Tilt Adjustment Landing Leg Design

5.5 LAUNCH VEHICLE COMMUNICATIONS

Raspberry Pi Zero W ’LV’:

The Raspberry Pi Zero W was chosen from the PDR design matrix because of its high computational ability and integrated 802.11 wireless LAN capabilities. Electrical and computational specifications include a 1 GHz single core CPU, 512 MB RAM, a mini HDMI port, micro USB power, HAT-compatible 40 pin header, and a CSI camera connector.

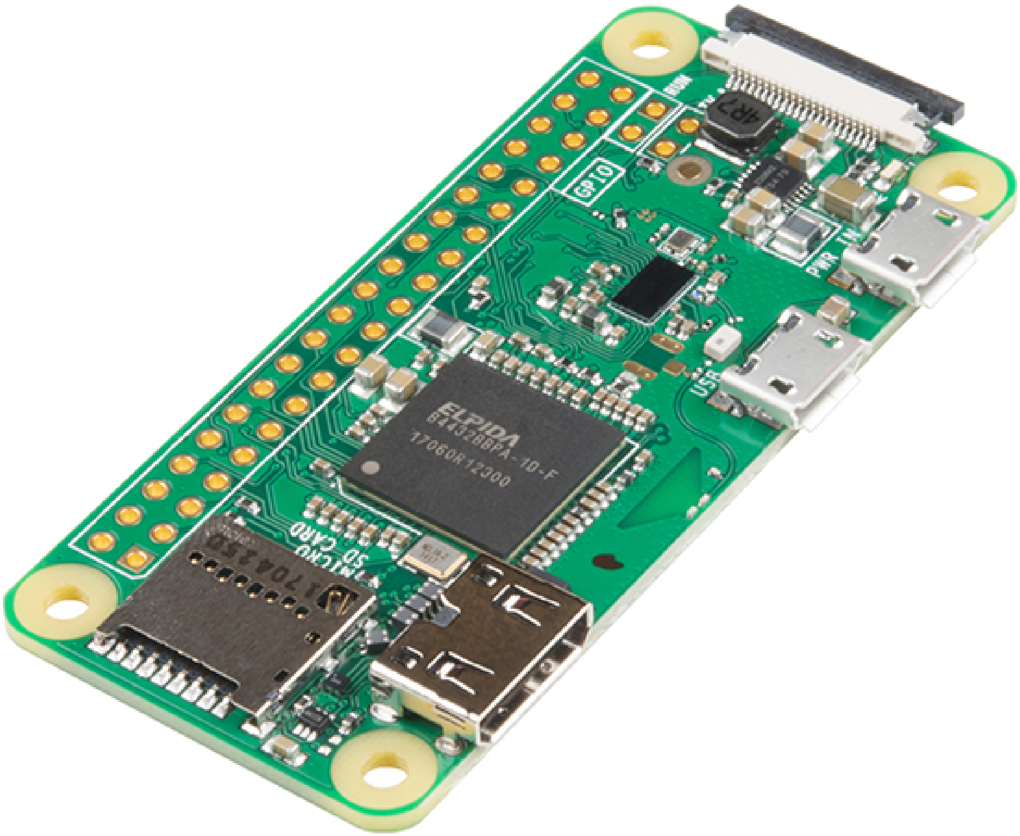


Figure 5.16: Raspberry Pi Zero W Unit

Omni-Directional Antenna ’LV’:

The HyperLink Wireless Omni-Directional Antenna was chosen for its excellent range capabilities. The specifications include a frequency range of 2400 to 2500 MHz, a gain of 5.5 dBi, an impedance of 50 ohm, a VSWR range of less than 2.0, a weight of 0.0440925 lb or 20 g, a length of 8.0 in, a reverse polarity SMA plug connector, a vertical polarization, an operating temperature range of between -40 and 185 degree F or -40 and 85 degree C, and a flame rating of UL 94HB.

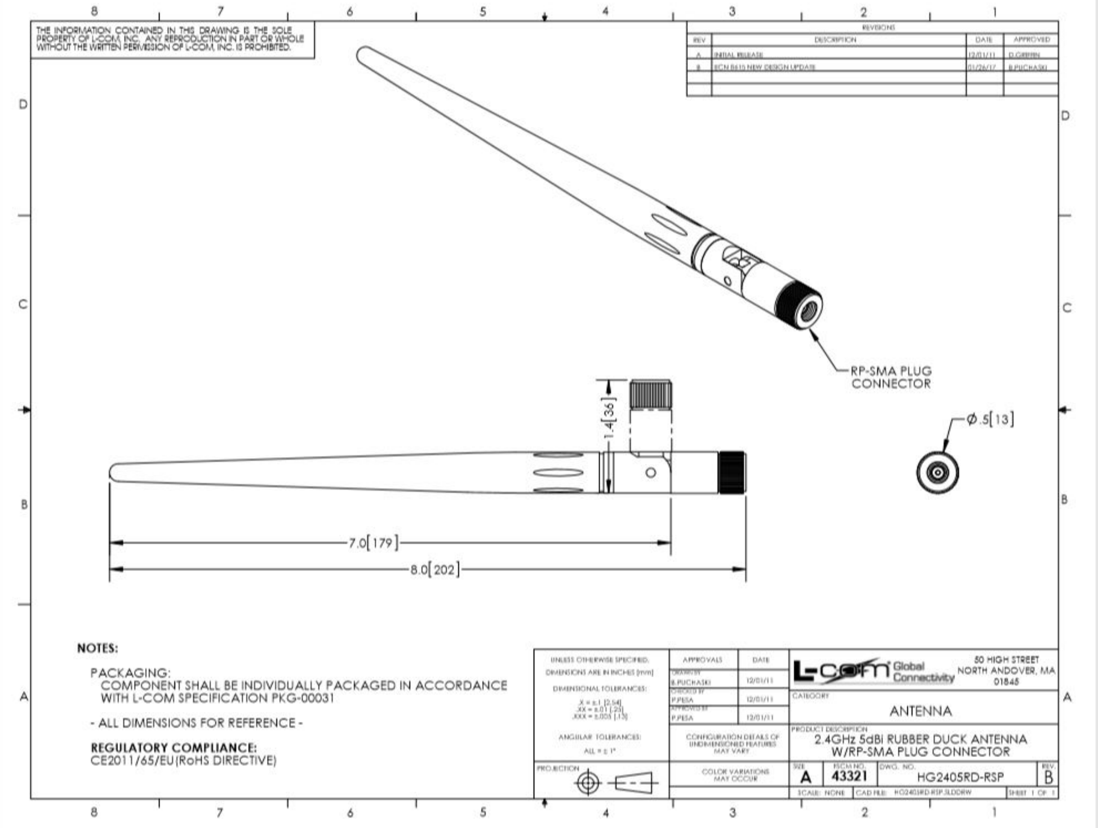


Figure 5.17: HyperLink Wireless Omni-Directional Antenna Drawing

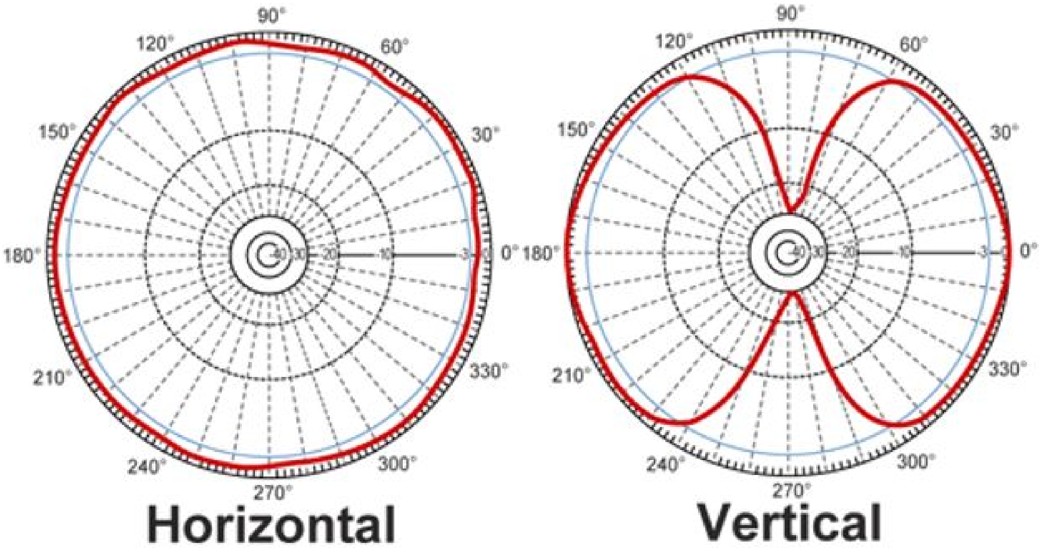


Figure 5.18: RF Antenna Gain Patterns

YAGI 2.4GHz Antenna 'LV':

Of the designs contemplated during the PDR, the 2.4GHz TP513 Yagi Antenna was chosen. It was chosen because it is easy to implement in conjunction with the Raspberry Pi's 2.4GHz WiFi capabilities. The directional aspect of the antenna will help boost the available range of communications, and the WiFi will have enough bandwidth to potentially support a camera stream for the payload vehicle. The electrical specifications include a frequency range between 2400 and 2483 MHz, a nominal impedance of 50 ohm, a gain of 17 dBi, an front to back ratio greater than 18 dB, a horizontal beam width of 25 degrees, a vertical beam width of 24 degrees, a maximum input power of 100 W, and an N female connector. The mechanical specifications include a support boom made of steel bracket, a mounting pole, an element material of aluminum, antenna weight of 1.01 lb, an operating temperature range between -40 degrees and 149 degrees.

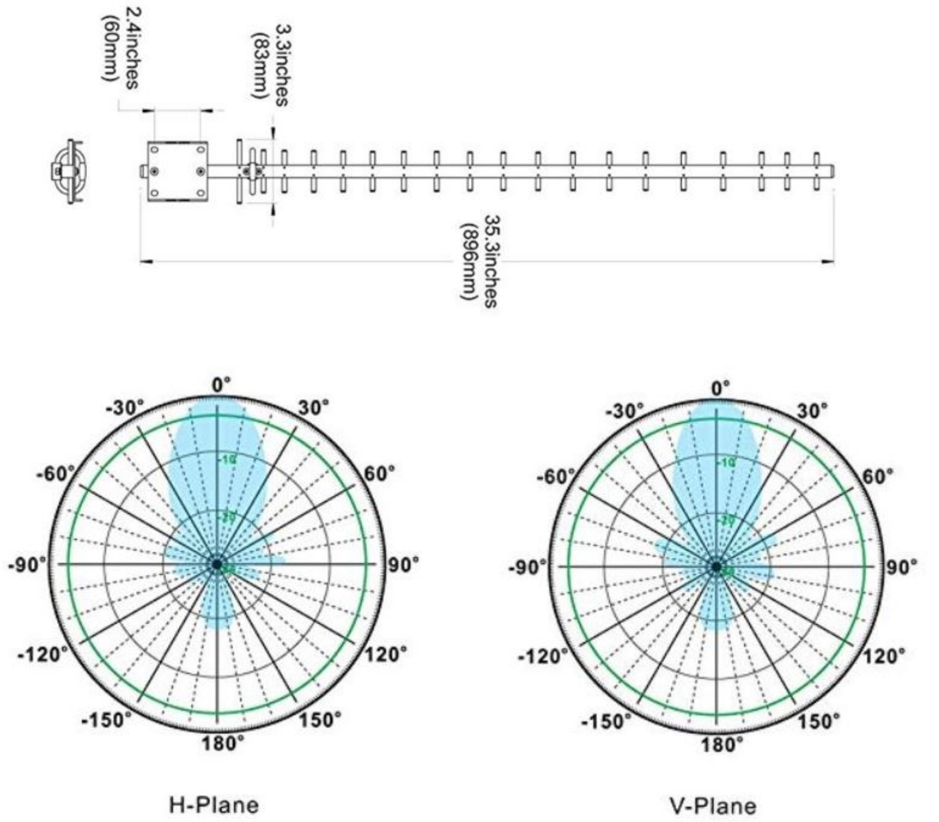
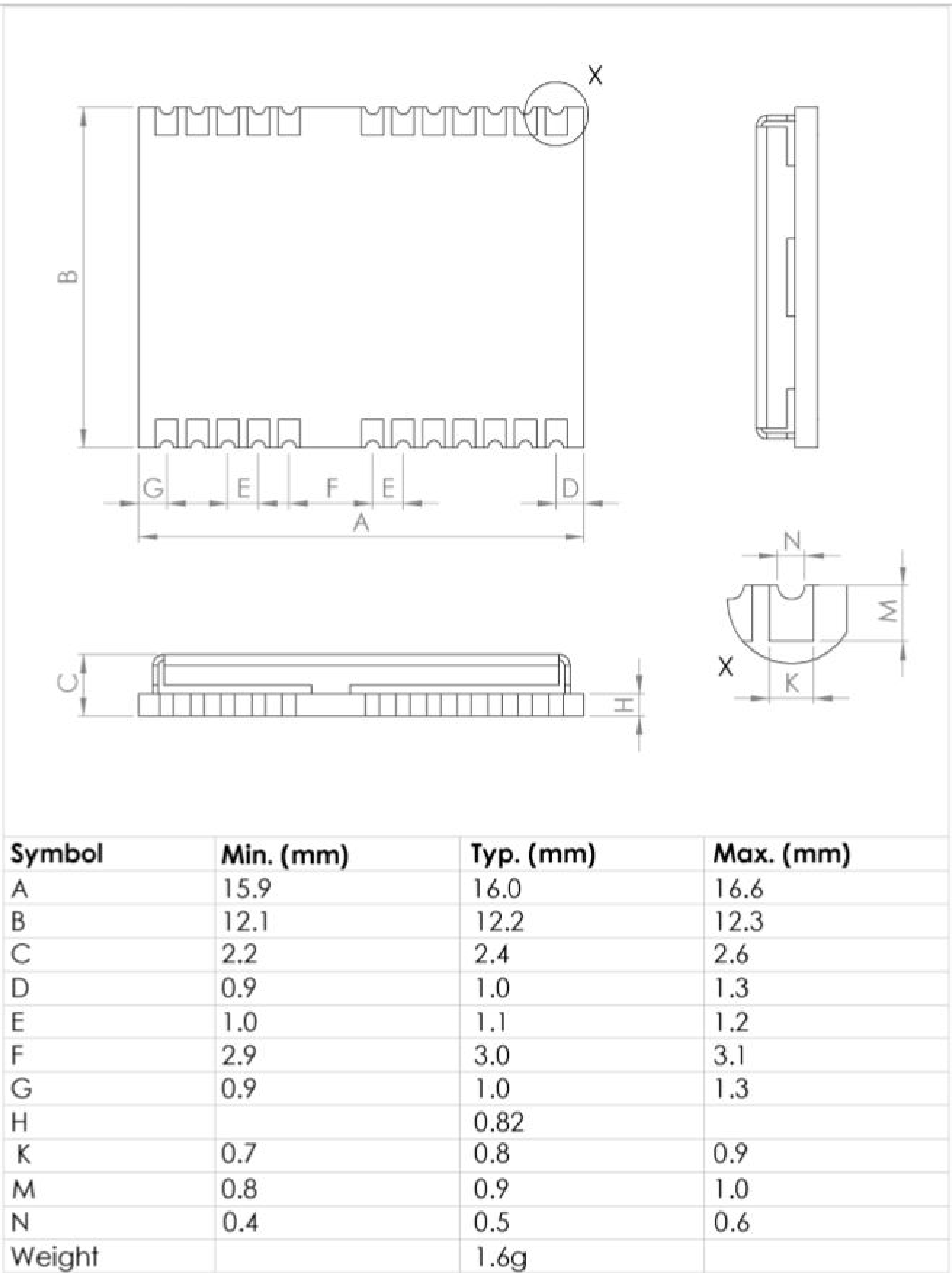


Figure 5.19: TP513 YAGI Antenna Drawing and Gain Patterns

NEO-M8N 'LV':

The NEO-M8N GPS module was chosen because it was the least expensive option considered, had the highest sensitivity, was the easiest to integrate within the functioning of the controller, and team members had the most experience with this module. The specifications include a 72-channel u-blox M8 engine receiver type, an accuracy of time pulse signals 30 ns for RMS and 60 ns for 99%, a configurable frequency of between 0.25 Hz and 10 MHz for time pulse signals, an operational dynamics limit of less than or equal to 4 g (assuming airborne less than 4 g platform), an operational altitude limit of 31.06856 mi, an operational velocity limit of 1118.47 mph, a velocity accuracy of 0.164042 ft/s (50% at 98.4252 ft/s), a heading accuracy of 0.3 degrees (50% at 98.4252 ft/s), a max navigation update of 5 Hz, time-to-first-fix with a cold start of 26 s, time-to-first-fix with a hot start of 1 s, time-to-first-fix with an aided start of 2 s (dependent on aiding data connection speed and latency), and a sensitivity of -167 dBm.



Symbol	Min. (mm)	Typ. (mm)	Max. (mm)
A	15.9	16.0	16.6
B	12.1	12.2	12.3
C	2.2	2.4	2.6
D	0.9	1.0	1.3
E	1.0	1.1	1.2
F	2.9	3.0	3.1
G	0.9	1.0	1.3
H		0.82	
K	0.7	0.8	0.9
M	0.8	0.9	1.0
N	0.4	0.5	0.6
Weight		1.6g	

Figure 5.20: NEO-M8N Technical Drawing

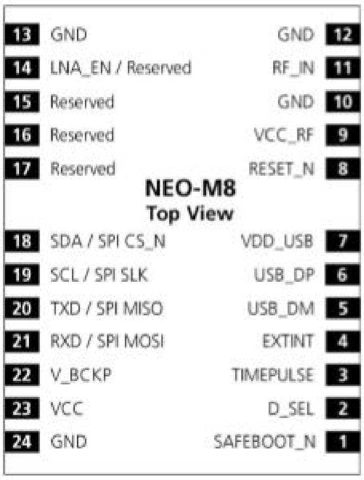


Figure 5.21: NEO-M8N Pin Assignment

A4988 Stepper Driver:

The A4988 stepper driver is a micro-stepping driver with over-current protection and a heat sink. Individual specifications include, operating voltage range of 8 volts to 35 volts, logic voltage range of 3 volts to 5.5 volts, and a maximum current per phase of 2.00 Amps. The battery array that will be used for the motor will be plugged into this driver since this driver handles all current and voltage input for the stepper motor. The stepper driver receives two (2) input signals from the Raspberry Pi Zero W to operate the payload withdrawal system.

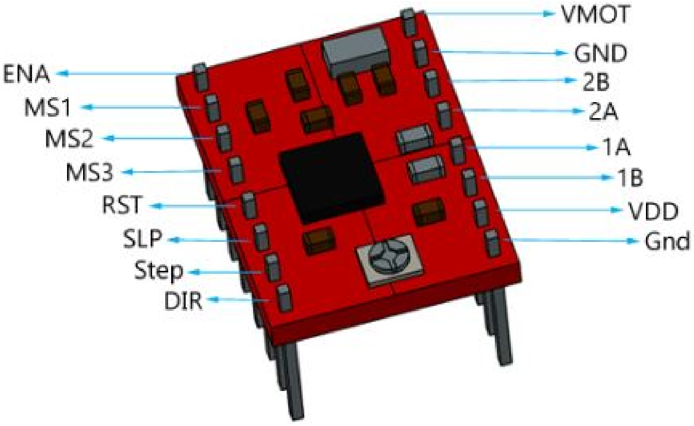


Figure 5.22: A4988 Pin Assignment

MCP3002 Battery Monitoring:

An MCP3002 analog to digital converter will be used to monitor the battery voltage supply to the Pi Zero W. The MCP3002 is capable of 75 kilo-samples per second at 2.7 volts, The MCP3002 will use a voltage divider to bring the 5 volt battery down to manageable voltages and then can be programmed to give read outs at specific levels. These readout will be sent to the Pi Zero W, which will send the data back to the ground station for further action.

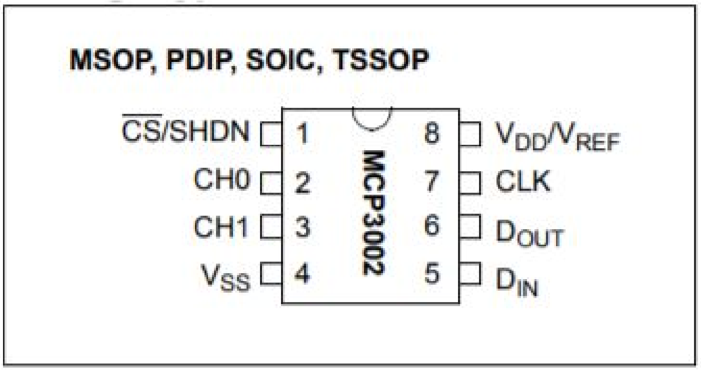


Figure 5.23: MCP3002 Pin Layout

PCA9685:
The PCA9685 is a 16 HAT servo driver which will take 2 inputs from the Raspberry pi Zero W and be able to control 16 independent servos. This driver will communicate with the Pi Zero W to operate 5 retention servos and 2 linear actuators used in the TALL system. discussed in the *Payload* section.

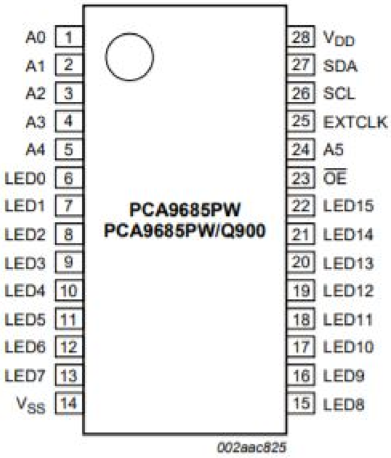


Figure 5.24: PCA9685 Pin Assignment

Launch Vehicle Communications Architecture:
Starting from the ground station, we will have a laptop connected to our router. The laptop

will display a command line from Microsoft Visual Studio that will be also connected to the Raspberry Pi unit on the launch vehicle through ground station antenna. The ground station will have a primary YAGI 2.4GHz antenna reserved for the launch vehicle payload bay. The YAGI antenna will be locked on to the payload bay Raspberry Pi through a HyperLink Wireless Omni-Directional antenna. There, a NEO-M8N GPS module will give the ground station a stream of data that can be interpreted to give us coordinates of the launch vehicle. Also present is an MCP3002 unit, which will provide the ground station with voltage readings. Finally, both an A4988 Stepper Driver and a PCA9685 Servo driver will be connected to the launch vehicle Raspberry Pi. The A4988 Stepper Driver will receive input from the ground station to activate the payload withdrawal system. The PCA9685 Servo Driver will receive input from the ground station to activate the TALL system and/or the payload retention system.

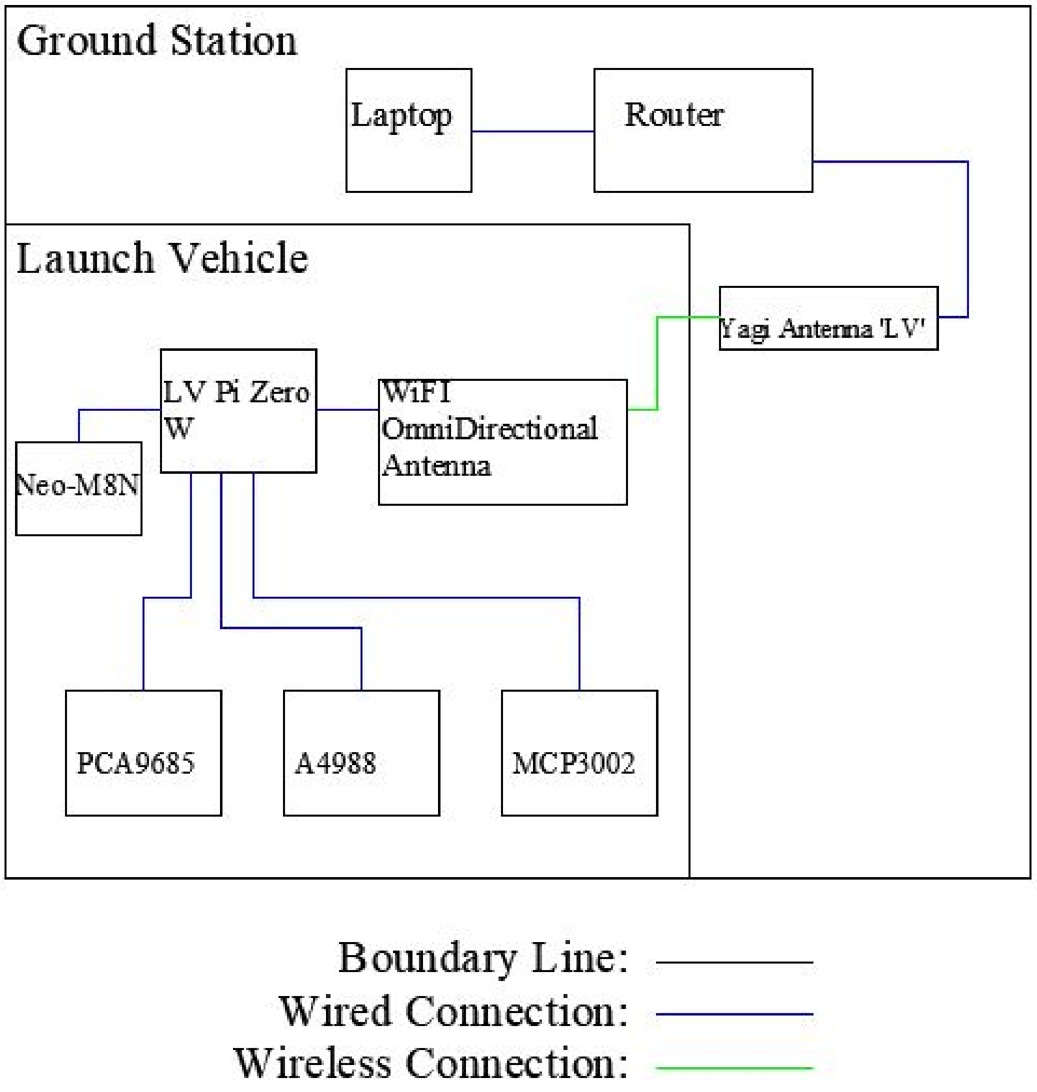


Figure 5.25: Launch Vehicle Communications Block Diagram

5.6 MISSION PERFORMANCE PREDICTIONS

Given the LV success criteria, predictions on its ability to perform on competition are given in terms of its ability fulfill each criterion.

1. LV reaches a minimum of 3,500 feet AGL while remaining below 5,500 feet AGL.
   Simulations place the highest and lowest apogees well with this range: **Success Predicted**.
2. Initial recovery system deploys and maintains connection to lower body
   Ground testing with BlueTube™and similar airframes give the team confidence that apogee ejection will go smoothly: **Success predicted**.
3. Main recovery system ejects and deploys successfully without harming mission systems or LV
   Subscale flight failure has prevented any additional data from being collected on the reliability of this new system: **More testing required**.
4. LV lands in the predetermined orientation.
   Subscale flight failure has prevented any additional data from being collected on the reliability of this new system: **More testing required**.
5. Payload deployment system is intact and actuates successfully.
   Simulation data and new robust drone chasis model suggest the payload systems can withstand flight forces. The reliability of actuation and deployment of full scale system remains to be seen: **More testing required**.

6 PAYLOAD

6.1 MISSION VEHICLE:

As previously described, the MV has made dramatic changes subsequent to PDR completion. The payload has been renamed to Droney to reflex these considerable changes. Droney is a generative design drone body with carbon fibre boom arms and carbon fibre feet. It has two modes, a stowed mode and a flight configuration mode. Images below show the MV in both of these modes. Decisions on final components for the full scale construction and testing process have been made. Information about the design and decision process that followed PDR will also be included. The individual component make up will be described in the following sections along with their interactions within and outside of the MV. Dimensions of all MV components can be found in Appendix 9.2 and 9.3 or later in this section.

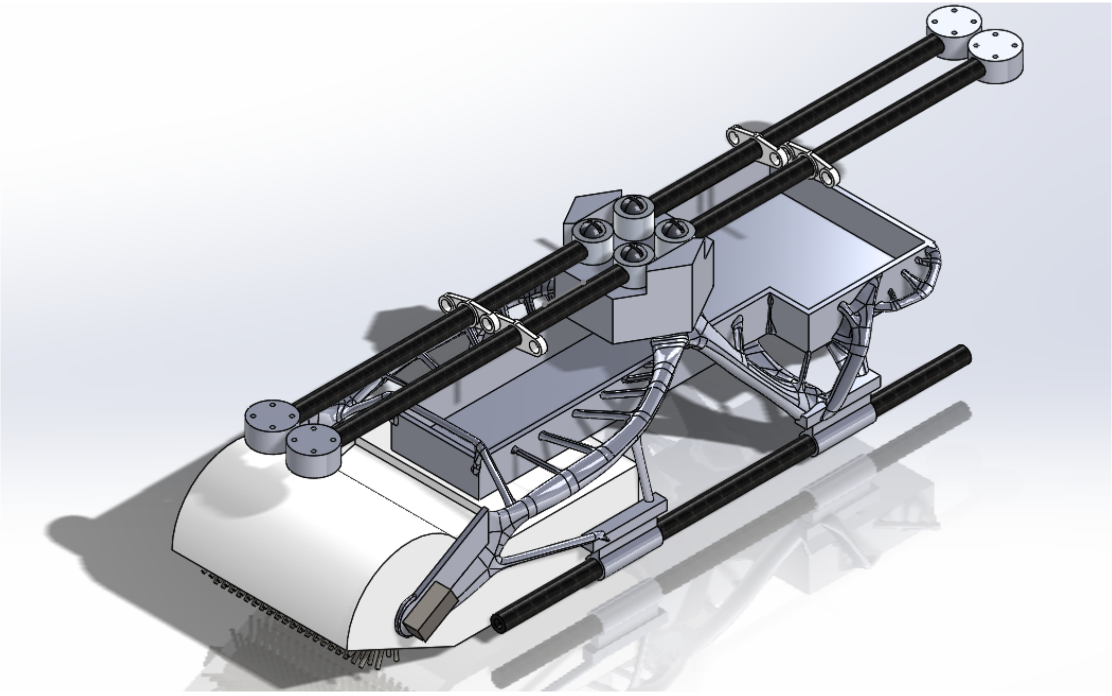


Figure 6.1: Droney Stowed Mode

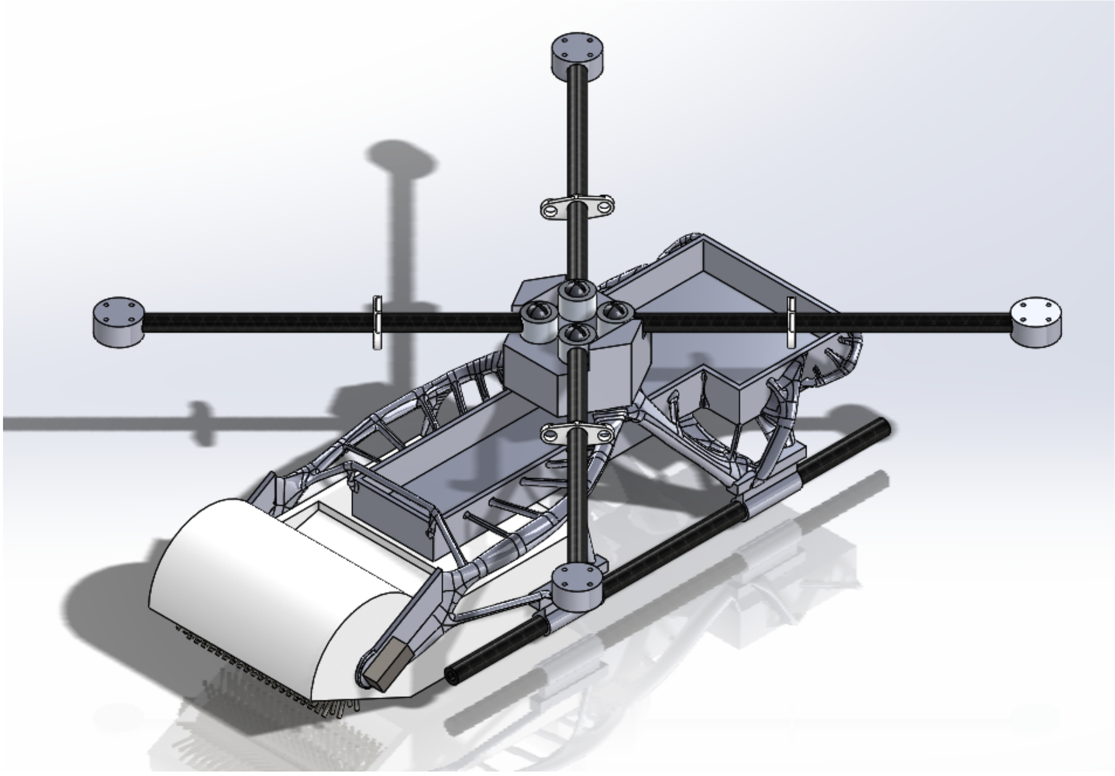


Figure 6.2: Droney Flight Configuration Mode

6.1.1 MISSION VEHICLE BODY:

Mission Vehicle Chassis

In the PDR process it was identified that the team's mission vehicle was not adequately designed, or reviewed. In addition, the LV team was alerted to a kinetic energy issued that required a lighter MV for its solution. The decision was made to preform another material and design study on the structure of the MV.

Fusion 360 and it's generative design feature were chosen to preform this study. Seven different materials were considered, with manufacturing processes limited to 3-D printing and CNC machining. To preform this study the program needs a starting geometry, boundary conditions, and load cases. The initial geometries and load conditions can be seen in the Figure 6.3 below. With this information the system generates numerous iterations each time reducing weight without compromising the structural integrity. The results of this study are displayed in Figure 6.4.

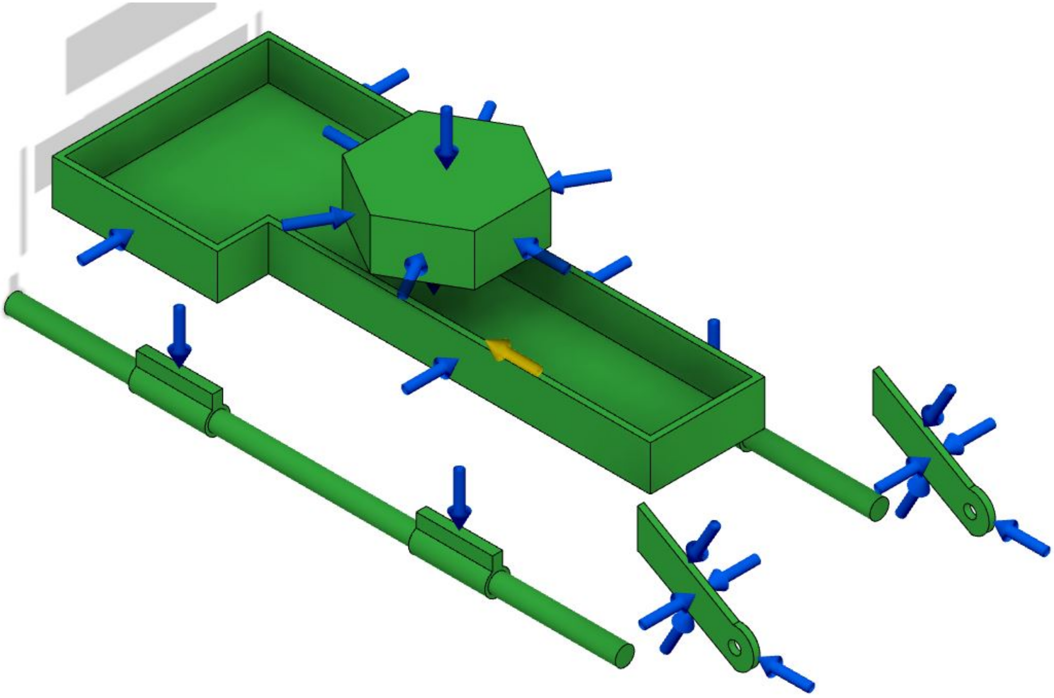


Figure 6.3: 3 Lbs Distributed Loads for Generative Chassis Design

The results of this study demonstrated that a 3-D printed structure made of a plastic would result in the lightest mission chassis. It can also be interpreted that a Nylon structure has a factor of safety that is almost 80 times that of the lightest option ABS. The design made from ABS is only .01kg Lighter. It was decided that it would be in the teams best interest to have a greater factor of safety in the 3lb distributed load case. Before this version of the Generative design chosen as the final decision for mission chassis a FEA was preformed on the unmodified chassis. The results of this FEA can be found in Appendix 9.2, as well as the dimensions of the Nylon designed chassis. This study was preformed with loads of 10lbs and 15lbs in multiple locations throughout the structure. The results indicate that even with the increased loads the structure retains a factor of safety of between 2 and 8. This enough evidenced to choose this version of the drone chassis to begin full scale construction and testing. The retention system, carriage system and communications interactions are unchanged by this change in chassis design.

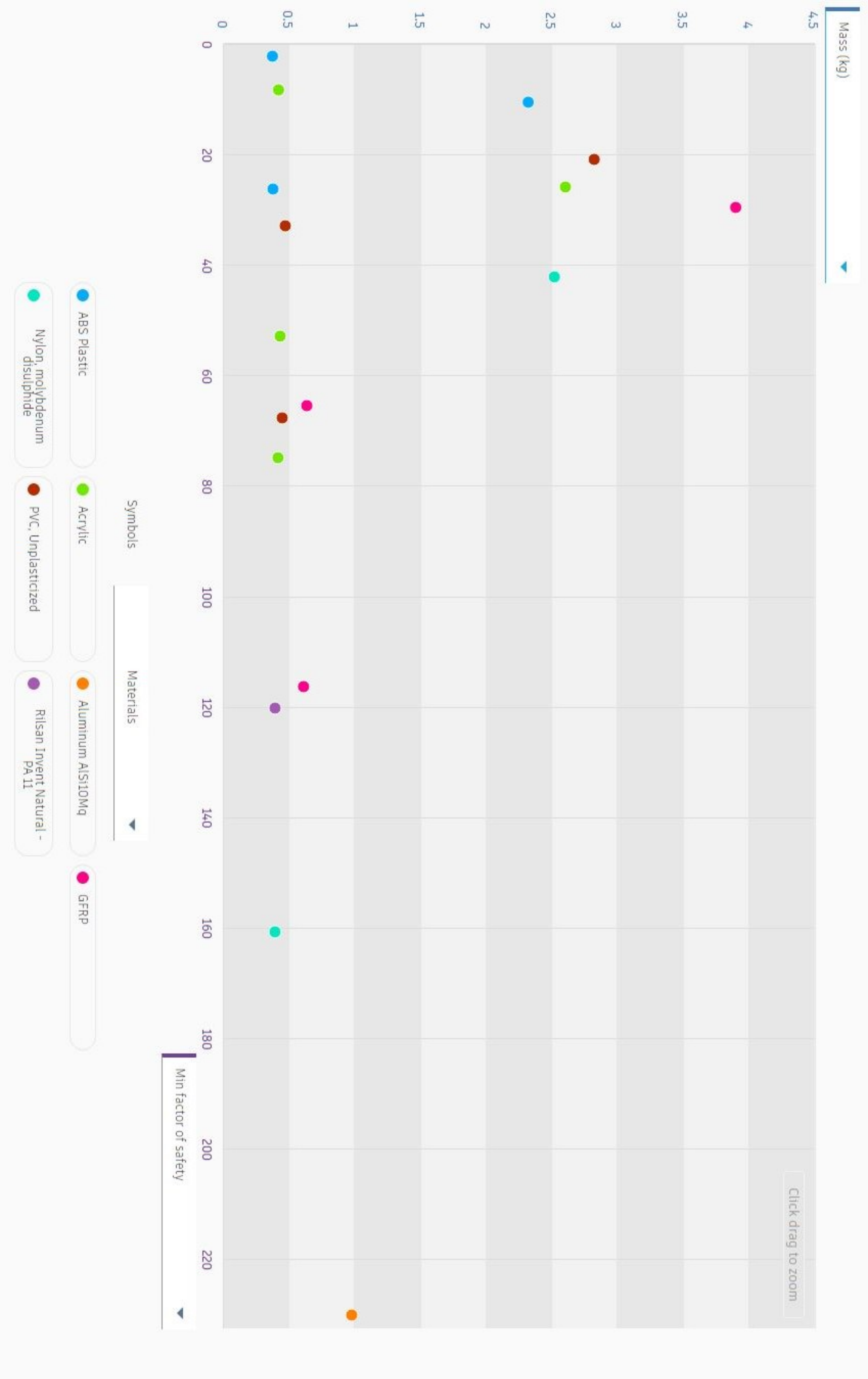


Figure 6.4: Material study with load conditions described in Figure 6.3

Mission Vehicle Rotor Boom Assembly

A major structural component, the rotor assembly mounting block has retained its general shape and location on the drone chassis. There are four motor booms to support 4 motors for propulsion. Materials of choice are carbon fiber tubes for the before mentioned booms, with inserts made of aluminum. Inserts shall be epoxied into place. All booms will pivot about aluminum 1/4-20 shafted bolts also functioning as retention for the entirety of the rotor boom assembly. The release mechanism was designed with simplicity and ability to be reset in mind. The system utilized elastic surgical tubing in addition to two servo. The elastic tubing is used to create tension between both port booms, and both starboard booms. This tension is the force that keeps the booms deployed during flight operations. While stowed both forward, and aft booms will be compressed together and pinned in place using an extension on the servo arm. When the system transitioned into a flight configuration the servos actuate releasing the pinned booms, allowing the elastic tubing to pull them into place.

6.1.2 MISSION VEHICLE COMMUNICATION

Raspberry Pi Zero W 'MV':
The Raspberry Pi Zero W 'MV' was chosen from the PDR design matrix because of its high computational ability and integrated 802.11 wireless LAN capabilities. Electrical and computational specifications include a 1 GHz single core CPU, 512 MB RAM, a mini HDMI port,micro USB power, HAT-compatible 40 pin header, and a CSI camera connector. The Raspberry Pi Zero W will control several systems on board drone such as the Flight Controller, GPS, LoRa data transmission, and Wifi data transmission.

Navio2:
The Navio2 is a Raspberry Pi HAT that will be used as the flight controller. The Navio2 will be connected to the drone's ESCs, NEO-M8N GPS, and will be controlled by the Raspberry Pi Zero W 'MV'. Specifications include 12 servo output ports, an average of less that 150 mAmps current consumption, and a supply voltage of 4.75 volts to 5.25 volts.

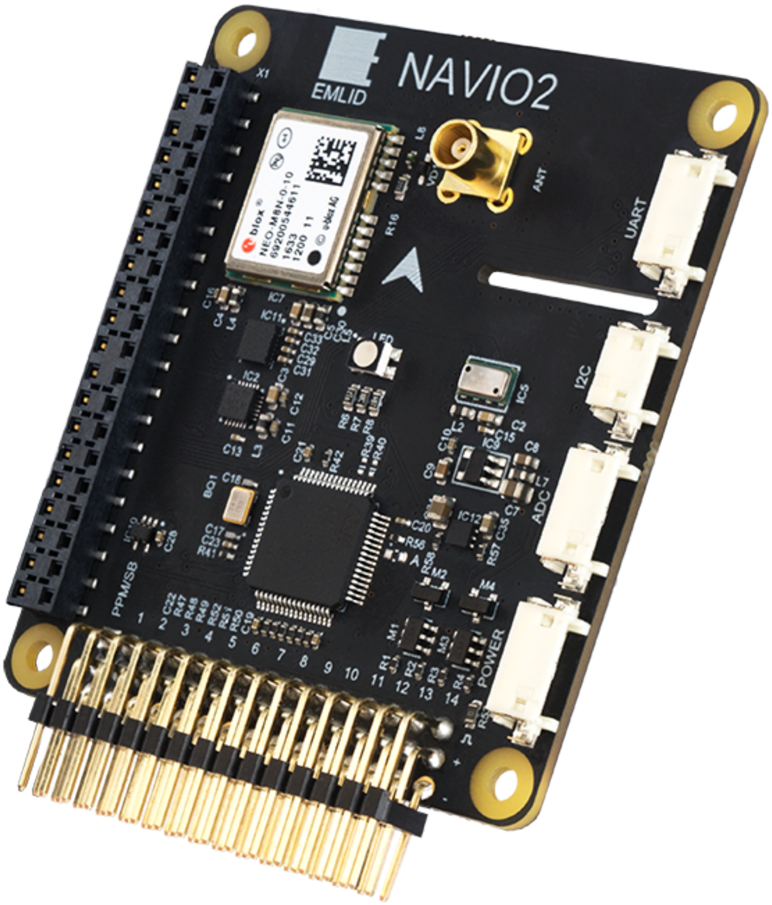


Figure 6.5: Navio2 Pi HAT

Omni-Directional Antenna 'MV':

The HyperLink Wireless Omni-Directional Antenna 'LV' was chosen for its excellent range capabilities. The specifications include a frequency range of 2400 to 2500 MHz, a gain of 5.5 dBi, an impedance of 50 ohm, a VSWR range of less than 2.0, a weight of 0.0440925 lb or 20 g, a length of 8.0 in, a reverse polarity SMA plug connector, a vertical polarization, an operating temperature range of between -40 and 185 degree F or -40 and 85 degree C, and a flame rating of UL 94HB. This antenna will be connected to the Raspberry Zero W 'MV' to expand the built in WiFi range. This antenna will be used to transmit telemetry to the Ground Station. Refer to *Figures 5.2* and *5.3* for drawing and gain pattern.

YAGI 2.4GHz Antenna 'MV':

Of the designs contemplated during the PDR, the 2.4GHz TP513 Yagi Antenna was chosen. It was chosen because it is easy to implement in conjunction with the Raspberry Pi's 2.4GHz WiFi capabilities. The directional aspect of the antenna will help boost the available range of communications, and the WiFi will have enough bandwidth to potentially support a camera stream for the payload vehicle. The electrical specifications include a frequency range between 2400 and 2483 MHz, a nominal impedance of 50 ohm, a gain of 17 dBi, an front to back ratio greater than 18 dB, a horizontal beam width of 25 degrees, a vertical beam width of 24 degrees, a maximum input power of 100 W, and an N female connector. The mechanical specifications include a support boom made of steel bracket, a mounting pole, an element material of aluminum, antenna weight of 1.01 lb, an operating temperature range between -40 degrees and 149 degrees. This antenna will be connected to the Ground Station router to receive telemetry from the Raspberry Pi Zero W 'MV'. Refer to *Figure 5.4* for drawing and gain pattern.

NEO-M8N 'MV':

The NEO-M8N GPS module was chosen because it was the least expensive option considered, had the highest sensitivity, was the easiest to integrate within the functioning of the controller, and team members had the most experience with this module. The specifications include a 72-channel u-blox M8 engine receiver type, an accuracy of time pulse signals 30 ns for RMS and 60 ns for 99%, a configurable frequency of between 0.25 Hz and 10 MHz for time pulse signals, an operational dynamics limit of less than or equal to 4 g (assuming airborne less than 4 g platform), an operational altitude limit of 31.06856 mi, an operational velocity limit of 1118.47 mph, a velocity accuracy of 0.164042 ft/s (50% at 98.4252 ft/s), a heading accuracy of 0.3 degrees (50% at 98.4252 ft/s), a max navigation update of 5 Hz, time-to-first-fix with a cold start of 26 s, time-to-first-fix with a hot start of 1 s, time-to-first-fix with an aided start of 2 s (dependent on aiding data connection speed and latency), and a sensitivity of -167 dBm. The NEO-M8N will send data to the Raspberry Pi Zero W 'MV' which will transmit the GPS coordinates to the Ground Station via WiFi or LoRa if WiFi transmission is out of range. Refer to *Figures 5.5* and *5.6* for technical drawing and pin assignment.

LoRa Antenna:

The Readytosky 3DR Telemetry Kit was chosen for our backup communication system because of its high sensitivity and low power consumption. The specifications include a receiver sensitivity to -121 dBm, transmitting power up to 200 mW, and an air data rate up to 500 $kbps$. The Telemetry kit will be attached to the Raspberry Pi Zero W 'MV' as well as the Ground Station Laptop to transmit GPS telemetry if the drone leaves the WiFi transmission range.

Mission Vehicle Communications Architecture:

Starting from the ground station, the Readytosky 3DR telemetry kit ground unit will be connected to the laptop. Through the laptop, the Readytosky ground unit will be connected to its complimentary air unit on the payload vehicle. The Readytosky 3DR telemetry kit will be a secondary communication system, should the primary system fail, and will be connected to the payload vehicle's Raspberry Pi. The laptop will hook up to our router and, similarly to the launch vehicle's payload bay, a YAGI antenna and a WiFi Omni-Directional Antenna will link the router to our mission vehicle's Raspberry Pi.

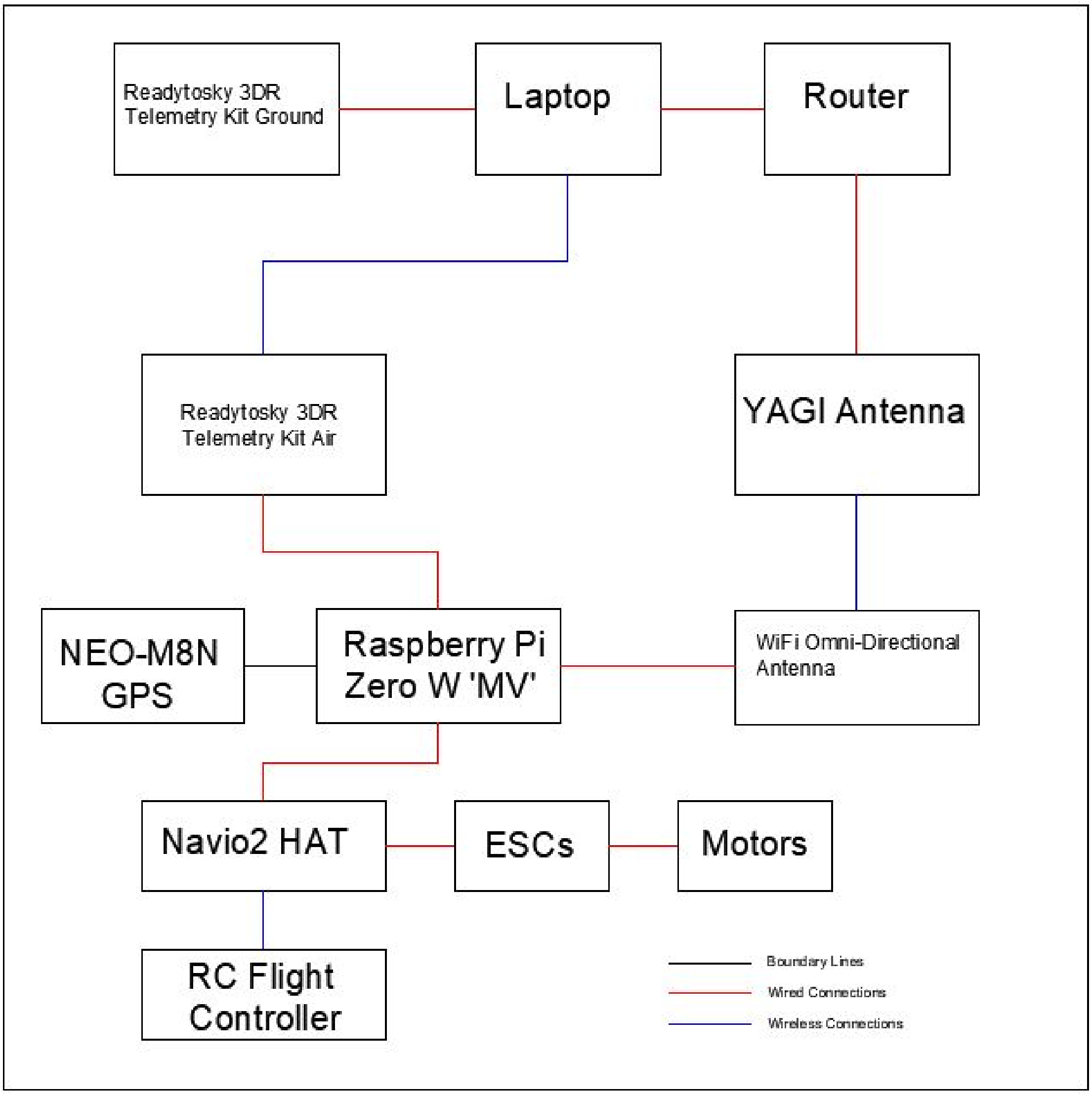


Figure 6.6: Mission Vehicle Communications Block Diagram

Mission Vehicle Drive train

An online program named eCalc was used to choose the drive train components for the MV. The basis of the calculations is that the RaspberryPi would require we use a 3s to match required voltages for its operation. As for the size, many different options were testing to find composition of different KV motors and propellers. The longest range and flight time combination was when using a 10000mAh 3s LiPo, 9in propellers and four EMAX RSII-2306-1900 motors will a KV of 1900. With this set up program projected a maximum draw of close to 65A, this would required the team to choose a 70A controller. The ESC chosen was the HobbyKing Red Brick 70A ESC v2. This controller will have the ability to handle all current needs. Using this setup the projected maximum distance the MV can travel is almost 1.9 miles. For further information about the study reference the attached information in Appendix 9.4.

6.2 WITHDRAWAL SYSTEM

Winch System:
A Nema 17, 5.22 $lb * in$ max hold torque, stepper motor will be used to reel in the guide wire which will pull the carriage out the open end of the rocket body. The stepper motor will be operated with an A4988 stepper driver and powered with a payload bay housed battery array. The stepper motor will be attached to the carriage in a snatch block system using two (2) wire guides. Fifteen (15) pound fishing line will be used as the connection line to the carriage. The spool will be constructed from a dowel and was designed with a recessed portion of the spool to keep the connection wire centrally located. The spool will be keyed to match the motors output shaft. A wire guide will be mounted near the open end of the rocket body to act as the pulley for the carriage to be drawn towards as the winch pulls the guide wire in.

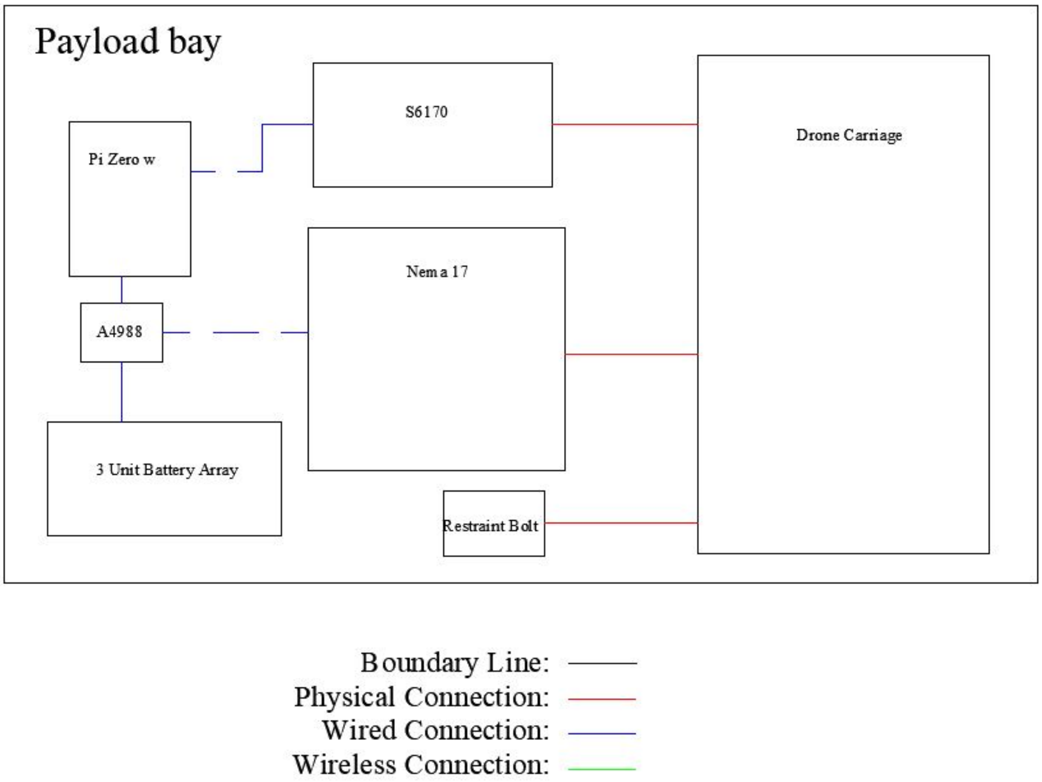


Figure 6.7: Winch System Block Diagram

Stepper Motor:
The Nema 17 motor is a bipolar stepper motor with maximum hold torque of 5.22 $lb * in$. Other specifications include, maximum voltage input of 2.80 Volts, maximum Amps/Phase of 2.00 Amps, and a mass of .88 lbm. The motor is rated at an insulation class B and can withstand temperatures up to 266 degrees Fahrenheit.

A4988 Stepper Driver:
The stepper driver receives two (2) input signals from the Raspberry Pi Zero W to operate the Nema 17. Refer back to *Launch Vehicle Communications* for detailed over view of the A4988.

Mid-Torque Servo:
A Spektrum S6170 digital servo will be used as the restraint servo. Individual Specifications include, operational voltage range of 4.8 volts to 6.0 volts, a mass of 1.20 oz, and operational torque range of 70 $oz * in$ to 80 $oz * in$ dependent upon the voltage input.

Retention Latch:
This latch is the same design that is used to retain the drone onto the drone carriage. The latch is being used because the function it is designed for is similar to what is required for the drone carriage retention. This feature can be seen in Figure 6.11

Restraint Bolt:
The restraint bolt used will be a stainless steel bolt cut to the proper length needed. The bolt

will be secured to the rocket body with epoxy.

Wire guides:

The wire guides used will be washers cut to shape and mounted using epoxy.

Connection wire:

The connection wire will be fifteen (15) pound fishing line.

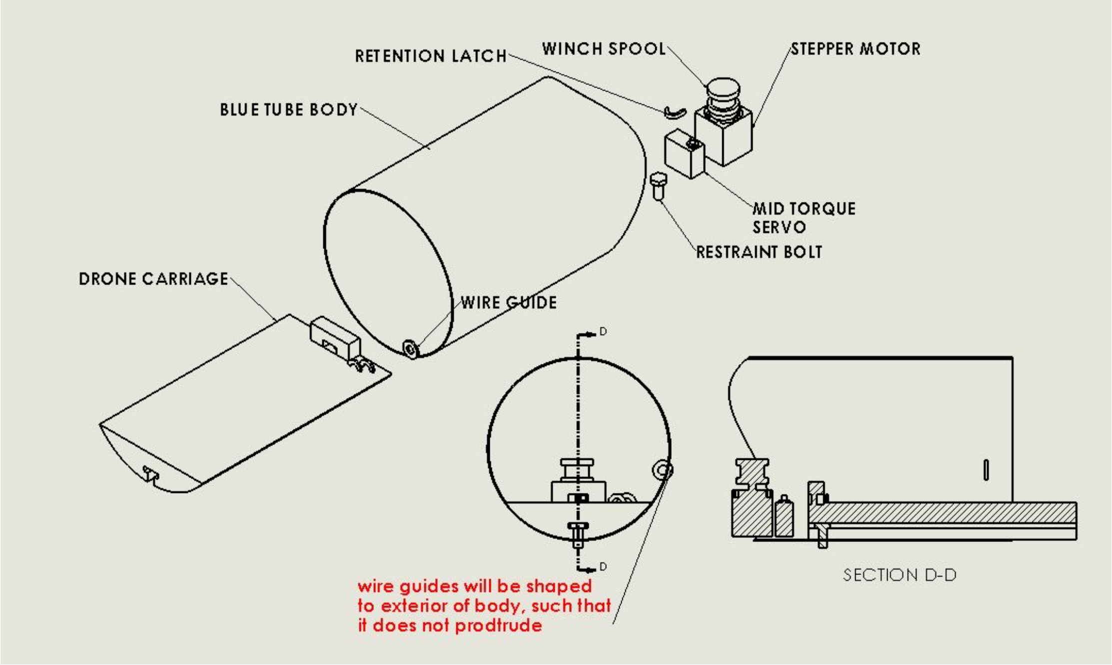


Figure 6.8: Winch System Assembly

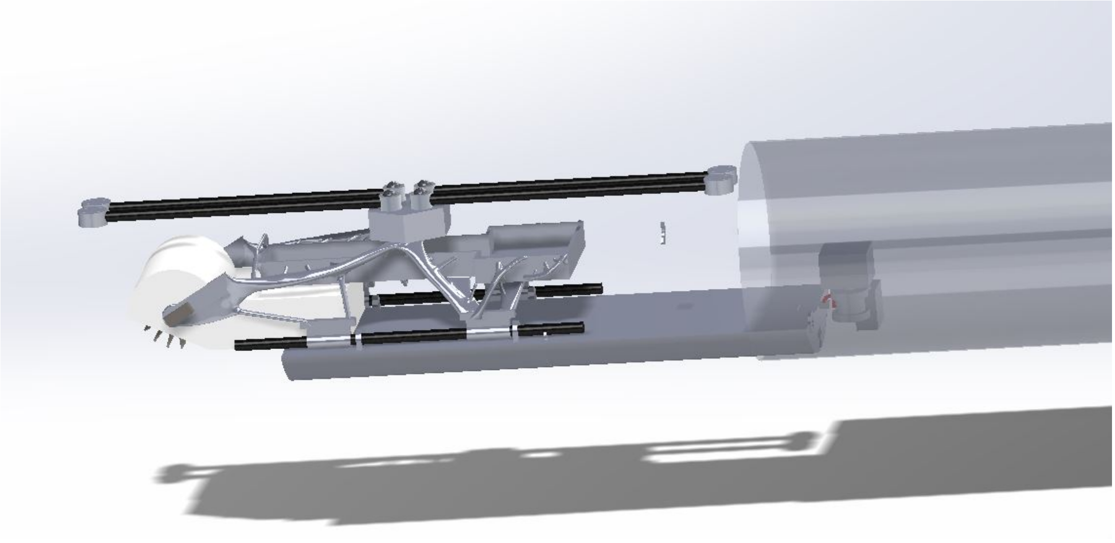


Figure 6.9: Winch System Assembly Extended in Rocket

Deployment Carriage:
Foremost, a T-slot was added to the under side of the carriage to keep it in place along with the retained drone. PVC plastic will be inlaid on the rounded bottom on the carriage to help reduce friction between then carriage and the rocket body. A bolt will be placed near the restraint hook servo which the T-slot of the carriage will be keyed into. This interaction will act as the radial and tangential restraint mechanism to prevent the carriage from moving within the rocket body. For this design a mid torque Spektrum S6170 digital servo will be used as the restraint servo. The hook will be attached to the arm with small bolts and epoxy and the arm will be screwed in to the top of the servo. A single bolt, opposed to a rail, is used because restraint is only necessary while the carriage is in then stowed position. Once the body has landed horizontally, gravity and the rocket body walls will keep the carriage in the correct position. Washers will be embedded in the carriage wood and secured with epoxy to enable the snatch block system of the winch. The connection line will be secured with both a non-slipping knot and epoxy as added protection against slippage and unravelling. Finally, the manner in which the carriage restraint hook interacts with the carriage has been redesigned for better ease of manufacturing and compatibility with components. A U-shaped wooden block will be secured to the carriage with screws and epoxy. A hole will be drilled in the block to allow a bolt to be secured between the carriage and the U-block. The center bolt will be the rod that the restraint hook acts against to prevent axial movement within the rocket body. A shock cord will be attached to the restraint block just mentioned. The cord will be of appropriate length such that the drone carriage cannot fully exit the rocket body.

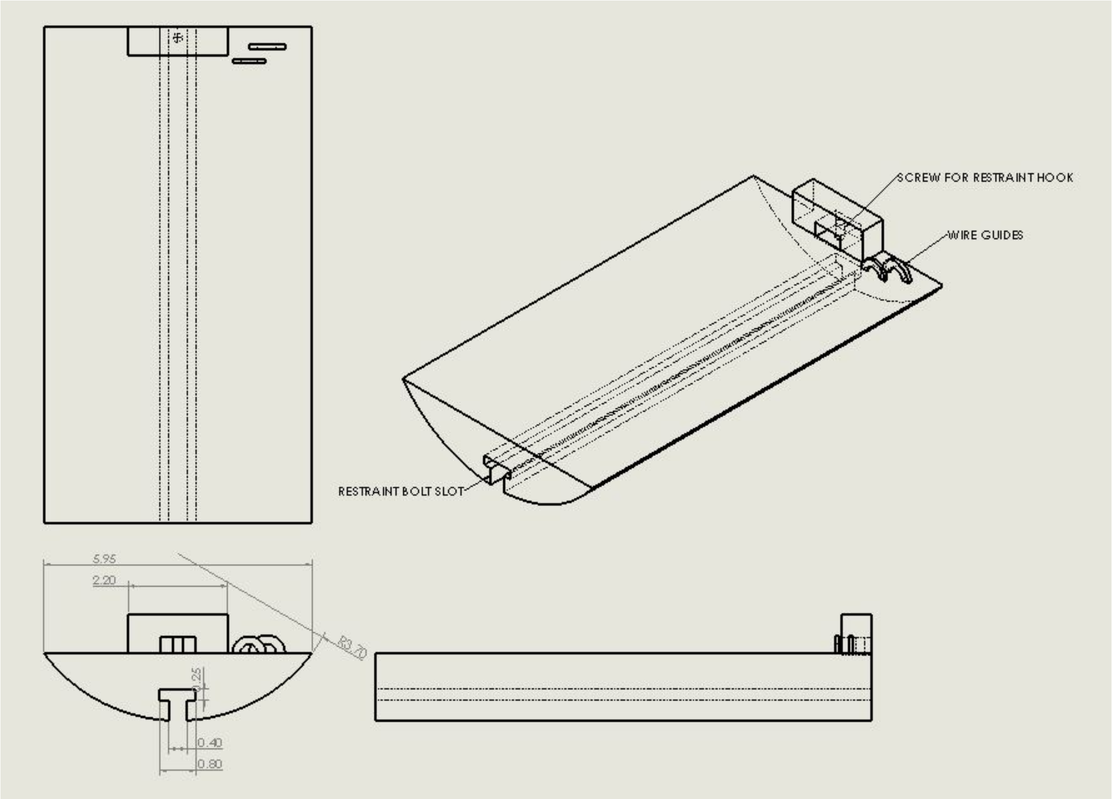


Figure 6.10: Winch System Carriage

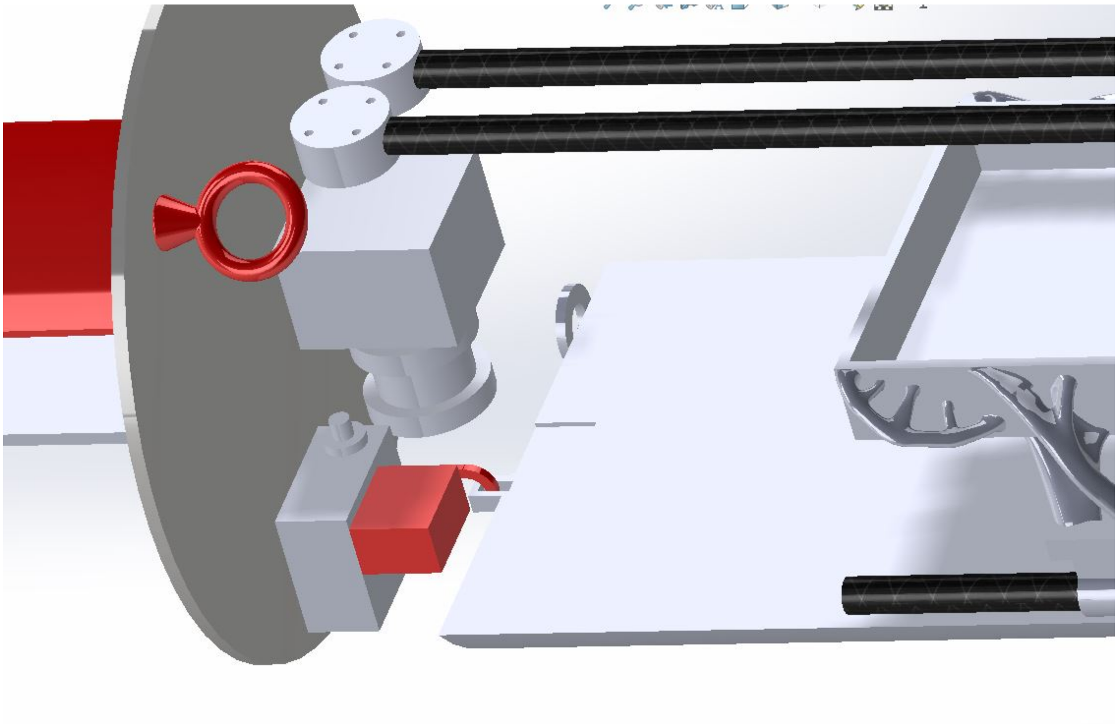


Figure 6.11: Carriage Locking System

6.3 PAYLOAD RETENTION SYSTEM

Over-Leg Latch Retention System:

Of the designs contemplated during the preliminary design review, the over-leg latch system was chosen. The components involved include four over-leg latches and four separate servos. The latches were originally designed to be made of wood, but this was changed to aluminum alloy 6061 after tests involving the latches. This alternative system was chosen over the others because it offered a low overall weight, a low chance of the system bringing harm to the payload vehicle, consistent durability with the components, and a simplicity in the coding process that allowed for high reliability in the system.

Over-Leg Latches:

The latches will be milled from aluminum alloy 6061 using tools available at WMU. Aluminum alloy 6061 has mechanical properties such as a tensile strength of 35,000 psi, a yield strength of 21,000 psi, and a modulus of elasticity of 10,000 ksi. These dimensions are justified because they must be small enough to attach easily to the servos, the bend must be large enough to accommodate for the diameter of the payload vehicle's legs, and the inner bend cannot be a perfect half circle due to the potential of the payload vehicle's legs being caught on the latches. The dimensions of the latches were changed after tests were conducted.

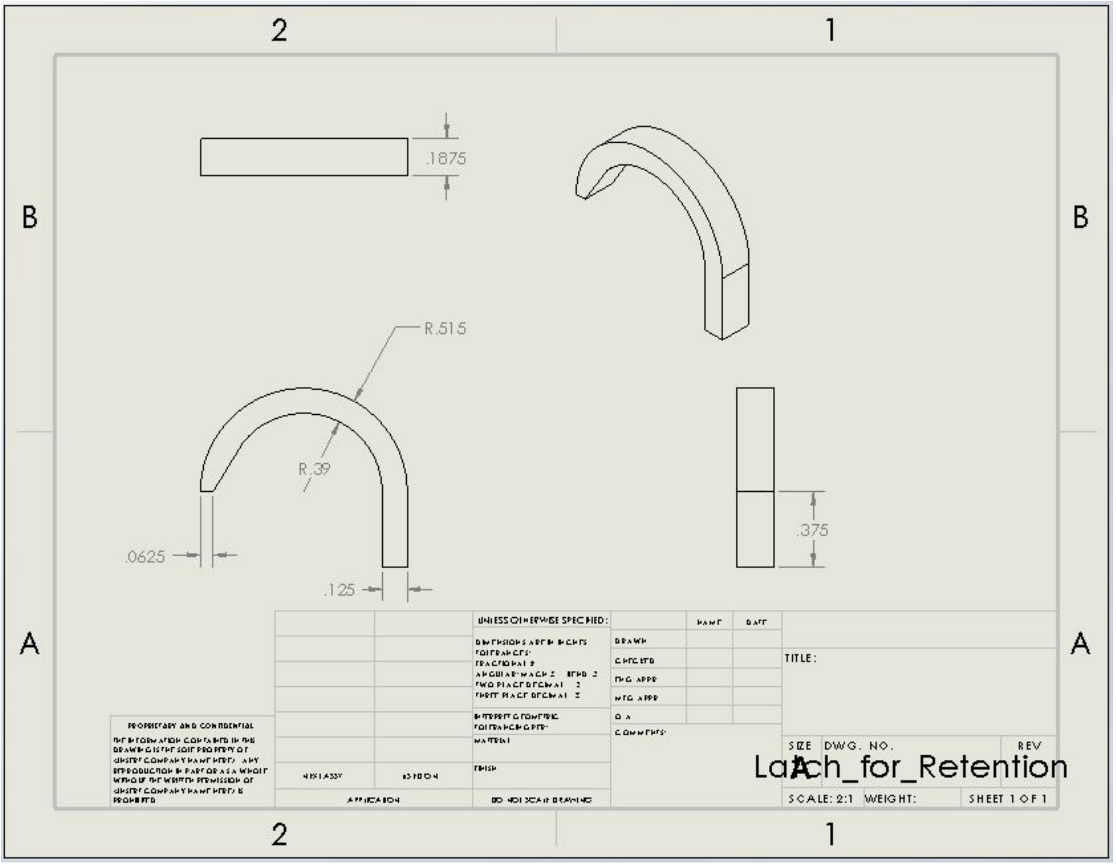


Figure 6.12: Latches for Payload Retention

Servos:

Four EMAX ES08MAII 12g Analog Metal Gear Servos were purchased from an outside source. Individual specifications include an optimal voltage input between 4.8 V and 6.0 V, a standard direction of counter-clockwise, a stall torque of 0.1094 $ft * lbs$ for 4.8 V and 0.1313 $ft * lbs$ for 6.0 V, an operating speed of 0.12 seconds per 60 degrees for 4.8 V and 0.10 seconds per 60 degrees for 6.0V, dimensions of 0.905512x0.4527559x0.944882 in (length by width by height), a weight of 0.00440925 lbs, a metal gear train, and an analog servo type. For simplicity of drawing, servos are represented as cubes occupying one cubic inch of space.

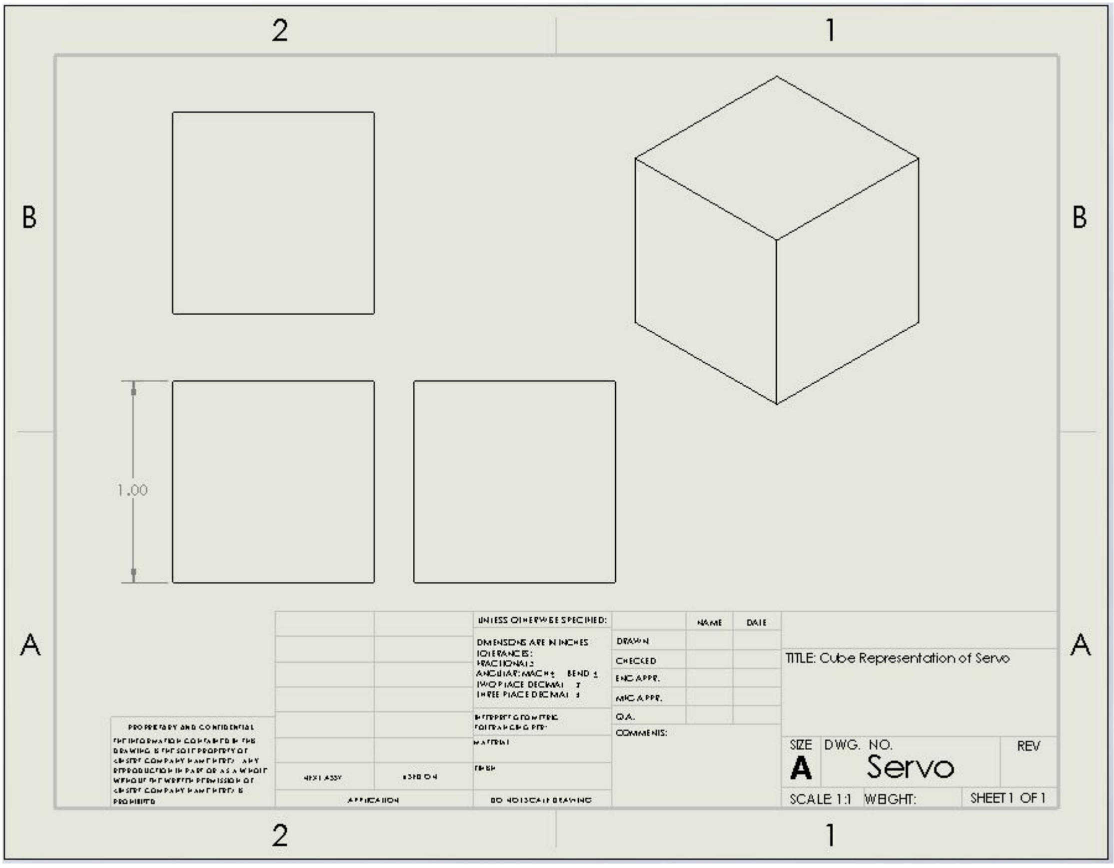


Figure 6.13: Cube Representation of Servos for Payload Retention

Payload Retention System Assembly:

For the retention assembly, the four retention latches will be attached to the four individual servos, which in turn will be connected to the servo driver. The servo driver will receive its control signal from the payload bay Raspberry Pi, which in turn is controlled from the ground station. The Raspberry Pi will interpret the data from the servos to continuously inform the ground station on the condition of the servos. The retention latches will be mirrored along the length-wise axis of the deployment carriage. The retention system assembly will be placed on the deployment carriage, with space allowed for fitting the servos. The deployment carriage will have semi-circular grooves to allow for the drone legs to fit in, with a compressible membrane at the bottom of the grooves. Servos will be placed such that they will be near the ends of the legs. The retention latches, then, can not only restrict movement along the width-wise axis and vertical axis, but also the length-wise axis. During pre-launch set-up, the servos will receive commands from the Raspberry Pi to rotate into position. This will put the retention latches over the payload vehicle legs. The legs will be compressed by both the retention latches and the compressible membrane attempting to expand. Once the launch vehicle completes touchdown, the Raspberry Pi will prompt the servos to rotate the retention latches off the payload vehicle's legs, allowing for the mission to proceed.

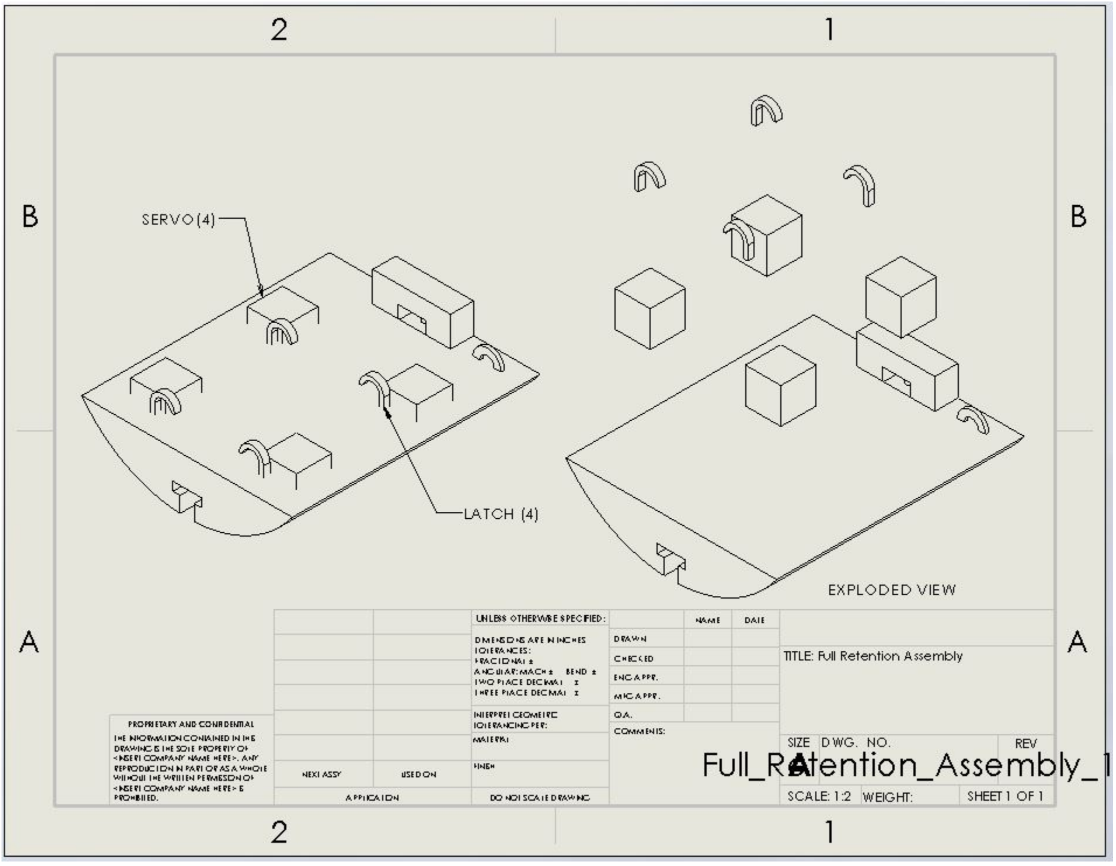


Figure 6.14: Payload Retention Assembly with Exploded View

6.4 PAYLOAD OBJECTIVE SYSTEM

From the preliminary designs the brush roller was chosen to continue development. The brush roller, similar to that of the front of a vacuum cleaner, will consist of a motor that will drive a spinning brush to push the simulated ice into a collection bin. Since the mission objective was was derived from lunar ice mining, the design heavily focused on retrieving a very large sample. This affected the how the brush roller was designed and why the design was chosen. This design was chosen over the other preliminary designs because of the simplicity, high reliability, low power consumption, durable construction, and of course the high volume of obtainable sample.

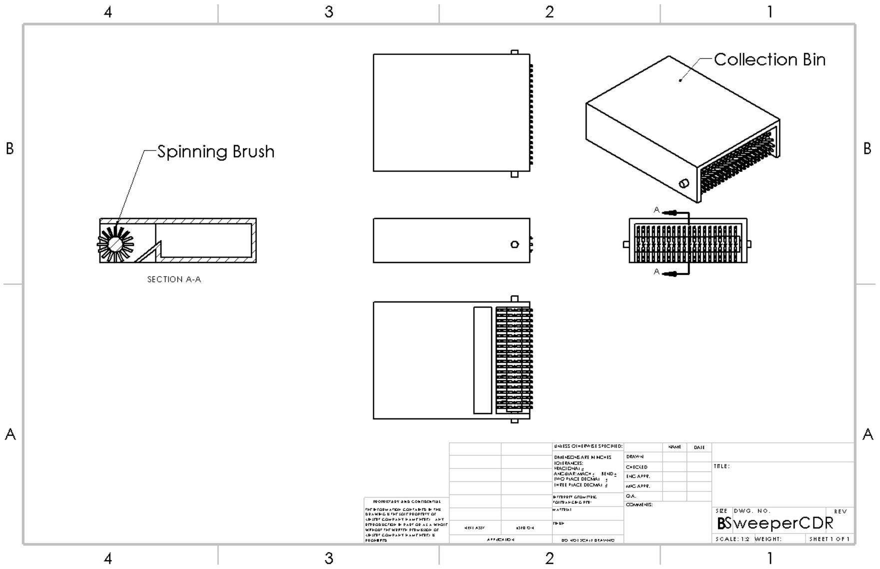


Figure 6.15: Test Payload Objective System

Storage Bin:

An initial testing apparatus was constructed out of polycarbonate. This was developed for a proof of concept. The final storage bin will be 3-D printed using PLA which is a durable plastic filament.

Motor:

A Mabuchi Motors RS-540SH series motor will be used to to drive the brush. The optimal input voltage falls between 4.8 volts and 9.6 volts. At the nominal voltage of 9.6 V the motor is able to operate at unloaded speeds of 23400 revolutions per minute with a current of 1.6 amps. At max efficiency the motor will produce .023 lb*ft of torque. The stalling torque and current are .159 lb*ft and 57 amps respectively. The motor weights approximately 160 grams. A band will be wrap around the motor drive shaft and the shaft of the brush to allow the brush to spin. This is will be done to move the motor from the side of the container to a location that will minimize footprint.

Brush:

A vacuum rolling brush will be used for our spinning brush. This will be cut to the dimensions needed which will span across the collection bin. The brush will also need space to allow for a band connected to the drive shaft of the motor.

7 SAFETY

7.1 PREFACE

ARC's highest priority is the safety of its members and spectators during its activities. All members have signed a safety contract indicating their willingness to abide by all regulations governing HPR and UAV operation. The ARC safety officer maintains an online depository of hazardous material data, a safety manual, other regulations, and safety analyses for the team. To ensure the highest chances of flight and mission success, the previous hazard and failure mode analyses have been revised to determine the greatest risk factors. In addition, comprehensive design analysis and validation plans have been created to outline the team's testing plans. The risk assessment scales have been revised to include five levels of severity, and occurrence is now represented numerically to enable the computation of total risk and risk priority numbers.

7.2 PERSONNEL HAZARD ANALYSIS

To ensure the safety of team members and spectators during construction and flight operations, hazards in the lab and vehicle failure modes were examined to determine their risk for personal injury. Tables 7.1 and 7.2 show the severity and occurrence likelihood scales used in the hazard analysis. For each hazard, the severity and likelihood values were multiplied together to obtain a total risk value between 1 and 25.

Value	Severity	Result	Action Required
1	Acceptable	Negligible injuries to personnel	None, though PPE is suggested
2	Marginal	Minor injuries to personnel	PPE, first aid
3	Moderate	Significant or long-lasting injuries to personnel	PPE, first aid, medical care
4	Severe	Life-threatening or permanent injuries to personnel	PPE, first aid, restriction of activity to authorized personnel, emergency medical care
5	Catastrophic	Death or permanently debilitating injury	PPE, first aid, restriction of activity to authorized personnel, emergency medical care

Table 7.1: Severity scale for personnel hazard analysis.

Value	Likelihood	Probability	Action Required
1	Very Unlikely	<5%	None, though testing/analysis is suggested
2	Unlikely	5% - 25%	Testing/analysis
3	Possible	26% - 50%	Testing/analysis, or documented approval by subsystem and subteam leads if mitigation not possible
4	Likely	51% - 89%	Testing/analysis, or documented approval by team leads and safety officer if mitigation not possible
5	Very Likely	>90%	Testing/analysis, or documented approval by team leads, safety officer, and appropriate NASA personnel if mitigation not possible

Table 7.2: Occurrence likelihood scale for personnel hazard analysis.

7.2.1 BUILD PHASE

The build phase of the vehicle requires the use of tools and chemicals in a workspace shared with many team members and other university organizations. In addition, team members enter ARC with varying amounts of hands-on experience. These factors combine to produce several potentially dangerous scenarios. These risks as well as their causes and effects are defined in Table 7.3 and assigned risk values. Severity values of 5 indicate a situation where death or debilitating injury is possible in a worst-case scenario.

Type of Hazard	Cause	Effect	Sev	Occ	Risk
Cancer	Prolonged exposure to carcinogens, ingestion of hazardous materials	Development of cancer, other immediate symptoms	4	1	4
Chemical contact with eye	Not washing hands, chemical spray, not wearing safety glasses	Irritation, temporary or permanent blindness, burns	5	2	10
Chemical spill	Leaving containers open, fatigue, carelessness, cluttered workspace	Burns, risk of fire, toxic fumes, slipping hazard	4	2	8
Electric shock	Frayed power cords, circuits not grounded, improper wiring	Electrocution, burns, shock	4	1	4
Fall from a height	Standing on tables/chairs, carelessness on stepstools/ladders	Bruises, sprains, broken bones, severe head injury	5	2	10
Fire	Flammable materials, electrical failure, open flames	Burns, smoke, irritation, death	5	1	5
Flying debris	Improper handling, machinery failure, structural failure	Eye injury, blunt injuries, head injury, loss of consciousness	5	1	5
Improper tool handling	Fatigue, lack of training, carelessness	Cuts, bruises, minor blood loss	2	3	6
Life threatening injury	Structural failure, machinery failure, fatigue, lack of training, carelessness, ingestion of hazardous material, machinery point of operation contact	Severe head injury, profuse bleeding, nerve damage, broken bones, dismemberment, poisoning	5	1	5
Respiratory irritation	Fume exposure, heavy sanding, not using dust mask/breathing mask	Difficulty breathing, coughing, irritation, choking	3	2	6
Sharp edges	Blades, unsanded parts, lack of training	Cuts, minor blood loss	2	3	6
Toxic fumes	Leaving containers open, prolonged exposure to hazardous materials	Disorientation, dizziness, nausea	3	2	6
Tripping	Leaving items on floor, power cords in walkways, running	Bruises, twists/sprains, head injury	3	2	6
Unclean workspace	Not covering open wounds, not cleaning blades/tools/tables	Infection, illness	2	2	4

Table 7.3: Risk values of personnel hazards during build phase.

The most severe risks to personnel in the build phase are chemicals entering the eye, falling from a height, flying debris, and any other life-threatening injury from a build activity. The most likely causes of injury are improper tool handling and sharp edges. The ARC safety manual contains applicable lab policies such as regular hand washing, use of PPE, only standing on structures designed for standing, not working when fatigued, and keeping body parts clear of the point of operation of machinery. In addition, the safety officer helps oversee build operations to ensure these policies are followed. Table 7.4 summarizes the mitigations for these build hazards, and the applicable safety policies can be found in the ARC safety manual.

Type of Hazard	**Risk**	**Prevention**	**Detection**
Cancer	4	Enforcement of lab protocols, limiting exposure to carcinogens	Oversight by team leads and safety officer
Chemical contact with eye	10	Enforcement of lab protocols, wearing safety glasses, regular hand washing, emergency eye wash, emergency contact information	Oversight by team leads and safety officer
Chemical spill	8	Enforcement of lab protocols, wearing gloves, keeping workspace clear, first aid kit, emergency contact information, safety shower	Oversight by team leads and safety officer
Electric shock	4	Enforcement of lab protocols, inspection of power cords and circuits	Oversight by team leads and safety officer
Fall from a height	10	Enforcement of lab protocols, standing only on structures designed for it	Oversight by team leads and safety officer
Fire	5	Enforcement of lab protocols, knowing location of fire extinguisher, emergency contact information	Oversight by team leads and safety officer, facility fire detection system
Flying debris	5	Enforcement of lab protocols, wearing safety glasses, training of members on machinery usage, emergency contact information	Oversight by team leads and safety officer
Improper tool handling	6	Enforcement of lab protocols, training of members on tool usage, first aid kit	Oversight by team leads and safety officer
Life threatening injury	5	Enforcement of lab protocols, wearing safety glasses and other PPE, training of members on machinery/tool usage, emergency contact information	Oversight by team leads and safety officer
Respiratory irritation	6	Enforcement of lab protocols, wearing dust/breathing masks, workspace ventilation	Oversight by team leads and safety officer
Sharp edges	6	Enforcement of lab protocols, training of members on tool usage, pointing blades away from self, wearing thick gloves, first aid kit	Oversight by team leads and safety officer
Toxic fumes	6	Enforcement of lab protocols, use of dust masks or breathing masks	Oversight by team leads and safety officer
Tripping	6	Enforcement of lab protocols, maintaining clear walkways, first aid kit, emergency contact information	Oversight by team leads and safety officer
Unclean workspace	4	Enforcement of lab protocols, regular cleaning of tools, first aid kit	Oversight by team leads and safety officer

Table 7.4: Mitigation methods of personnel hazards during build phase.

7.2.2 ASSEMBLY/FLIGHT PHASE

Similarly, preparing and launching the vehicle is dangerous due to the flammability of energetics and batteries in the rocket, the large amounts of stored chemical energy in the motor, the magnitudes of the forces the vehicle is subjected to, and the kinetic energy of the vehicle's descent. In addition, team members have varying degrees of experience with high powered rockets. These factors combine with the presence of spectators at launches to produce several potentially dangerous situations. These risks, their causes, annd their effects are defined and assigned risk values in Table 7.5. Severity values of 5 indicate a situation where death or debilitating injury to personnel or spectators is possible in a worst-case scenario, such as the vehicle flying into a crowd.

The most severe risks to personnel in the flight phase are fires, an erratic LV trajectory, and ballistic descent. The most likely risks are fires, ballistic descent, loss of MV control, and premature altimeter detonation. To mitigate these risks, all ARC personnel will wear PPE during flight operations, inspect the vehicle thoroughly prior to any launch, and use checklists to assemble and launch the vehicle. In addition, the design will be analyzed and

Type of Hazard	Cause	Effect	Sev	Occ	Risk
Brush fire	Launch area not cleared, motor failure, explosion	Spread of fire, burns, smoke	5	2	10
Flying debris	Structural failure, premature separation or release	Eye injury, cuts, bruises, minor blood loss, toxic materials released	4	1	4
Erratic LV trajectory	Unstable vehicle, high winds, motor failure, structural failure, launch rail improperly oriented	Blunt injuries, bruises, concussion, cuts, head injury, death	5	1	5
Ballistic descent	Staging failure, parachute failure	Blunt injuries, bruises, concussion, cuts, head injury, death	5	2	10
Airborne black powder	Secondary altimeters fire after staging has occurred	Eye irritation or injury	3	1	3
MV loss of control	Loss of power, signal interference, prop failure	Cuts, bruises, minor blood loss, head injury	4	2	8
Premature altimeter detonation	Improper altimeter setup, wiring issue, safety switch disengaged prematurely	Eye injury, hearing injury, dizziness, bruises	4	2	8

Table 7.5: Risk values of personnel hazards during flight phase.

Type of Hazard	Risk	Prevention	Detection
Brush fire	10	Have fire suppression equipment on hand, clear launch pad of flammable materials, inspect motor prior to flight	Use of checklists to inspect vehicle
Flying debris	4	Ensure personnel clear of launch area during flight, inspect prior to launch	Use of checklists to inspect vehicle
Erratic LV trajectory	5	Ensure personnel clear of launch area during flight, inspect prior to launch, wear safety glasses, maintain visual contact with vehicle	Use of checklists to inspect vehicle
Ballistic descent	10	Ensure personnel clear of launch area during flight, inspect staging systems and parachutes prior to launch, maintain visual contact with vehicle	Use of checklists to inspect vehicle
Airborne black powder	3	Wear safety glasses	N/A
MV loss of control	8	Inspect MV before flight, maintain visual contact, ensure full battery charge	Use of checklists to inspect vehicle and verify battery charge
Premature altimeter detonation	8	Wear safety glasses, follow checklists, verify altimeter configuration prior to flight	Use of checklists to inspect vehicle

Table 7.6: Mitigation methods of personnel hazards during flight phase.

validated as described in the following sections to address failure modes that cause situations where these risks arise. Table 7.6 summarizes these mitigation methods.

7.3 Design Failure Modes and Effects Analysis

Per the recommendations following the PDR, the preliminary DFMEA was replaced by a subsystem-level analysis of possible failure modes. Ten subsystems were defined, and boundary and parameter diagrams were created for each of them. The ideal functions and error states for each subsystem were identified, and component-level causes for each failure mode were also specified. In addition, noise and control factors that affect the subsystem's functionality were also specified. The results were then placed into standard DFMEA tables, and analyses and tests were designed based on the results.

For the DFMEAs, the meaning of the severity rating is changed as shown in Table 7.7, and the ease of issue detection prior to a flight test is measured by a detectability rating as shown in Table 7.8. The occurrence likelihood scale is the same as that used for the personnel hazard analysis. A detectability rating of 5 indicates that over 75% of issues associated with the failure mode can only be detected by flight testing. Detectability for failure causes from interactions of systems outside the scope of the given DFMEA are given as N/A, as they are detected using methods covered in that system's DFMEA. Systems with redundant components have severity and occurrence ratings with an R; this indicates the severity and occurrence of all redundant components failing. Failure of only a single component of these redundant sets is considered separately. Multiplying the severity, occurrence, and detectability together yields a risk priority number, which is used to prioritize analyses and tests. The priority classification for RPN ranges is given in Table 7.9.

Value	**Severity**	**Result**	**Action Required**
1	Acceptable	Little to no impact on mission	None, though testing/analysis is suggested
2	Marginal	Minor impact on mission, full success possible	Testing/analysis
3	Moderate	Major impact on mission, partial success possible	Testing/analysis, or documented approval by subsystem and subteam leads if mitigation not possible
4	Severe	Loss of mission	Testing/analysis, or documented approval by team leads and safety officer if mitigation not possible
5	Catastrophic	Loss of mission and danger to spectators/personnel	Testing/analysis, or documented approval by team leads, safety officer, and appropriate NASA personnel if mitigation not possible

Table 7.7: Severity scale for design failure modes and effects analyses.

Value	**Detectability**	**Meaning**	**Action Required**
1	Easily Detectable	Ground tests will easily detect all items of interest	Implementation of tests
2	Detectable	Ground tests will likely detect all items of interest, but unexpected failures due to component flaws may occur	Analysis and implementation of tests
3	Not Easily Detectable	Ground tests will detect at least 75% of all items of interest, with no more than 25% requiring flight testing to detect	Analysis, implementation of tests, and inspection of build work, or documentation of approval by subsystem and subteam leads if mitigation not possible
4	Barely Detectable	Ground tests will detect between 25% and 75% of items of interest, but 25% to 75% require flight testing	Analysis and inspection of build work, or documentation of approval by team leads and safety officer if mitigation not possible
5	Impossible to Detect	Greater than 75% of items of interest can only be realistically tested in flight	Thorough analysis and inspection of build work, or documentation of approval by team leads, safety officer, and appropriate NASA personnel if mitigation not possible

Table 7.8: Detectability scale for design failure modes and effects analysis.

RPN Ranking	**RPN (Sev x Occ x Det) Range**
Critical	>= 65
Important	37, 64
High	19, 36
Normal	9, 18
Low	1, 8

Table 7.9: Risk priority number ratings for design failure mode and effects analyses.

Due to their large size, the DFMEA tables are located in the first section of the appendices and will be referenced in the following sections. Mitigation of these failure modes will be done by performing analyses and tests as outlined in the Design Analysis Plan and Design Verification Plan, respectively.

7.3.1 SUBSYSTEM-SPECIFIC DFMEAS

7.3.1.1 DRONE CARRIAGE The drone carriage is a system designed to move the mission vehicle out of the electronics/payload bay so that it can take off and begin its mission. To be successful, the carriage must remain secure during the flight, deploy steadily when commanded from the ground station for most possible landing terrains, and extend such that the drone will clear the body tube. Several potential error states for these functions have been identified, and their causes and effects are shown in Table 9.1 in the appendices.

The failure modes with the highest severity (values of 5 in Table 9.1) are those that involve the carriage not remaining restrained during the flight phase. Any shift in the carriage's location has the potential to shift the vehicle's center of gravity, which can result in a complete loss of vehicle stability in a worst-case scenario. This would not only lead to a loss of the vehicle and mission, but would place personnel and spectators in danger. Other severe failure modes are those that prevent the drone from taking off, such as the carriage not actuating or incompletely extending. These modes would result in a loss of mission, but would not jeopardize personnel safety.

The most likely failure causes (occurrence values of 3 in Table 9.1) are launch loads/vibrations damaging systems, material properties of the restraint hook not being able to withstand flight loads, and the placements of the restraint bolt and actuation line washers preventing a successful deployment. The primary concern for the washers is a varying line of action of the force pulling the carriage out of the body tube. As the winch pulls the carriage forward, the washer will pass over the carriage and then be perpendicular to the direction of travel, preventing it from aiding in carriage deployment. In addition, the use of a single restraint bolt introduces the possibility of a moment about the bolt during deployment, especially when considering the carriage-mounted washer is not centered. These failure modes can all result in a loss of mission, and the failure of the restraint hook can lead to a loss of LV stability.

The least detectable failure causes (values of 5 in Table 9.1) are structural failure of the restraint hook in flight and free rotation of the winch reel while in flight, as these require exposure to the flight environment to be fully examined. In the case of the restraint hook, loss of the vehicle and mission as well as a risk to ground personnel can result. Free rotation of the winch reel poses a similar risk, but the restraint hook would prevent the winch from pulling the carriage forward.

7.3.1.2 DRONE RETENTION SYSTEM The drone retention system is designed to keep the mission vehicle firmly attached to the carriage until after touchdown and carriage actuation. To be successful, this system must prevent the drone from moving during the entire flight phase and completely release it when commanded from the ground station. The error states for these functions have been identified, and their causes and effects are summarized in Table 9.2 found in the appendices.

The most severe failure modes (values of 5 in Table 9.2) are those that allow the mission vehicle to freely move in the payload bay during the flight phase. Shifts in the vehicle's center of gravity can lead to a total loss of stability as well as the loss of the vehicle and mission.

These failure modes result from the structural failure or premature release of one or more of the over-leg latches.

The most likely failure causes (values of 3 in Table 9.2) are damage to the system by launch loads/vibrations, structural failure of the latches, failure of the locking system for the latches, and incomplete securing of the MV when the latches are active. These failures pose a risk of LV instability, loss of vehicle and mission, and danger to personnel on the ground.

The least detectable failure cause (value of 5 in Table 9.2) is structural failure of the over-leg latches during flight, as the only complete verification of the restraint's effectiveness is a flight test. Other causes that are difficult to detect are damage to components by loads/vibrations, but vibration effects can be observed during ground testing. These failures can lead to loss of the vehicle and mission and pose a risk to ground personnel.

7.3.1.3 LV COMMS/CONTROL SYSTEM The LV comms/control system is designed to relay the location of the LV and enable control of the drone carriage, drone retention, and landing leg systems. To be successful, this system must maintain two-way communication with the ground station, relay battery voltages of systems, relay accurate GPS coordinates of its location, actuate servos when commanded, and disconnect fromm the MV when it deploys. Error states associated with these functions are found in Table 9.3 in the appendices.

The most severe failure modes (values of 5 in Table 9.3) are those that can result in loss of the vehicle. If both communication and visual contact with the LV are lost, the vehicle location will be unknown. This will prevent execution of the mission and pose a risk to ground personnel, as one cannot remain clear of a vehicle that cannot be located. A premature command sent to servos in the electronics/payload bay can also result in loss of the vehicle due to deployment of the landing leg or initiation of the MV release sequence, which both cause the vehicle to become unstable.

The most likely failure causes (values of 3 in Table 9.3) are the vehicle flying out of range, batteries not being fully charged, and launch loads/vibrations damaging the system. These factors can all result in a loss of the vehicle and mission if full communication and control functionality is lost.

The least detectable failure cause (value of 5 in Table 9.3) is saturation of the GPS module during flight, which can only be simulated through a flight test. It is also difficult to fully simulate the effects of launch loads and vibrations on the system, as launch loads can only be produced in flight.

7.3.1.4 SAMPLE RETRIEVAL SYSTEM The sample retrieval system is designed to collect simulated lunar ice from a designated collection area. To be successful, this system must be toggled via ground commands, intake at least 150 mL of sample material without jamming or breaking, and contain the sample material during transport away from the collection area.

Failure modes associated with these criteria are found in Table 9.4 in the appendices.

The most severe failure modes (values of 4 in Table 9.4) are those that result in complete inability to intake sample material, therefore leading to a loss of mission. Such failure modes include failure to engage or disengage on ground command, premature engagement, a complete jam during intake, and sample material being lost during transport.

The most likely failure causes (values of 4 in Table 9.4) are collecting too much sample material for the collection bin to hold, sample loss due to MV orientation, and overflow back into the brush roller from the collection bin. These can lead to loss of all sample material or preventing the MV from flying. It is also fairly likely that launch loads/vibrations will cause damage to the system.

The least detectable failure causes (values of 4 in Table 9.4) are damage to the system incurred from launch loads and vibrations. While vibration testing can be conducted on the ground, flight testing is the only way to subject the system to flight loads.

7.3.1.5 Mission Vehicle The purpose of the mission vehicle is to depart the LV landing location for the sample retrieval site, enable collection of the sample, and transport the sample away from the retrieval site. To be successful, the mission vehicle must maintain two way communication with the ground station, awaken when signaled by the LV comms/control system, relay accurate GPS coordinates of its location, deploy its rotor booms and toggle the sample retrieval system when commanded by the ground station, maintain first person view capability during the mission, and remain stable and controllable during flight. Error states associated with these functions are found in Tables 9.5 and 9.6 in the appendices.

The most severe failure modes (values of 5 in Tables 9.5 and 9.6) are those that involve loss of control/stability or structural failure, such as loss of all communications, loss of GPS tracking, or structural failures. If the mission vehicle loses stability or control capability, it is a hazard to the safety of personnel and spectators. Loss of GPS tracking and visual contact while the MV is flying would lead to difficulty locating the MV, as the first person view is most useful for short-range navigation. This also poses a risk to personnel on the ground.

The most likely failure causes (values of 3 in Tables 9.5 and 9.6) are insufficient battery charge, flying out of range, GPS saturation, failures of the rotor boom system, and damage from launch loads/vibrations. These causes contribute to failure modes that result in the loss of vehicle stability and the mission, and they also pose a risk to ground personnel and spectators.

The least detectable failure causes (values of 5 in Tables 9.5 and 9.6) are GPS module saturation and debris damage to the FPV camera. The launch loads that the GPS module will be exposed to cannot be simulated without flight testing, and debris impacting the FPV camera cannot be predicted with certainty. While damage by launch loads can result in the loss of the vehicle and mission, damage to the FPV camera can be worked around as long as visual contact and GPS tracking are maintained.

7.3.1.6 GROUND STATION The ground station serves as a tracking and control system for all active parts of the vehicle, including the electronics/payload bay and the mission vehicle. In addition, it tracks the avionics bay/upper launch vehicle, but does not provide control functionality. To be successful, this system must provide telemetry from the MV and LV, send commands to their respective Raspberry Pi computers throughout the mission, and maintain two-way communication with the MV flight controller through an RC controller. Failure modes of these functions are found in Table 9.7 in the appendices.

The most severe failure modes (values of 5 in Table 9.7) are those that lead to loss of all telemetry and control capability for the LV or MV. If command capability is lost the MV can fail to deploy or be unable to fly, and the mission then cannot be completed. If telemetry is lost along with visual contact, the vehicle and mission may be lost. Loss of control and location of the MV or LV poses a danger to spectators and personnel, who would then be unable to avoid the vehicle.

The most likely failure causes (values of 3 in Table 9.7) are loss of power from the power supply, an unexpected router shutdown, and insufficient WiFi antenna range. These can result in complete loss of all LV and MV communications or, in the case of WiFi antennas, a partial loss of MV communications.

The least detectable failure causes (values of 2 in Table 9.7) are unexpected shutdowns of the computer or router. These can be caused by disconnection from the power supply, an accidental button press, or a cause internal to the computer or router. A complete loss of communications would result from either of these causes.

7.3.1.7 LANDING LEG The purpose of the landing leg is to stabilize the LV upon landing in an orientation such that the carriage can deploy unimpeded by terrain. To be successful, this system must deploy upon command from the ground, withstand the impact force of landing, and raise the electronics/payload bay to be level with the horizon on most possible landing terrains. The error states associated with these functions are found in Table 9.8 in the appendices.

The most severe failure mode (value of 5 in Table 9.8) is premature deployment of the leg. If this occurs during the flight, a total loss of stability of the LV would result, leading to a loss of the vehicle and mission as well as significant risk to ground personnel and spectators.

The most likely failure causes (values of 3 in Table 9.8) are insufficient servo force to deploy the leg, deployment during flight caused by a pressure gradient, and damage to the system by launch loads/vibrations. These modes can lead to a premature deployment or a failure to deploy, which both jeopardize the mission.

The least detectable failure cause (value of 5 in Table 9.8) is a pressure gradient causing premature deployment of the leg. The airflow needed to simulate the flight environment cannot be generated on the ground with the available equipment. Similarly, flight loads cannot be simulated on the ground, so failures due to flight loads/vibrations are also difficult to detect.

7.3.1.8 AVIONICS BAY The avionics bay is designed to initiate secondary and main staging of the vehicle at the appropriate times to facilitate safe recovery. To be successful, the system must fire e-matches at apogee to initiate drogue chute deployment, fire e-matches as 550 ft AGL to initiate main chute deployment, and fire in such a way that the rest of the vehicle is not damaged. Error states associated with these functions are found in Table 9.9 in the appendices.

The most severe failure modes (values of 5 in Table 9.9) are those resulting in a premature parachute deployment, no parachute deployment, or a structural failure. These modes can lead to a loss of LV stability, a ballistic descent of the vehicle, or falling debris, which all cause (or are symptomatic of) the loss of the vehicle and mission. In addition, an uncontrolled recovery phase is a major risk to ground personnel and spectators.

The most likely failure causes (values of 3 in Table 9.9) are insufficiently charged batteries and damage to the system by launch loads/vibrations. These causes can lead to complete failures of both secondary and main staging, a ballistic descent, and the loss of the vehicle and mission.

The least detectable failure cause (value of 4 in Table 9.9) is damage to the system by launch loads/vibrations because only vibrations can be realistically simulated on the ground. It is also difficult to test material properties under the loads that the vehicle will experience during flight.

7.3.1.9 UPPER LV/SECONDARY RECOVERY The upper launch vehicle and secondary recovery system shield the avionics bay from flight loads, deploy the drogue chute for the secondary recovery phase, lower the upper LV components to touchdown, and relay the location of the upper LV to the ground station. To be successful, the system must maintain structural integrity during launch, deploy the drogue chute at apogee to stabilize the entire vehicle, lower the upper LV at a safe velocity for touchdown, and relay the accurate GPS coordinates of the system. Failure modes relating to these functions are summarized in Table 9.10 in the appendices.

The most severe failure modes (values of 5 in Table 9.10) are those that result in the loss of LV stability, an uncontrolled or rapid descent, or the loss of the entire vehicle. These failure modes, in addition to leading to loss of the mission, endanger personnel and spectators on the ground because the vehicle will be traveling at a dangerous velocity. Loss of accurate GPS location of the upper LV following a successful main staging leads to loss of a portion of the LV, but it is the lightest portion of the vehicle and is no longer critical to mission success following main staging. Therefore, a reduced severity is applied to this failure mode.

The most likely failure causes (values of 3 in Table 9.10) are improper stowage or line tangling on the drogue chute, damage to the parachute material, and damage to the system by launch loads/vibrations. A parachute must be folded very precisely and carefully in order to deploy correctly, and team members have varying experience with this. In addition, flight loads and vibrations can loosen or move parachute components around if they are not properly restrained.

The least detectable failure causes (values of 3 in Table 9.10) are nosecone structural failure, chute line tangling, and damage to the system by launch loads/vibrations. It cannot be guaranteed that chute lines will not tangle upon staging, and the manner in which they tangle varies between deployments. In addition, it is difficult to simulate the loads the system will experience without subjecting them to the flight environment.

7.3.1.10 LOWER LV/PRIMARY RECOVERY The purpose of the lower LV and primary recovery system is to propel the vehicle to its target altitude, remain stable during flight, and lower the vehicle's motor and the mission vehicle to a safe touchdown. To be successful, the system must ignite the motor when commanded and launch to the target altitude, remain stable during the flight phase, separate normally and deploy the main chute at 550 ft AGL, and land safely in the orientation needed for MV deployment. The failure modes for these criteria are shown in Table 9.11 in the appendices.

The most severe failure modes (values of 5 in Table 9.11) are those which result in risks of fire or explosion, a loss of LV stability, or a rapid/uncontrolled descent. These modes can result in loss of the vehicle and mission while also endangering those on the ground. The lower launch vehicle contains the most flammable material and the majority of the vehicle's weight, making it the most dangerous portion of the vehicle during the flight phase.

The most likely failure causes (values of 3 in Table 9.11) are separation of the launch lugs from the vehicle, structural failure of the motor mount, improper centering ring or motor mount installation, improper installation or separation of the fins, improper main parachute stowage, partial detachment of the main chute from the LV, and damage to the system from launch loads/vibrations. All of these causes have the potential to destabilize the vehicle during the boost or recovery phases, and they can lead to loss of the vehicle and mission. In addition, they pose a significant risk to those on the ground.

The least detectable failure mode (value of 5 in Table 9.11) is asymmetrical or abnormal burn of the motor. Since the motor is purchased commercially, any defects will not be detectable until the motor has been ignited. It is also difficult to detect the effect of launch loads on the system, as this environment's effects can only be accurately observed during a flight.

7.3.2 SYSTEM-WIDE CONCERNS

When considering all DFMEAs conducted on the launch and mission vehicles, several common failure causes emerge. The most pervasive of all possible failure causes is the effect of launch loads and vibrations on each subsystem and the vehicle as a whole. Since the launch loads cannot be simulated on the ground, it is imperative that the effects of vibrations be thoroughly simulated on the ground to reduce the unknown effects of the flight environment. Another pervasive risk is material properties not being able to withstand flight loads. Therefore, the maximum loads of all materials used in the construction of the competition vehicle must be researched and checked against the maximum loads each component is expected to experience during flight. The maximum expected loads can be found using simulation software and static analysis methods.

Another commonality among the DFMEAs is the risk for loss of power. A drained MV or LV electronics/payload bay battery results in the loss of the mission. The risk of depletion of an altimeter bay battery is mitigated by redundancy of altimeter system, but depletion of all altimeter batteries would result in failed staging and the loss of the vehicle and mission. To mitigate this risks, the charging of batteries to be used on a flight vehicle will be documented. For each charge, the number assigned to the particular battery, time of charge initiation, time of disconnection from charging unit, voltage across the terminals prior to and after charging, and the responsible team member will be tabulated.

Other common failure modes, such as a loss of wireless connection, disconnection of wired components, and improper installation will be mitigated through the use of pre-flight inspections and checklists as well as the ground tests and analyses described in the design analysis and verification plans.

7.4 ENVIRONMENTAL HAZARD ANALYSIS

The failure modes of the vehicle pose several safety risks to the surrounding environment and its wildlife. In addition, several environmental factors have the potential to impede mission success. The severity scale used for the environment on vehicle hazard analysis is the same as that used in the DFMEAs, while the vehicle on environment hazard analysis uses the severity scale shown in Table 7.10. The occurrence scale and risk value are obtained in the same manner as the personnel hazard analyses.

Value	Severity	Result	Action Required
1	Acceptable	Little to no impact on environment	None, though testing/analysis is suggested
2	Marginal	Temporary impact on environment that is easily removable	Testing/analysis
3	Moderate	Minor damage to environment that is more difficult to remove	Testing/analysis, or documented approval by subsystem and subteam leads if mitigation not possible
4	Severe	Significant damage to environment or harm to wildlife that is difficult to remove	Testing/analysis, or documented approval by team leads and safety officer if mitigation not possible
5	Catastrophic	Major environmental impact and harm to wildlife with long term consequences or immediate risks	Testing/analysis, or documented approval by team leads, safety officer, and appropriate NASA personnel if mitigation not possible

Table 7.10: Severity scale for analysis of vehicle effects on environment.

7.4.1 ENVIRONMENT ON VEHICLE

The vehicle will be exposed to several uncontrollable factors that affect its flight and mission, such as the weather, signals from other teams, launch delays, the properties of the sample material, and static electricity. These hazards and their effects on the vehicle are defined in Tables 7.11 and 7.13.

Subsystem	Environmental Hazard	Effect	Sev	Occ	Risk
Drone Carriage	Hilly terrain at landing site	Carriage actuation system cannot deploy drone	4	3	12
Drone Carriage	Extremely hot or cold temperature	Different material thermal expansions impede deployment	3	2	6
Drone Carriage	Precipitation	Damage to mechanical and electrical components	4	2	8
Drone Retention	Extremely hot or cold temperature	Different material thermal expansions impede release	2	2	4
Drone Retention	Precipitation	Damage to mechanical and electrical components	4	2	8
LV Comms/Control	Extremely hot or cold temperature	Variation in battery drainage time, damage to electrical components	3	3	9
LV Comms/Control	High humidity	GPS coordinate inaccuracy	3	3	9
LV Comms/Control	Signals from other teams	Interference prevents comm/control or results in premature commands	4	1	4
LV Comms/Control	Launch delays	Lower battery levels at time of launch, possible charge depletion	4	2	8
LV Comms/Control	High static electricity	Damage to electrical components	4	2	8
LV Comms/Control	Precipitation	Damage to electrical components	4	2	8
Sample Retrieval	Extremely hot or cold temperature	Different material thermal expansions impede smooth operation	2	2	4
Sample Retrieval	Sample material unit volume larger than anticipated	Jam of roller during sample intake	3	3	9
Sample Retrieval	Sample material unit density higher than anticipated	Material too heavy to be obtained by roller, drone too heavy to fly	3	2	6
Mission Vehicle	Extremely hot or cold temperature	Air density and electrical component responses result in thrust variations	2	3	6
Mission Vehicle	High winds	Loss of MV stability or difficulty maintaining control	5	3	15
Mission Vehicle	Flying debris	Damage to MV, loss of thrust, loss of MV	5	1	5
Mission Vehicle	High static electricity	Damage to electrical components	4	2	8
Mission Vehicle	Precipitation	Damage to electrical components	4	2	8

Table 7.11: The first half of risk values of environmental effects on the vehicle.

Subsystem	Environmental Hazard	Risk	Prevention	Detection
Drone Carriage	Hilly terrain at landing site	12	Test deployment of carriage on unlevel ground	N/A
Drone Carriage	Extremely hot or cold temperature	6	Test deployment of carriage in various temperature conditions	Weather report included in preflight checklists
Drone Carriage	Precipitation	8	Do not fly in precipitation	Weather report included in preflight checklists
Drone Retention	Extremely hot or cold temperature	4	Test release in various temperature conditions	Weather report included in preflight checklists
Drone Retention	Precipitation	8	Do not fly in precipitation	Weather report included in preflight checklists
LV Comms/Control	Extremely hot or cold temperature	9	Test operation of comm/control systems in various temperature conditions	Weather report included in preflight checklists
LV Comms/Control	High humidity	9	Protect GPS module from humidity using physical shield (if board safeguard not included)	Weather report included in preflight checklists
LV Comms/Control	Signals from other teams	4	Use of WiFi for all primary telemetry and control, declaration of unique LoRa frequency for secondary MV telemetry	N/A
LV Comms/Control	Launch delays	8	Implementation of power-saving configurations prior to launch, documentation of battery charge	Verification of charge on checklists, long-duration idle tests of vehicle to ensure batteries remain charged
LV Comms/Control	High static electricity	8	Keep vehicle attached to ground prior to launch, do not fly when lightning present	Weather report included in preflight checklists
LV Comms/Control	Precipitation	8	Do not fly in precipitation	Weather report included in preflight checklists
Sample Retrieval	Extremely hot or cold temperature	4	Test in various temperature conditions	Weather report included in preflight checklists
Sample Retrieval	Sample material unit volume larger than anticipated	9	Test varying sizes of simulated sample material	N/A
Sample Retrieval	Sample material unit density higher than anticipated	6	Test varying densities of simulated sample material	N/A
Mission Vehicle	Extremely hot or cold temperature	6	Test drone flight in various temperature conditions	Weather report included in preflight checklists
Mission Vehicle	High winds	15	Do not fly in high winds	Weather report included in preflight checklists
Mission Vehicle	Flying debris	5	Maintain visual contact with MV and avoid objects that produce debris (such as trees)	Weather report included in preflight checklists
Mission Vehicle	High static electricity	8	Do not fly when lightning present	Weather report included in preflight checklists
Mission Vehicle	Precipitation	8	Do not fly in precipitation	Weather report included in preflight checklists

Table 7.12: Mitigation methods for the first half of environmental effects on the vehicle.

Subsystem	Environmental Hazard	Effect	Sev	Occ	Risk
Ground Station	Signals from other teams	Interference prevents comm/control or results in premature commands	4	1	4
Ground Station	High static electricity	Damage to electrical components	4	2	8
Ground Station	Precipitation	Damage to electrical components	4	2	8
Landing Leg	Rough terrain at landing site	Structural damage	3	3	9
Landing Leg	Extremely hot or cold temperature	Different material thermal expansions impede deployment	3	2	6
Avionics Bay	Extreme temperature or pressure	Main altimeters engage staging early or late	5	2	10
Avionics Bay	High static electricity	Risk of premature detonation, damage to electrical components	5	2	10
Avionics Bay	Precipitation	Damage to mechanical and electrical components	4	2	8
Avionics Bay	Humidity	E-match failure	4	2	8
Upper LV	High winds	Damage to drogue chute, upper LV drifts out of operations area	5	3	15
Lower LV	High static electricity	Premature motor ignition	5	3	15
Lower LV	Wind shear	Damage to LV, loss of stability, loss of vehicle and mission	5	2	10
Lower LV	Extreme temperature or pressure	Variations in motor thrust, loss of LV stability	5	2	10
Lower LV	High winds	Damage to main chute, lower LV drifts out of operations area	5	3	15
Lower LV	Launch rail beyond safe operation angle	Dangerous flight trajectory	5	1	5
Lower LV	Humidity	Ignition failure	4	2	8
General	Trees	Loss of vehicle components during recovery phase	4	2	8
General	Bodies of water	Loss of vehicle components during recovery phase	4	2	8

Table 7.13: The second half of risk values of environmental effects on the vehicle.

Subsystem	**Environmental Hazard**	**Risk**	**Prevention**	**Detection**
Ground Station	Signals from other teams	4	Use of WiFi for all primary telemetry and control,declaration of unique LoRa frequency for secondary MV telemetry	N/A
Ground Station	High static electricity	8	Keep systems grounded, do not operate when lightning present	Weather report included in preflight checklists
Ground Station	Precipitation	8	Do not operate in precipitation	Weather report included in preflight checklists
Landing Leg	Rough terrain at landing site	9	Drop testing	N/A
Landing Leg	Extremely hot or cold temperature	6	Test deployment of leg in various temperature conditions	Weather report included in preflight checklists
Avionics Bay	Extreme temperature or pressure	10	Verify altimeters are properly calibrated	Altimeter verification included in checklists
Avionics Bay	High static electricity	10	Do not disengage safeties or fly when lightning present	Weather report included in preflight checklists
Avionics Bay	Precipitation	8	Do not fly in precipitation	Weather report included in preflight checklists
Avionics Bay	Humidity	8	Monitor weather throughout entire countdown	Weather report included in preflight checklists
Upper LV	High winds	15	Do not fly in high winds	Weather report included in preflight checklists
Lower LV	High static electricity	15	Do not disengage safeties or fly when lightning present	Weather report included in preflight checklists
Lower LV	Wind shear	10	Monitor weather throughout entire countdown	Weather report included in preflight checklists
Lower LV	Extreme temperature or pressure	10	Do not fly in extreme weather conditions	Weather report included in preflight checklists, vehicle inspection prior to launch
Lower LV	High winds	15	Do not fly in high winds	Weather report included in preflight checklists
Lower LV	Launch rail beyond safe operation angle	5	N/A	Verification of launch rail angle prior to launch
Lower LV	Humidity	8	Monitor weather throughout entire countdown	Weather report included in preflight checklists
General	Trees	8	Launch in clear area	N/A
General	Bodies of water	8	Launch in clear area	N/A

Table 7.14: Mitigation methods for the second half of environmental effects on the vehicle.

The most severe risks to the launch vehicle from the environment are hilly or rough terrain at the landing site, extreme temperature or pressure, high humidity, variances in sample unit volume, high winds/wind shear, and high static electricity. These factors can preclude drone carriage deployment, affect altimeter sensors and GPS coordinates, reduce effectiveness of electrical components, cause a roller jam, lead to a loss of stability, prematurely ignite the motor, or lead to the loss of the vehicle and mission. Since the probability of these events cannot be influenced, they must either be avoided or accounted for in vehicle design. The landing leg system and sample retrieval system will be tested beyond their design scenarios to observe how they perform in more difficult situations. Weather-related factors will be avoided, and their presence will result in a launch delay or cancellation in the interest of safety. These and other mitigations are summarized in Tables 7.12 and 7.14.

7.4.2 VEHICLE ON ENVIRONMENT

In the event of a vehicle failure, the effects on the environment can be severe or long-lasting. To minimize the likelihood of negative impacts, possible influences the vehicle can have on the environment have been identified and analyzed. These influences are summarized and assigned risk values in Table 7.15. Severity values of 5 indicate either a risk of affecting the success of other teams' missions, severe damage to plant life, and/or fatally injuring animal life.

Subsystem	Environmental Hazard	Effect	Sev	Occ	Risk
LV Comms/Control	Signals interfere with other teams	Signals prevent other teams from communicating/controlling vehicles	5	1	5
Sample Retrieval	Loose sample material falling from MV	Sample material spread on ground	3	3	9
Mission Vehicle	Vehicle loses thrust/control	Hard impact with ground, prop damage to ground, debris, damage to wildlife	4	2	8
Ground Station	Signals interfere with other teams	Signals prevent other teams from communicating/controlling vehicles	5	1	5
Landing Leg	Separates from LV or gets embedded in ground	Falling debris, damage/injury to wildlife	4	2	8
Avionics Bay	Stages with excessive force	Falling debris, damage/injury to wildlife	5	2	10
Avionics Bay	Secondary altimeters fire after successful primary firing	Falling debris, release of hazardous material, injury to wildlife	5	3	15
Avionics Bay	Staging does not occur	Uncontrolled descent, high-energy impact	5	1	5
Upper LV	Drogue chute failure or separation from components	Uncontrolled descent, high-energy impact, falling debris, damage/injury to wildlife	5	2	10
Upper LV	Landing outside of mission area	Damage to or impact on functionality of wildlife habitats	3	1	3
Lower LV	Motor failure	Fire, flying debris, uncontrolled descent, damage/injury to wildlife	5	1	5
Lower LV	Loss of vehicle stability during launch	Dangerous flight trajectory, fire, high-energy impact, damage/injury to wildlife	5	1	5
Lower LV	Main chute failure or separation from components	Uncontrolled descent, high-energy impact, falling debris	5	3	15
Lower LV	Landing outside of mission area	Damage to or impact on functionality of wildlife habitats	3	1	3

Table 7.15: Risk values of effects of the vehicle on environment.

The most severe risks the vehicle poses to the environment are spreading loose sample material, staging with excessive force, firing secondary altimeters after successful staging, and parachute failures. Loose sample material and black powder may be harmful to animal life if ingested, and black powder increases the chance of fire in the area. A staging event imparting excessive force to the vehicle can result in structural failure and falling debris, which endangers wildlife. A parachute failure can result in a ballistic descent, which can lead to a fire at the impact site, damage to plant life, or fatal injury to animal life immediately underneath the descending vehicle. To mitigate these risks, contingency plans for material cleanup will be arranged with the proper personnel, the vehicle will be flown in areas with minimal wildlife, and tests/analyses will be performed to minimize the chances of vehicle failure.

Subsystem	Environmental Hazard	Risk	Prevention (beyond that in DAP)	Detection (beyond that in DVP)
LV Comms/Control	Signals interfere with other teams	5	Use of WiFi for primary communications and declaration of unique LoRa frequency for secondary	N/A
Sample Retrieval	Loose sample material falling from MV	9	Test sample retrieval system in mission scenario	N/A
Mission Vehicle	Vehicle loses thrust/control	8	Fly clear of wildlife, prepare for material cleanup if needed	Inspect vehicle prior to flight
Ground Station	Signals interfere with other teams	5	Use of WiFi for primary communications and declaration of unique LoRa frequency for secondary	N/A
Landing Leg	Separates from LV or gets embedded in ground	8	Fly clear of wildlife, prepare for material cleanup if needed	Inspect vehicle prior to flight
Avionics Bay	Stages with excessive force	10	Verify force exerted by e-matches and ensure it does not exceed design loads, prepare for material cleanup if needed	N/A
Avionics Bay	Secondary altimeters fire after successful primary firing	15	Verify timing of altimeters and ensure secondaries only fire if primaries fail, prepare for material cleanup if needed	N/A
Avionics Bay	Staging does not occur	5	Check altimeter system prior to launch	N/A
Upper LV	Drogue chute failure or separation from components	10	Check drogue chute stowage and attachments prior to launch	N/A
Upper LV	Landing outside of mission area	3	Fly clear of wildlife, arrange for contingency recovery if needed, do not fly in high winds	Weather report included in preflight checklists
Lower LV	Motor failure	5	Arrange for contingency fire suppression if needed, inspect vehicle prior to launch	N/A
Lower LV	Loss of vehicle stability during launch	5	Verify vehicle design stability, inspect vehicle prior to launch, do not fly in dangerous weather conditions	Weather report included in preflight checklists
Lower LV	Main chute failure or separation from components	15	Check main chute stowage and attachments prior to launch	N/A
Lower LV	Landing outside of mission area	3	Fly clear of wildlife, arrange for contingency recovery if needed, do not fly in high winds	Weather report included in preflight checklists

Table 7.16: Mitigation methods for effects of the vehicle on environment.

7.5 LAUNCH OPERATIONS PROCEDURES

7.5.1 ASSEMBLY

While constructing and designing the rocket for competition, the assembly process and other pre-flight checks were kept in mind. This includes the assembly of the rocket on launch day and the packing of all necessary materials to aid in the assembly. A series of pre-launch checklists have been made by the WMU ARC team, which will explain the entirety of the assembly process. The necessary items for the assembly include:

- Nose Cone
- Nose Cone mounted GPS
- Auxiliary Telemetry Bay
- Avionics Bay
- Altimeter Sled
- Bulk Heads
- Payload Bay
- Mission Systems
- Aft Body Section
- Motor Casing

- Motor Retainer
- All Necessary Batteries
- Shock Chords
- Main Parachute
- Drogue Parachute
- Hardware; bolts, nuts, shear pins etc.
- Wadding

Before anything can be assembled all parts of the rocket must be inspected.

1. Inspect fins for straightness and possible damage.
2. Inspect fillets for any cracks or delamination.
3. Inspect aft section of body for damage.
4. inspect fore section of body for damage.
5. Inspect motor retainer for any cracks or bends.
6. Check over the entire airframe for possible damage and for cleanliness.
7. Inspect the nosecone for any deformation or large chips in paint.
8. Inspect mission systems for any cracks or markings.
9. Check that all hardware is tightly secured
10. Check altimeters are securely fastened.
11. Make sure all batteries are fully charged
12. Check parachutes for any rips or tears.

7.5.2 FLIGHT

Before any recovery systems can be assembled the overall flight worthiness of the rocket must be analyzed. This involves in depth inspections of the rocket itself.

1. Start by inspecting the nose cone for any damage.
2. Inspect the fins for any damage and for overall straightness.
3. Inspect the fillets on all 8 fins for any cracks or damage.
4. Inspect each body section for chips or zippering.
5. Inspect motor retainer for cracks or bends.
6. Inspect the motor casing for any marks, dents, or any thing that could cause potential failures.
7. Check airframe, couplers, and canister for shear pins and remove any found.

8. Make sure nose cone fits tightly into fore body tube.
9. Check that drone's batteries are fully charged.
10. Look over drone that it is not damaged in anyway.
11. Insert drone into the payload bay.

7.5.3 RECOVERY

There are several procedures that will be needed for a successful recovery preparation. Each parachute needs to be properly loaded and then the preparation of recovery components integrated into the airframe need to be executed. The first item to pack is the drogue parachute. It is necessary to follow all theses steps to avoid failure.

1. Retrieve the drogue parachute and place it on a flat surface.
2. Inspect for any tears or rips in the chute.
3. Look over the deployment bag for any rips or tears.
4. Ensure the none of the parachute lines are tangled or knotted.
5. Further inspect the lines for any burns or frays.
6. Secure drogue to swivel and ensure even amounts of line are being used.
7. Once tied to swivel ensure there are no tangles in the lines.
8. Roll the drogue parachute.
9. Fold the parachute in half so 2 opposite squares are on one another.
10. Fold the remaining 2 squares under the top and create a point in the center of the parachute.
11. Bring the lines together and lay them running up along the right 3rd line of the chute so the swivel is at the top.
12. Fold the left 3rd of the chute over the lines, only 1-2" of the lines should be exposed out the bottom.
13. Tightly roll the drogue parachute from the top until it is bundled.
14. Wrap the bundle with masking masking tap to secure it and label the tape "Drogue".

The second item to pack is the Main Parachute. It is necessary to follow all theses steps to avoid failure.

1. Lay out the main parachute on a flat surface and ensure the parachute lines are below the main parachute.
2. Gather the sets of lines and position some in the middle, some to the left, and the others to the right.

3. Wrap tape around each set of lines to make sure they stay together.
4. Flatten the canopy as much as possible by removing the air from it.
5. Fold the right side of the canopy in half by taking the furthest edge of the outside and folding it onto the center line.
6. Repeat the previous step but for the other side.
7. Fold the canopy in half along the center line.
8. Ensure the canopy is folded into a rectangular shape.
9. Pack the folded canopy into the deployment bag with the shock chord facing out by compressing it until it fits.
10. Take all the lines and fold them over the deployment bag. Then, double back the lines to the bottom of the bag, and guide the folded section through the bands of on bag.
11. Repeat the previous step for each section of bands.
12. Fold the deployment bag flap over the parachute lines. Take masking tape and tape the bag shut.
13. Ensure all masking tape is removed before launch.

The recovery procedure is the Fore Altimeter Bay. It is necessary to follow all theses steps to avoid failure. This process does involve black powder, which should be kept separate from any ignition or heat sources.

1. Test 9 V batteries to make sure both are fully charged.
2. Place batteries into their cases.
3. Double check to make sure batteries are secured.
4. Test all connections with multimeter.
5. Turn on altimeters and listen to the beeps to make sure connections are good.
6. Insert charge leads through fore ejection pressure seal.
7. Cut extra leads leaving approximately 2 inches to connect to.
8. Insert the leads into the appropriate altimeter terminals.
9. Secure the leads by tightening the terminal screws.
10. Insert black powder into fore blast cup.
11. Insert a small amount of dog barf into the blast cup as well.
12. Cover blast cup with masking tape and ensure that no black powder spills out.
13. Repeat the previous three steps for loading the aft blast cup.
14. Secure the the bay by placing both bulkheads on each side of the bay.
15. Fasten down the bulkheads with the nuts and make sure it is tightly secured.

Once all of these steps are complete all recovery systems on the rocket will be ready for flight.

7.6 LANDING

1. Ensure 10000mAh LiPo is fully charged.
2. Ensure Raspberry Pi Power Pack is fully charged.
3. Ensure 3 9V batteries are fully charged.
4. Restrain the LiPo into the Droney using Velcro wraps .
5. Place 9V Batteries into their secure containers.
6. Secure Raspberry Pi Power Pack into Payload Bay.
7. Connect LiPo to the "MV" Raspberry Pi.
8. Connect Raspberry Pi Power Pack to "LV" Raspberry Pi.
9. Load Droney into the Launch vehicle.
10. Connect all Raspberry Pi’s to wireless network.
11. Test communication speed quality.
12. Ensure all GPS on board are working properly.
13. Using the ground station lock down Droney with the retention system.
14. Visually check that all servos have latched over the drone legs.

After the completion of all of these steps the Mission Vehicle is properly prepared a successful mission, and is ready for the launch pad.

8 PROJECT PLAN

8.1 REQUIREMENTS COMPLIANCE

To ensure compliance with all requirements for USLI, ARC maintains a project requirements compliance plan. All USLI requirements and methods of compliance are listed in Tables 8.1-8.3. All requirement numbers highlighted in green have been met, and all requirements in yellow are on schedule to be met during the full-scale build phase, through testing and analysis, or during the remaining period before launch day. The requirements highlighted in orange are significantly behind schedule, and emphasis will be given to these items. Requirement 1.5 (200 STEM participants engaged) is a high priority because the team did not deliver the reports from the first outreach event of the year in time for them to be considered. Several STEM outreach events are approaching, and the documentation will be submitted for these events. Requirement 2.17 (subscale launch) was granted an extension by USLI management due to the failure of the initial flight. A new subscale vehicle will be constructed, and the cause of the previous failure (friction-held altimeter battery disconnecting) will be rectified in the new vehicle.

Requirement No.	Requirement Description	Compliance Method	Compliance Type
1.1	Students will do 100% of project and submit new work	Design of all-new vehicle, no faculty advisors involved in design/build except to intervene for safety reasons	Procedural
1.2	Provide/maintain project plan	Creation of project plan to be maintained throughout design process	Procedural
1.3	FN team members must be identified by PDR	N/A, no FN members on team	Procedural
1.4	Identification of team members attending launch week activities	Most active students will travel, student mentor will travel, no adult educators will travel	Procedural
1.5	At least 200 participants engaged in STEM outreach	Organization of several outreach events throughout academic year and submission of engagement reports	Procedural
1.6	Establishment of social media presence	Website, Instagram, and Facebook page have been established and are updated	Procedural
1.7	Email deliverables to project management by deadline	Complete all materials prior to due date and email ahead of time in case of issues sending	Procedural
1.8	Deliverables in PDF format	Save all deliverables in PDF format	Procedural
1.9	Provide detailed table of contents for all reports	Create table of contents for every report	Procedural
1.10	Include page no. on all report pages	Ensure page number is included on bottom of page	Procedural
1.11	Team will provide computer equipment for video teleconferences	Team has equipment for video teleconferences	Procedural
1.12	Teams required to use provided launch pads canted away from crowd	Team will use provided launch pads	Procedural
1.13	Each team must have a mentor	Team has student mentor	Procedural
2.1	Vehicle delivers payload to apogee between 3,500 and 5,500 AGL	Simulate vehicle trajectory and perform demonstration flights	Simulation, demonstration
2.2	Teams must identify target altitude at PDR	Altitude has been declared	Procedural
2.3	Vehicle will carry one commercial barometric altimeter	Altimeter will be installed	Procedural
2.4	Launch vehicle will be designed for recovery/reuse	Vehicle will be designed for reuse, team experience in reusing high powered rockets	Demonstration
2.5	LV will have no more than four independent sections	Vehicle has only two independent sections on descent and shoulder/coupler length requirements have been met	Design
2.6	Preparation for flight occurs within 2 hrs of start of window	Dress rehearsals (dry) and use of checklists	Procedural
2.7	Vehicle can remain launch ready for at least 2 hours	Long-duration idle tests	Test
2.8	Vehicle can be launched by standard 12 V DC firing system	Use of such a system on all flight tests	Demonstration
2.9	No additional circuitry or GSE required for launch	Such systems will not be used on the vehicle	Design, procedural
2.10	Vehicle will use a commercial solid motor using APCP which is declared by CDR	Such a motor will be used and declared in the CDR	Design, procedural
2.11	Launch vehicle must be single stage	Design will only use a single stage	Design
2.12	Total impulse will not exceed L-class	L-class motor will be used on the vehicle	Design
2.13	Pressure vessels will be RSO approved and meet specific criteria	N/A, no pressure vessels on vehicle	Design
2.14	Launch vehicle will have static stability margin of 2 at rail exit	Simulate vehicle launch and calculate vehicle stability during all flight phases	Simulation, analysis
2.15	Structural protuberances must be aft of burnout CoG	Fins will be mounted aft of the burnout CoG, which will be verified in simulations	Simulation, design, analysis
2.16	Launch vehicle will accelerate to at least 52 fps at rail exit	Simulate vehicle launch	Simulation
2.17	Teams must launch and recover a subscale model prior to CDR that is newly constructed, carries an altimeter, and resembles full scale vehicle	EXTENSION GRANTED - Will perform reflight of subscale at earliest available date	Demonstration

Table 8.1: The first third of the ARC project requirements compliance plan for the USLI competition.

Requirement No.	Requirement Description	Compliance Method	Compliance Type
2.18.1	Teams must perform a Vehicle Demonstration Flight prior to FRR in final flight configuration with newly constructed vehicle, launch day motor, and payload mass simulators	Vehicle will be constructed and flown as stipulated	Demonstration
2.18.2	Teams must perform a Payload Demonstration Flight prior to the deadline with same final rocket and final payload	Payload will be constructed and flown as stipulated	Demonstration
2.19	FRR addendum required for any team completing a Payload Demonstration flight or NASA-mandated Vehicle Demonstration Reflight following FRR submission	Such a report will be submitted by the deadline if required	Procedural
2.20	Team name and contact information will be on vehicle airframe and all separable components	Such information will be affixed to all independent components	Procedural
2.21	All LiPo batteries will be protected from impact, brightly colored, marked as a fire hazard, and easily distinguishable	LiPo batteries will be marked as stipulated	Procedural
2.22.1	Vehicle will not use forward canards	No canards included in design	Design
2.22.2	Vehicle will not use forward firing motors	No forward firing motors included in design	Design
2.22.3	Launch vehicle will not use motor expelling titanium sponges	Such a motor is not included in design	Design
2.22.4	Vehicle will not use hybrid motor	Vehicle uses a commercial solid motor	Design
2.22.5	Vehicle will not use a cluster of motors	Vehicle uses a single motor	Design
2.22.6	Vehicle will not use friction fitting for motors	Vehicle will use an epoxied motor mount and centering rings for motor attachment	Design
2.22.7	Vehicle will not exceed Mach 1 during flight	Simulate vehicle launch	Simulation
2.22.8	Ballast will not exceed 10% of total wet unballasted weight on pad	Weight verifications prior to flight, ballast will be ensured to conform to requirements	Design, procedural, analysis
2.22.9	Transmissions will not exceed 250 mW per transmitter	Power calculation for all transmitters aboard	Analysis
2.22.10	Transmissions will not create excessive interference	WiFi used for all primary communications, unique LoRa frequency declared for secondary telemetry	Design
2.22.11	Excessive/dense metal will not be used in construction	Primary construction materials are cardboard and balsa	Design
3.1	Recovery will be staged, with drogue deploying at apogee and main deploying at lower altitude	Such a recovery staging has been designed	Design
3.1.1	Main chute shall not deploy below 500 ft	Main staging occurs at 550 ft AGL	Procedural
3.1.2	Apogee event will not contain delay greater than 2 seconds	Primary apogee event is immediate, secondary (redundant) is at 1 second	Procedural, design
3.1.3	Motor ejection is not a permissible deployment	Motor will not be jettisoned and will land with LV	Design
3.2	Each team must perform a ground ejection test for both drogue and main chutes	Such tests will be conducted prior to subscale/full scale launches	Test
3.3	Each independent section of LV will have no greater than 75 ft-lbf of kinetic energy at landing	Kinetic energy calculation and simulation of all independent components	Simulation, analysis
3.4	Recovery system will contain redundant commercial altimeters	All altimeters are redundant	Design
3.5	Altimeters run from dedicated, commercially available batteries	Altimeter systems are fully independent and run from commercial batteries	Design
3.6	Altimeter arming will occur from dedicated exterior switches when vehicle is in launch configuration	Such switches are included in altimeter system design	Design
3.7	Each arming switch will be locked in the ON position for launch	Such switches will be purchased and implemented	Design
3.8	Recovery circuits will be fully independent of payload circuits	Recovery circuits are isolated from payload circuits	Design
3.9	Removable shear pins will be used for main and drogue parachute compartments	Shear pins will be used for both staging events	Design
3.10	Recovery area will be limited to 2,500 ft from launch pads	Simulation of downrange drift in various wind conditions	Simulation
3.11	Descent time will be limited to 90 seconds	Simulation of flight to verify descent time	Simulation
3.12	Electronic tracking devices must be equipped and active on independent sections that do not land with LV	Such devices are included in vehicle design	Design

Table 8.2: The second third of the ARC project requirements compliance plan for the USLI competition.

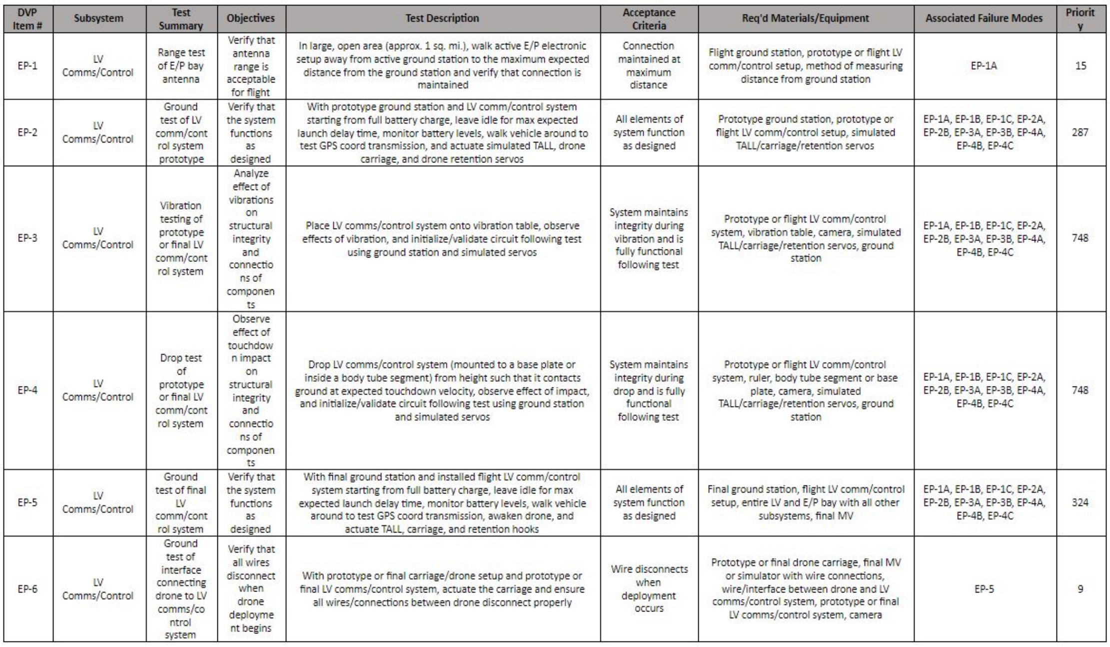
Requirement No.	Requirement Description	Compliance Method	Compliance Type
3.13.1	Recovery altimeters are located in separate compartment within vehicle from any transmitting/magnetic device	Avionics bay is physically isolated from all other systems	Design
3.13.2	Recovery electronics will be shielded from all onboard transmission devices	Avionics bay is physically isolated from all other systems	Design
3.13.3	Recovery electronics will be shielded from all onboard magnetic field generating devices	Avionics bay is physically isolated from all other systems	Design
3.13.4	Recovery electronics will be shielded from any other onboard devices affecting operation	Avionics bay is physically isolated from all other systems	Design
4.1	N/A: middle/high school teams		
4.2	Payload will launch/land safely in high powered rocket and recover simulated ice, with 1 additional experiment allowed	Payload will be designed to withstand flight loads and will not contain additional experiment	Design
4.3.1	Launch vehicle will launch from NASA-designated launch pad	NASA-designated pad will be used for launch	Procedural
4.3.2	Teams must recover sample from one of five recovery areas	Mission vehicle will recover sample from one of designated recovery sites	Procedural
4.3.3	Recovery sample will be at least 10 mL	Team design target is 150 mL, tests show collected amounts well in excess of this amount	Design, test
4.3.4	Sample must be stored and transported at least 10 ft from recovery area	Sample will be transported 10 ft or more from recovery location by air	Design, test
4.3.5	Teams must abide by all FAA and NAR rules/regulations	Regulations are kept on file and team members have agreed to abide by them	Procedural
4.3.6	Black powder and other energetics may only be used for in-flight recovery systems	Energetics are only included for in-flight recovery systems	Design
4.3.7.1	Mechanical system will retain payload to prevent premature deployment	Such a system has been designed	Design
4.3.7.2	Retention system will withstand flight forces	System will be tested and analyzed to ensure it will withstand flight loads	Test, analysis
4.4.1	Any element jettisoned during recovery will be given approval by RSO in real time to jettison	RSO permission will be given prior to release of mission vehicle after landing	Procedural
4.4.2	UAV payloads deployed during descent will be tethered with RC release mechanism until RSO clears release	Mission vehicle does not deploy during descent phase	Procedural
4.4.3	Teams flying UAVs will abide by applicable FAA regulations	Regulations are kept on file and team members have agreed to abide by them	Procedural
4.4.4	UAVs heavier than 0.55 lb will be registered with FAA and have registration number marked on vehicle	Mission vehicle will be weighed and registered with the FAA	Procedural
5.1	Launch/safety checklists will be used and included in FRR report and used in later events	Such checklists will be produced and utilized	Procedural
5.2	Student safety officer must be identified who will be responsible for section 5.3	Such a student has been identified	Procedural
5.3.1	Safety officer will monitor team activities with safety emphasis during design, construction, assembly, ground tests, subscale/full scale launches, launch day, recovery, and STEM engagement	Safety officer will monitor activities and ensure team leads also monitor activities	Procedural
5.3.2	Safety officer will implement safety procedures for construction, assembly, launch, and recovery activities	Safety officer has written team safety manual and will participate in creation of safety checklists	Procedural
5.3.3	Safety officer will manage and maintain current revisions of hazard/failure mode analyses, procedures, and chemical data	Safety officer maintains online depository of documents for team safety	Procedural
5.3.4	Safety officer will assist in writing/development of hazard analyses, failure mode analyses, and procedures	Safety officer has performed all DFMEAs/hazard analyses, written team safety manual, and will assist in creation of checklists	Procedural
5.4	Teams will comply with rules/guidance of local rocketry club RSOs at all launch sites	Team communicates with local rocketry club authorities and abides by regulations while at other launch sites	Procedural
5.5	Teams will abide by all FAA rules	Regulations are kept on file and team members have agreed to abide by them	Procedural

Table 8.3: The final third of the project requirements compliance plan for the USLI competition.

8.2 TESTING

8.2.1 LAUNCH VEHICLE COMMUNICATIONS TESTING

As listed in the DFMEA, there are six tests that will be conducted to prove integrity of the design, with objectives, success criteria, and methodology listed below.



DVP Item #	Subsystem	Test Summary	Objectives	Test Description	Acceptance Criteria	Req'd Materials/Equipment	Associated Failure Modes	Priority
EP-1	LV Comms/Control	Range test of E/P bay antenna	Verify that antenna range is acceptable for flight	In large, open area (approx. 1 sq. mi.), walk active E/P electronic setup away from active ground station to the maximum expected distance from the ground station and verify that connection is maintained	Connection maintained at maximum distance	Flight ground station, prototype or flight LV comm/control setup, method of measuring distance from ground station	EP-1A	15
EP-2	LV Comms/Control	Ground test of LV comm/control system prototype	Verify that the system functions as designed	With prototype ground station and LV comm/control system starting from full battery charge, leave idle for max expected launch delay time, monitor battery levels, walk vehicle around to test GPS coord transmission, and actuate simulated TALL, drone carriage, and drone retention servos	All elements of system function as designed	Prototype ground station, prototype or flight LV comm/control setup, simulated TALL/carriage/retention servos	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	287
EP-3	LV Comms/Control	Vibration testing of prototype or final LV comm/control system	Analyze effect of vibrations on structural integrity and connections of components	Place LV comms/control system onto vibration table, observe effects of vibration, and initialize/validate circuit following test using ground station and simulated servos	System maintains integrity during vibration and is fully functional following test	Prototype or flight LV comm/control system, vibration table, camera, simulated TALL/carriage/retention servos, ground station	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	748
EP-4	LV Comms/Control	Drop test of prototype or final LV comm/control system	Observe effect of touchdown impact on structural integrity and connections of components	Drop LV comms/control system (mounted to a base plate or inside a body tube segment) from height such that it contacts ground at expected touchdown velocity, observe effect of impact, and initialize/validate circuit following test using ground station and simulated servos	System maintains integrity during drop and is fully functional following test	Prototype or flight LV comm/control system, ruler, body tube segment or base plate, camera, simulated TALL/carriage/retention servos, ground station	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	748
EP-5	LV Comms/Control	Ground test of final LV comm/control system	Verify that the system functions as designed	With final ground station and installed flight LV comm/control system starting from full battery charge, leave idle for max expected launch delay time, monitor battery levels, walk vehicle around to test GPS coord transmission, awaken drone, and actuate TALL, carriage, and retention hooks	All elements of system function as designed	Final ground station, flight LV comm/control setup, entire LV and E/P bay with all other subsystems, final MV	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	324
EP-6	LV Comms/Control	Ground test of interface connecting drone to LV comms/control system	Verify that all wires disconnect when drone deployment begins	With prototype or final carriage/drone setup and prototype or final LV comms/control system, actuate the carriage and ensure all wires/connections between drone disconnect properly	Wire disconnects when deployment occurs	Prototype or final drone carriage, final MV or simulator with wire connections, wire/interface between drone and LV comms/control system, prototype or final LV comms/control system, camera	EP-5	9

Figure 8.1: DFMEA Table with Respect to the LV Communications and Control System

EP-1:

This test observes the maximum range of the electronics/payload bay antenna. The test will verify that the ground station and the launch vehicle will remain connected through their communication systems. If the antenna fails the test for the expected maximum distance between the ground station and the launch vehicle, then a new antenna will be needed.

EP-2:

This test observes the endurance of the batteries. It will look to make sure that the system's batteries can withstand a max launch delay time and still have enough charge to operate mission-critical systems. If the batteries run out of charge before the maximum time delay is reached, the battery system will need to be modified to allow for longer endurance.

EP-3:

This test observes the effects of vibrations on the connections and the hardware of the LV communications system. The test simulates the conditions of vibrations during the launch. These conditions must be accounted for in the system design to maximize the chance of success for the communications system. If the results of the test give any reason to worry about the effectiveness of the communications system, vibration protection will need to be potentially added.

EP-4:

This test observes the effects of simulated touch down forces. Structural integrity of electrical connections, electrical components, and system functionality, and data transfer capabilities will be inspected. If any faults are found, necessary structural reinforcements will be made.

EP-5:

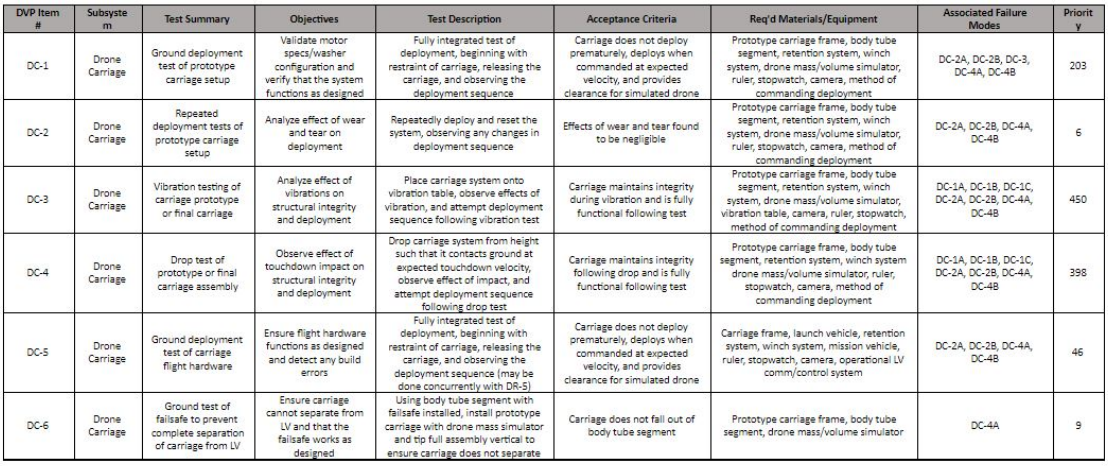
This test is to simulate the rocket remaining at standby on the launch pad. This test will observe the operational functionality of the system and power source after several hours. Specifically, the system must be able to send and receive data at an optimal level after remaining active for at least two (2) hours. If performance is negatively affected by time delay then additional power supply arrays will be added.

EP-6:

This test observes the proper disconnection of the drone from the launch vehicle. Tests would allow effects of pulling a cord out of a port on the drone as carriage is withdrawn to be observed. A proper disconnection would include no electrical component damage and the ability to reuse the cord to send data. If there is any concern about the integrity of the drone connection port, wire, or LV connection port, the wires and connections will be inspected for proper solder connections and wire integrity. Any necessary changes will be made to ensure proper operation.

8.2.2 Payload Withdrawal System

As listed in the DFMEA, there are six tests that will be conducted to prove the integrity of the design, with objectives, success criteria, and methodology listed below.



DVP Item #	Subsystem	Test Summary	Objectives	Test Description	Acceptance Criteria	Req'd Materials/Equipment	Associated Failure Modes	Priority
DC-1	Drone Carriage	Ground deployment test of prototype carriage setup	Validate motor specs/washer configuration and verify that the system functions as designed	Fully integrated test of deployment, beginning with restraint of carriage, releasing the carriage, and observing the deployment sequence	Carriage does not deploy prematurely, deploys when commanded at expected velocity, and provides clearance for simulated drone	Prototype carriage frame, body tube segment, retention system, winch system, drone mass/volume simulator, ruler, stopwatch, camera, method of commanding deployment	DC-2A, DC-2B, DC-3, DC-4A, DC-4B	203
DC-2	Drone Carriage	Repeated deployment tests of prototype carriage setup	Analyze effect of wear and tear on deployment	Repeatedly deploy and reset the system, observing any changes in deployment sequence	Effects of wear and tear found to be negligible	Prototype carriage frame, body tube segment, retention system, winch system, drone mass/volume simulator, ruler, stopwatch, camera, method of commanding deployment	DC-2A, DC-2B, DC-4A, DC-4B	6
DC-3	Drone Carriage	Vibration testing of carriage prototype or final carriage	Analyze effect of vibrations on structural integrity and deployment	Place carriage system onto vibration table, observe effects of vibration, and attempt deployment sequence following vibration test	Carriage maintains integrity during vibration and is fully functional following test	Prototype carriage frame, body tube segment, retention system, winch system, drone mass/volume simulator, vibration table, camera, ruler, stopwatch, method of commanding deployment	DC-1A, DC-1B, DC-1C, DC-2A, DC-2B, DC-4A, DC-4B	450
DC-4	Drone Carriage	Drop test of prototype or final carriage assembly	Observe effect of touchdown impact on structural integrity and deployment	Drop carriage system from height such that it contacts ground at expected touchdown velocity, observe effect of impact, and attempt deployment sequence following drop test	Carriage maintains integrity following drop and is fully functional following test	Prototype carriage frame, body tube segment, retention system, winch system drone mass/volume simulator, ruler, stopwatch, camera, method of commanding deployment	DC-1A, DC-1B, DC-1C, DC-2A, DC-2B, DC-4A, DC-4B	398
DC-5	Drone Carriage	Ground deployment test of carriage flight hardware	Ensure flight hardware functions as designed and detect any build errors	Fully integrated test of deployment, beginning with restraint of carriage, releasing the carriage, and observing the deployment sequence (may be done concurrently with DR-5)	Carriage does not deploy prematurely, deploys when commanded at expected velocity, and provides clearance for simulated drone	Carriage frame, launch vehicle, retention system, winch system, mission vehicle, ruler, stopwatch, camera, operational LV comm/control system	DC-2A, DC-2B, DC-4A, DC-4B	46
DC-6	Drone Carriage	Ground test of failsafe to prevent complete separation of carriage from LV	Ensure carriage cannot separate from LV and that the failsafe works as designed	Using body tube segment with failsafe installed, install prototype carriage with drone mass simulator and tip full assembly vertical to ensure carriage does not separate	Carriage does not fall out of body tube segment	Prototype carriage frame, body tube segment, drone mass/volume simulator	DC-4A	9

Figure 8.2: DFMEA Table with Respect to the Payload Withdrawal System

DC-1:

This test observes the legitimacy of the design as a whole and its effectiveness to perform its intended goal of payload withdrawal and proper retention. Without verification of this test, the system could potentially not complete its goals during and after launch. This test will be done with a full scale prototype with all designed components. The test will be performed in a rocket body housing tube and all flight connections and mounts will be present. Depending on the results of this test, the payload withdrawal system design might be altered to better achieve its goal.

DC-2:

This test observes the effect of repeated uses on the payload withdrawal system and its ability to function. Tests would allow for confirmation that the motor, servo, and connection line can withstand multiple uses without wear and tear affecting performance. This test will be done with a full scale prototype using all designed components. If there is any cause for concern from this test, then the connection line can be replaced with a stronger or more durable line and/or the design might change to better accommodate the abilities of the electronics.

DC-3:

This test observes the effect of vibrations on the system. Similar to DR-2, repeated tests would occur after a period of shaking the payload withdrawal system. Tests would allow for confirmation that the motor, servo, and restraint latch can withstand multiple uses without shaking of the system affecting performance. This test will be done with a full scale prototype using all designed components, proper flight connections, and mountings in the rocket body housing. If there is any cause for concern stemming from these tests, vibration protection options will be explored.

DC-4:

This test observes the effect of dropping the payload withdrawal system at the expected touchdown velocity. The primary objective is to notice how the carriage retention latch and carriage track withstand the force of landing. Any sign of fracture or bending would justify a stronger material for the latch or a more reinforced carriage track. Secondary objective is to see if there is any shift or breakage in other areas of the system that need to be addressed. This test will be done with a full scale prototype using all designed components, proper flight connections and mountings in the rocket body housing.

DC-5:

This test is a fully integrated test that will be completed before complete satisfaction in the design of the payload withdrawal system is confirmed. The test will use flight materials and systems simulating a real launch; these conditions are key to understanding if the payload withdrawal system works in conjunction with other systems. Standardized masses will be used to apply static weights and jerk forces. Each component will be observed and verified that it has not caused any damage to the rocket or system structural integrity. The results of this test would determine if there are any last-minute changes that must be made to the system for success. This test can be performed with a sub-scale model that interfaces with all full scale hardware and electronics.

DC-6:

This test observes the safety of the the payload withdrawal system if it were tilted in an angle below horizontal after landing or if the payload retention system were to fail in flight. This test can be performed using a full scale model and simulated payload mass attached to a full scale drone carriage. The test system will be turned vertical and the drone carriage and attached shock cord will be inspected for signs of damage. If there is any concern for the safety of the payload or possibility that the payload could eject at any point of the flight regardless of the retention system, the design will be altered to keep the payload and personnel safe.

Completed Tests:

Initially, an uphill pull strength test was conducted. This test was to simulate the material friction and possible body orientations upon landing and to see how the motor can handle these conditions. A sine bar was created from PVC pipe to elevate one end of the test track. A test sled was also created with PVC pipe tracks to help simulate the friction between the PVC inlaid drone carriage and the Bluetube. The stepper motor was controlled with an Arduino UNO micro-controller and driven with an A4988 stepper driver. The Arduino UNO was used because the test operator was more experienced with the operation of that micro-controller opposed to the Raspberry Pi Zero W. This difference should cause no variance in the operation of the motor because power distribution and control is handled by the A4988 stepper driver. Standardized masses were added to the test carriage and the motor was operated to see if it could pull the weighted carriage up the inclined test track.

Spool Diameter	1.005 in
Test Sled Mass	0.46164798 lbm
Test Bag Mass	0.09656247 lbm

Table 8.4: Known Initial Values

Angle	2.6662706 lbm	3.10719512 lbm	3.76858191 lbm	4.20950643 lbm
0 deg	Full Operation	Full Operation	Full Operation	Full Operation
5 deg	Full Operation	Full Operation	Full Operation	Full Operation
15 deg	Full Operation	Full Operation	Full Operation	Failure, Over Torque
25 deg	Full Operation	Full Operation	Failure, Over Torque	Failure, Over Torque
35 deg	Full Operation	Failure, Partial Over Torque	Failure, Over Torque	Failure, Over Torque
45 deg	Full Operation	Failure, Over Torque	Failure, Over Torque	Failure, Over Torque

Table 8.5: Uphill Testing Results - 2 Unit Battery Array

Angle	2.6662706 lbm	3.10719512 lbm	3.76858191 lbm	4.20950643 lbm
0 deg	Full Operation	Full Operation	Full Operation	Full Operation
5 deg	Full Operation	Full Operation	Full Operation	Full Operation
15 deg	Full Operation	Full Operation	Full Operation	Full Operation
25 deg	Full Operation	Full Operation	Full Operation	Failure, Over Torque
35 deg	Full Operation	Full Operation	Failure, Over Torque	Failure, Over Torque
45 deg	Full Operation	Failure, Over Torque	Failure, Over Torque	Failure, Over Torque

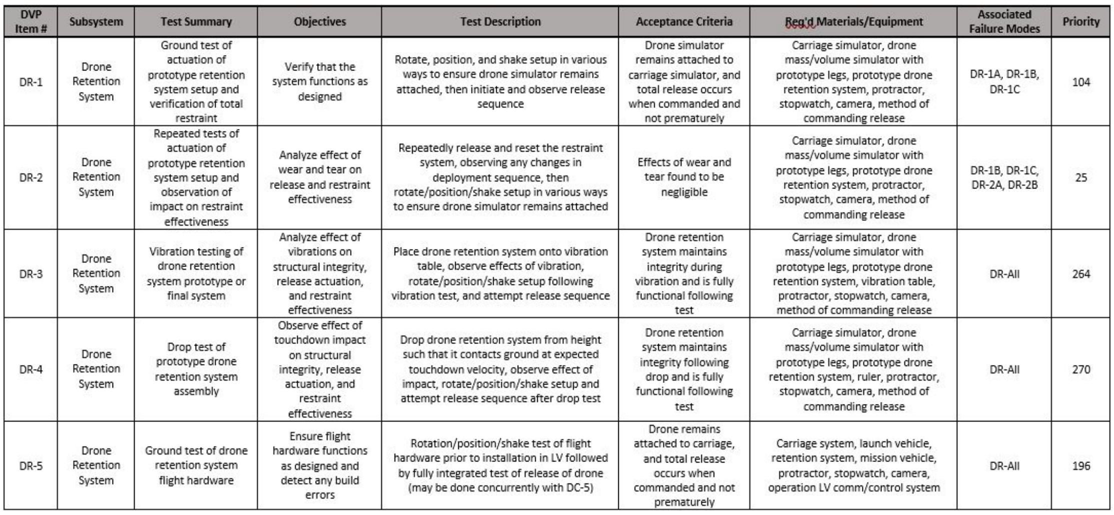
Table 8.6: Uphill Testing Results - 3 Unit Battery Array

Masses were converted from kilograms because available standardized masses were in kilograms. Mass ranges were chosen to test possible masses of drone and drone carriage. This test was completed using a created sine bar and track along with a created test carriage. The carriage was given PVC treads to help simulate the friction between the rocket body and PVC inserts designed for the drone carriage. The test carriage was also fitted with a snatch block system using wire guides similar to the designed drone carriage. The physical testing was carried out using an Arduino UNO, A4988 stepper driver, Nema 17 stepper motor, and a bread board to easily alter the battery array. During testing, the motor was held against the end of the track in the same location to help isolate the test system from outside forces. The motor was run, and observed to see if it could pull the test carriage and masses up the slope with out over-torquing itself.

From the results in *Table 8.2* and *Table 8.3*, it can be seen that the 3 battery array provides more reliable performance. For this reason the 3 battery array will be used to power the winch system on the final system.

8.2.3 PAYLOAD RETENTION SYSTEM

As listed in the DFMEA, there are five tests that should be conducted to prove the integrity of the design, with objectives, success criteria, and methodology listed below.



DVP Item #	Subsystem	Test Summary	Objectives	Test Description	Acceptance Criteria	Req'd Materials/Equipment	Associated Failure Modes	Priority
DR-1	Drone Retention System	Ground test of actuation of prototype retention system setup and verification of total restraint	Verify that the system functions as designed	Rotate, position, and shake setup in various ways to ensure drone simulator remains attached, then initiate and observe release sequence	Drone simulator remains attached to carriage simulator, and total release occurs when commanded and not prematurely	Carriage simulator, drone mass/volume simulator with prototype legs, prototype drone retention system, protractor, stopwatch, camera, method of commanding release	DR-1A, DR-1B, DR-1C	104
DR-2	Drone Retention System	Repeated tests of actuation of prototype retention system setup and observation of impact on restraint effectiveness	Analyze effect of wear and tear on release and restraint effectiveness	Repeatedly release and reset the restraint system, observing any changes in deployment sequence, then rotate/position/shake setup in various ways to ensure drone simulator remains attached	Effects of wear and tear found to be negligible	Carriage simulator, drone mass/volume simulator with prototype legs, prototype drone retention system, protractor, stopwatch, camera, method of commanding release	DR-1B, DR-1C, DR-2A, DR-2B	25
DR-3	Drone Retention System	Vibration testing of drone retention system prototype or final system	Analyze effect of vibrations on structural integrity, release actuation, and restraint effectiveness	Place drone retention system onto vibration table, observe effects of vibration, rotate/position/shake setup following vibration test, and attempt release sequence	Drone retention system maintains integrity during vibration and is fully functional following test	Carriage simulator, drone mass/volume simulator with prototype legs, prototype drone retention system, vibration table, protractor, stopwatch, camera, method of commanding release	DR-All	264
DR-4	Drone Retention System	Drop test of prototype drone retention system assembly	Observe effect of touchdown impact on structural integrity, release actuation, and restraint effectiveness	Drop drone retention system from height such that it contacts ground at expected touchdown velocity, observe effect of impact, rotate/position/shake setup and attempt release sequence after drop test	Drone retention system maintains integrity following drop and is fully functional following test	Carriage simulator, drone mass/volume simulator with prototype legs, prototype drone retention system, ruler, protractor, stopwatch, camera, method of commanding release	DR-All	270
DR-5	Drone Retention System	Ground test of drone retention system flight hardware	Ensure flight hardware functions as designed and detect any build errors	Rotation/position/shake test of flight hardware prior to installation in LV followed by fully integrated test of release of drone (may be done concurrently with DC-5)	Drone remains attached to carriage, and total release occurs when commanded and not prematurely	Carriage system, launch vehicle, retention system, mission vehicle, protractor, stopwatch, camera, operation LV comm/control system	DR-All	196

Figure 8.3: DFMEA Table with Respect to the Payload Retention System

DR-1:

This test observed the legitimacy of the design as a whole and its effectiveness to perform its intended retention goal. Without verification of this test, the system could potentially not complete its goals during launch. Experimental setup includes putting the drone and carriage in conditions such as holding them upside down, pulling on the drone, moving the drone from side to side, and rotating the drone body. Afterwards the release sequence was activated to confirm that the system works. Depending on the results of this test, the payload retention system design might be altered or completely changed to better achieve its goal.

DR-2:

This test observed the effect of repeated uses on the payload retention system and its ability to function. Tests would allow for confirmation that the servos and retention latches can withstand multiple uses without wear and tear affecting performance. Experimental setup included repeatedly activating and resetting the retention system. If there is any cause for worry stemming from these tests, then the retention latches will be made with stronger material and/or the servos will be replaced with ones that can handle larger loads.

DR-3:

This test observed the effect of vibrations on the system. Similar to DR-2, repeated tests would occur after a period of shaking the payload retention system. Testing allowed for confirmation that the servos and retention latches can withstand multiple uses without vibration affecting performance. Experimental setup included putting the payload retention assembly on a vibration table and recording any changes to the system. Then, the retention assembly was put in conditions such as holding it upside down, pulling on the drone, moving the drone body from side to side, and rotating the drone body. Afterwards the release sequence was activated and it was confirmed that the system works. If there is any cause for worry stemming from these tests, then the retention latches will be made with stronger material and/or the servos will be replaced with ones that can handle larger loads.

DR-4:

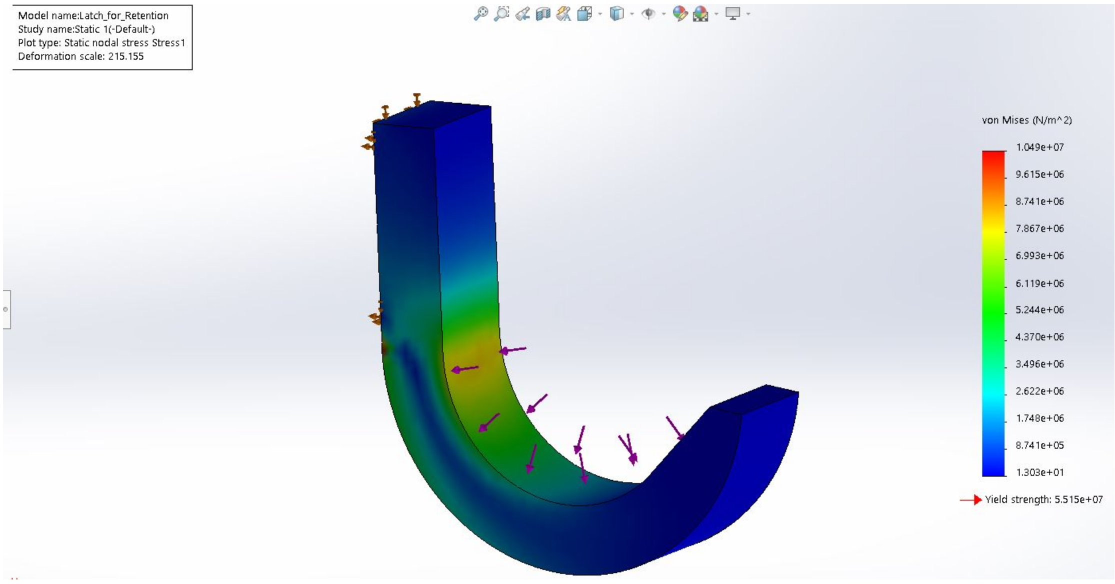
This test observed the effect of dropping the payload retention system at the expected touchdown velocity. The primary objective was to notice how the retention latch material holds during the drop. The experimental setup included dropping the payload retention assembly from a height such that it has the expected touchdown velocity. The retention assembly was put in various conditions such as holding it upside down, pulling on the drone, moving the drone body from side to side, and rotating the drone body. Afterward, the release sequence was activated to confirm that the system works. Any sign of fracture is a sign for concern, and would justify a stronger material for the retention latches.

DR-5:

This test is the final test that would be completed before obtaining complete satisfaction in the design of the payload retention system. The test would have actual materials and systems that would be used in the launch, simulating a real launch; these conditions are key to understanding if the payload retention system works in conjunction with other systems. Experimental setup includes shaking flight hardware and initiating the release sequence, observing any changes. Then, hardware would be installed into the LV, all systems involved with payload vehicle deployment would be assembled, and the system would be run through the entire deployment procedure. The results of this test would determine if there are any last-minute changes that must be made to the system for success.

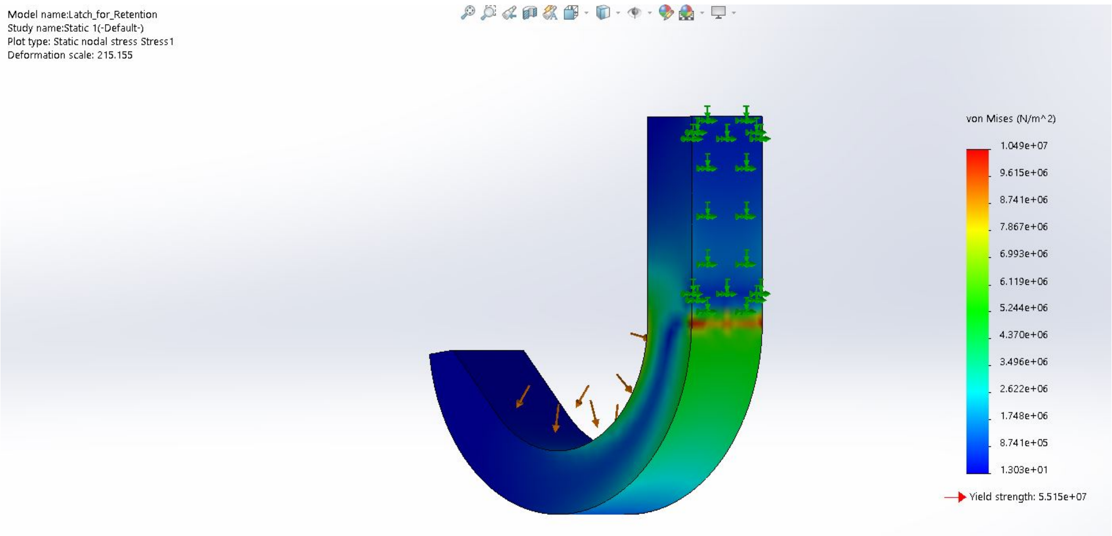
Completed Tests:

Two simulations were conducted in Solidworks before testing the retention latches. These simulations tested the static strength of the retention latches and the potential deformation due to buckling. The static simulation had conditions such that a force of 10 N, or 2.24809 lbf, was applied at the inside of the bend and the shank was fixed. The simulation gave a Von Mises distribution over the retention latch, along with a total yield strength. The results of this simulation allowed us to see what parts of the retention latch might falter due to the force applied.



Model name:Latch_for_Retention
Study name:Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 215.155

Figure 8.4: Forward View of SolidWorks Static Simulation



Model name:Latch_for_Retention
Study name:Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 215.155

Figure 8.5: Back View of SolidWorks Static Simulation

The buckling simulation had similar conditions to that of the static simulation. The simulation gave an Amperes distribution over the latch. When multiplied with the load applied, which was 10 N or 2.24809 lbf, this gave the force that the particular point on the latch could withstand before potentially deforming. The results of this simulation allowed us to see what parts of the retention latch might falter due to the sudden force applied, particularly at the meeting point of the bend and shank.

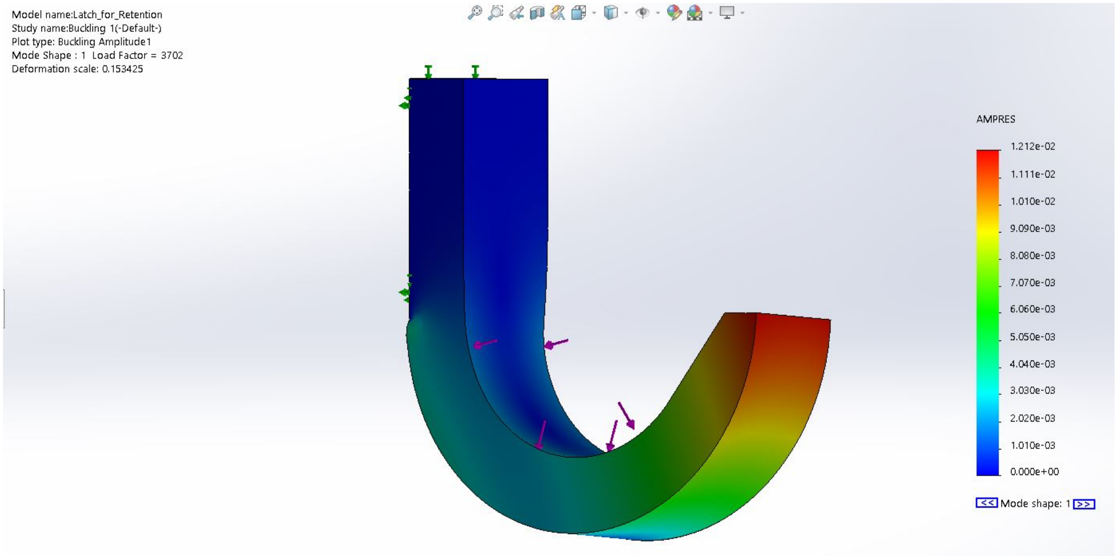

Model name:Latch_for_Retention
Study name:Buckling 1(-Default-)
Plot type: Buckling Amplitude1
Mode Shape : 1 Load Factor = 3702
Deformation scale: 0.153425

Figure 8.6: Front View of SolidWorks Buckling Simulation

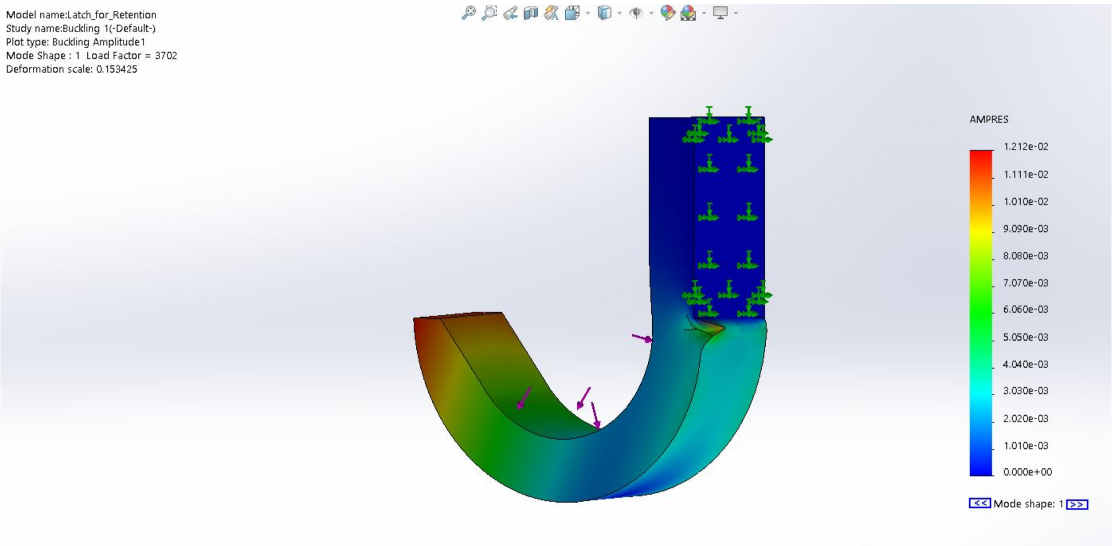

Model name:Latch_for_Retention
Study name:Buckling 1(-Default-)
Plot type: Buckling Amplitude1
Mode Shape : 1 Load Factor = 3702
Deformation scale: 0.153425

Figure 8.7: Back View of SolidWorks Buckling Simulation

Two tests were completed on the retention latches involving the static strength of the retention latches and how buckling affected the retention latches. The static testing involved fastening the retention latch to a vertical surface using epoxy, hanging masses that were tied to a connection wire on the retention latch, and observing any changes to the retention latch such as deformation or fracturing. Increments of approximately 0.551156 lb or 250 g were used; these weights were used because they are similar to the expected weight of the payload vehicle. A bag, weighing in at 0.096 lb or 43.4 g, was used for the 2.765 lbs and subsequent mass tests to better hold the individual masses. Non-standardized weights were used starting at 4.919 lb. All masses used had no observable changes on the retention latch, indicating a successful test and excellent static strength.

Mass Used (grams)	Mass Used (lbs)	Results
250	0.551156	Holds
500	1.10231	Holds
753.3	1.6607422	Holds
1000	2.20462	Holds
1254	2.764597	Holds
1504	3.315752	Holds
1754	3.866908	Holds
2004	4.418064	Holds
2231	4.918513	Holds
2469	5.443213	Holds
2706	5.965709	Holds
2946	6.494818	Holds

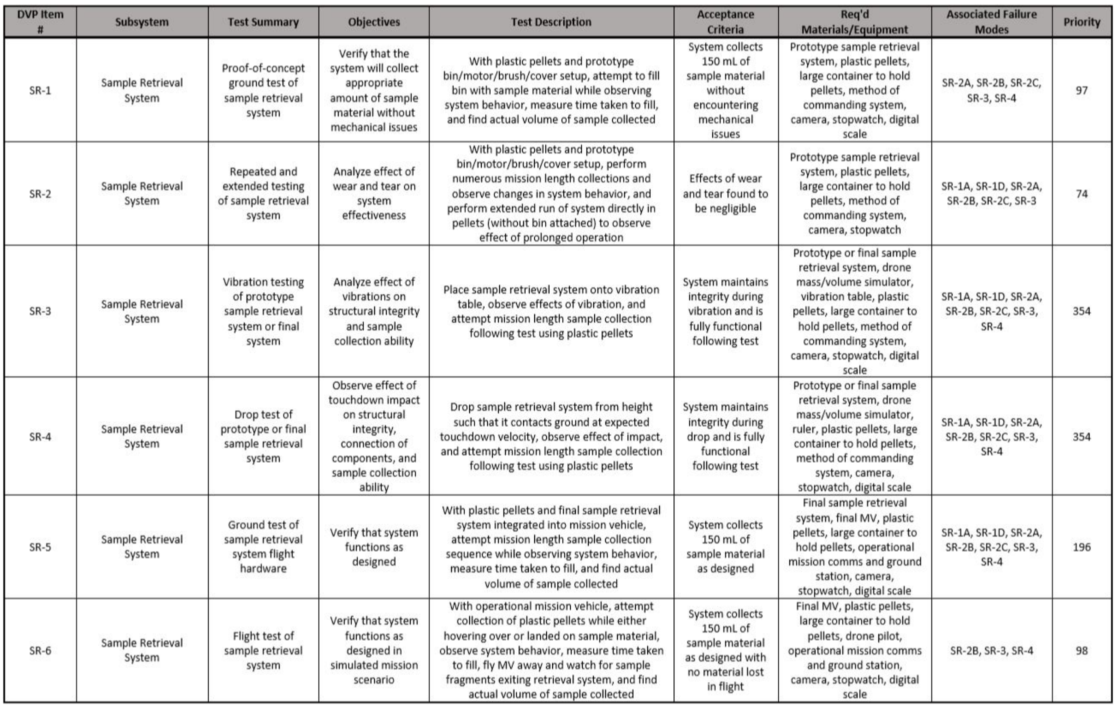
Table 8.7: Static Testing Results

The buckling testing involved fastening the retention latch to a vertical surface, hanging masses that were tied to a connection wire on the latch, lifting the mass two inches above the full extension of the connection wire, releasing, and observing any changes to the retention latch such as deformation or fracturing. The latch broke at both 1.198 lb and 1.653 lb at the meeting point of the bend and shank; as predicted by the buckling simulation. After the results were taken from testing, it was decided that the retention latches needed to be made of a material stronger and more consistent than wood. Aluminum alloy 6061 was chosen as the next best alternative, as it offered the next best material strength-to-weight ratio.

Mass Used (grams)	Mass Used (lbs)	Results
250	0.551156	Holds
500	1.10231	Holds
543.4	1.1979919	Breaks
750	1.65347	Breaks

Table 8.8: Buckling Testing Results

8.2.4 PAYLOAD OBJECTIVE SYSTEM



DVP Item #	Subsystem	Test Summary	Objectives	Test Description	Acceptance Criteria	Req'd Materials/Equipment	Associated Failure Modes	Priority
SR-1	Sample Retrieval System	Proof-of-concept ground test of sample retrieval system	Verify that the system will collect appropriate amount of sample material without mechanical issues	With plastic pellets and prototype bin/motor/brush/cover setup, attempt to fill bin with sample material while observing system behavior, measure time taken to fill, and find actual volume of sample collected	System collects 150 mL of sample material without encountering mechanical issues	Prototype sample retrieval system, plastic pellets, large container to hold pellets, method of commanding system, camera, stopwatch, digital scale	SR-2A, SR-2B, SR-2C, SR-3, SR-4	97
SR-2	Sample Retrieval System	Repeated and extended testing of sample retrieval system	Analyze effect of wear and tear on system effectiveness	With plastic pellets and prototype bin/motor/brush/cover setup, perform numerous mission length collections and observe changes in system behavior, and perform extended run of system directly in pellets (without bin attached) to observe effect of prolonged operation	Effects of wear and tear found to be negligible	Prototype sample retrieval system, plastic pellets, large container to hold pellets, method of commanding system, camera, stopwatch	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3	74
SR-3	Sample Retrieval System	Vibration testing of prototype sample retrieval system or final system	Analyze effect of vibrations on structural integrity and sample collection ability	Place sample retrieval system onto vibration table, observe effects of vibration, and attempt mission length sample collection following test using plastic pellets	System maintains integrity during vibration and is fully functional following test	Prototype or final sample retrieval system, drone mass/volume simulator, vibration table, plastic pellets, large container to hold pellets, method of commanding system, camera, stopwatch, digital scale	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3, SR-4	354
SR-4	Sample Retrieval System	Drop test of prototype or final sample retrieval system	Observe effect of touchdown impact on structural integrity, connection of components, and sample collection ability	Drop sample retrieval system from height such that it contacts ground at expected touchdown velocity, observe effect of impact, and attempt mission length sample collection following test using plastic pellets	System maintains integrity during drop and is fully functional following test	Prototype or final sample retrieval system, drone mass/volume simulator, ruler, plastic pellets, large container to hold pellets, method of commanding system, camera, stopwatch, digital scale	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3, SR-4	354
SR-5	Sample Retrieval System	Ground test of sample retrieval system flight hardware	Verify that system functions as designed	With plastic pellets and final sample retrieval system integrated into mission vehicle, attempt mission length sample collection sequence while observing system behavior, measure time taken to fill, and find actual volume of sample collected	System collects 150 mL of sample material as designed	Final sample retrieval system, final MV, plastic pellets, large container to hold pellets, operational mission comms and ground station, camera, stopwatch, digital scale	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3, SR-4	196
SR-6	Sample Retrieval System	Flight test of sample retrieval system	Verify that system functions as designed in simulated mission scenario	With operational mission vehicle, attempt collection of plastic pellets while either hovering over or landed on sample material, observe system behavior, measure time taken to fill, fly MV away and watch for sample fragments exiting retrieval system, and find actual volume of sample collected	System collects 150 mL of sample material as designed with no material lost in flight	Final MV, plastic pellets, large container to hold pellets, drone pilot, operational mission comms and ground station, camera, stopwatch, digital scale	SR-2B, SR-3, SR-4	98

Figure 8.8: Payload Objective System DFMEA Table

SR-1:

This test observes the legitimacy of the design and verifies that the design performs as intended. This test is crucial because all other testing would be wasted if the final product doesn't even perform the mission. The setup for this experiment will include having a container with a layer of black tinted PLA plastic pellets that will be used for the ice simulation. The prototype will be placed within the container and be turned on. The prototype will be allowed to run for a determined amount of time while a camera films the process to analyze. The system will be turned off and the sample collected will be measured. The results of this test could effect the design of the objective system, prompting a full redesign or subtle changes to affect performance.

SR-2:

This test observes the effects of repeated use on the payload objective system. This will allow for confirmation that all of the components of the system can withstand multiple uses without loss of performance. This will be done using the constructed prototype, which will include the storage bin, spinning brush, and motor. This test will be simmilar to SR-1, however it will run multiple times for longer duration. Depending on results from this test different components might need to be selected or redesigned.

SR-3:

This test observes the effects of vibrations that the system could expect to encounter anytime during the mission. This test will verify that the system can withstand vibrations associated with the mission. If any component causes concern after repeated vibrations the component may need to be redesigned or vibration protection could be implemented.

SR-4:

This test observes the effects of dropping the system at expected touchdown velocity. This test will verify that the system and the components maintain integrity and perform as expected; even after an expected touchdown impact. This test will include the prototype system and simulated weight from the rest of the payload being dropped from a certain height. Depending on results from this test different components might need to be selected or redesigned.

SR-5:

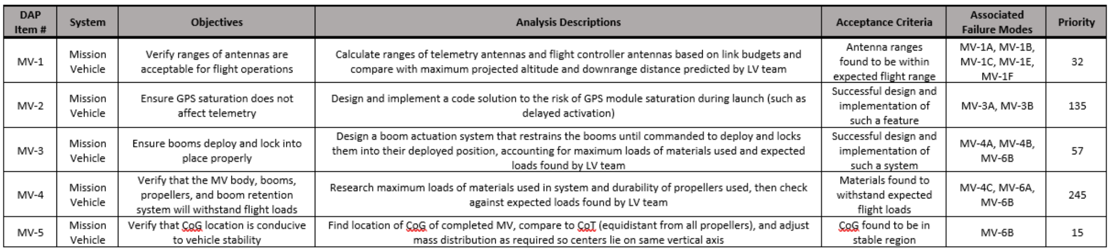
This test is a fully integrated test for all of the payload vehicle. This test will verify proper communication with the system and the entire payload. The results would most likely affect coding and communication the most, however small efficiency changes may need to be made on the system.

SR-6:

This test is a fully integrated test that simulates a full mission that will complete testing of the objective system. This test will include the entire payload vehicle and will gather a simulated sample. This test will verify proper communication with the system and the entire payload, adequate battery storage, and prove no sample loss on transportation. The results of this test would determine small changes that could be made to improve efficiency or complete verification of the system.

8.2.5 MISSION VEHICLE BODY

As listed in the DFMEA, there are five tests that should be conducted to prove the integrity of the design, with objectives, success criteria, and methodology listed below.



DAP Item #	System	Objectives	Analysis Descriptions	Acceptance Criteria	Associated Failure Modes	Priority
MV-1	Mission Vehicle	Verify ranges of antennas are acceptable for flight operations	Calculate ranges of telemetry antennas and flight controller antennas based on link budgets and compare with maximum projected altitude and downrange distance predicted by LV team	Antenna ranges found to be within expected flight range	MV-1A, MV-1B, MV-1C, MV-1E, MV-1F	32
MV-2	Mission Vehicle	Ensure GPS saturation does not affect telemetry	Design and implement a code solution to the risk of GPS module saturation during launch (such as delayed activation)	Successful design and implementation of such a feature	MV-3A, MV-3B	135
MV-3	Mission Vehicle	Ensure booms deploy and lock into place properly	Design a boom actuation system that restrains the booms until commanded to deploy and locks them into their deployed position, accounting for maximum loads of materials used and expected loads found by LV team	Successful design and implementation of such a system	MV-4A, MV-4B, MV-6B	57
MV-4	Mission Vehicle	Verify that the MV body, booms, propellers, and boom retention system will withstand flight loads	Research maximum loads of materials used in system and durability of propellers used, then check against expected loads found by LV team	Materials found to withstand expected flight loads	MV-4C, MV-6A, MV-6B	245
MV-5	Mission Vehicle	Verify that CoG location is conducive to vehicle stability	Find location of CoG of completed MV, compare to CoT (equidistant from all propellers), and adjust mass distribution as required so centers lie on same vertical axis	CoG found to be in stable region	MV-6B	15

Figure 8.9: DFMEA Table with Respect to the Mission Vehicle Body

MV-1:

This test verifies that the ranges of antennas are acceptable for flight operations. Telemetry antennas and flight controller antennas based on link budgets are used to calculate ranges.

This is compared with maximum projected altitudes and downrange distance predicted by the LV team.

MV-2:

This test is to ensure that GPS saturation does not affect telemetry. A code solution will be designed and implemented to the risk of GPS module saturation during launch(such as delayed activation).

MV-3:

It must be ensured that the rotor booms deploy and are restrained properly. This test calls for the development of a boom actuation system that leaves said booms restrained until commanded, and keeps them locked in their deployed position. This must account for maximum loads of the build materials and loads expected by the LV team.

MV-4:

This test is the guarantee the MV body, booms, propellers, and boom retention system will withstand flight loads. The maximum loads of materials used in the system and propellers must be compared against expected loads founds by the LV team.

MV-5:

CoG location must be verified to be conducive to vehicle stability. Once the MV is completed, the CoG must be located and compared to the CoT(equidistant from all propellers). Mass distribution will need to be adjusted as required so centers lie on the same vertical axis.

8.2.6 DESIGN ANALYSIS PLAN

Per the findings of the DFMEA, several failure causes require calculations, research, simulation, or other forms of analysis to mitigate. These required analyses are tabulated in the Design Analysis Plan (DAP) shown in Table 8.6. A higher resolution version of the DAP can be found in the team DFMEA depository, which can be found at:

https://drive.google.com/drive/u/1/folders/1Kc8U2xoarTPptHXaBHjlSp58PHiyLw9K

The priority values given for each analysis are the sum of the risk priority numbers of all failure causes mitigated by the analysis or test. For example, the RPNs of every failure cause that is mitigated by analysis DC-1 are added to obtain the priority score of DC-1. This number serves to give subteam leads a general idea of what analyses and tests need to be prioritized.

DAP Item #	Subsystem	Objectives	Analysis Descriptions	Acceptance Criteria	Associated Failure Modes	Priority
DC-1	Drone Carriage	Verify carriage system materials will withstand flight loads	Research maximum loads of materials used in all system components and check against expected loads found by LV team	Materials found to withstand expected flight loads	DC-1A, DC-1C, DC-2B, DC-4A, DC-4B	201
DC-2	Drone Carriage	Verify washer configuration, retention bolt, and step motor selected will successfully deploy carriage	Determine magnitude of all forces on carriage (weight, friction, etc.) and find location of washers that ensures carriage will be able to oppose these forces during deployment	Parameters of motor and washers validated	DC-2A, DC-2B, DC-3, DC-4A, DC-4B	103
DC-3	Drone Carriage	Verify retention bolt and hook configuration selected will restrain carriage during flight	Using maximum loads of materials and expected loads found by LV team, verify that hook and bolt will restrain carriage, and validate using simulations if possible	Parameters of bolt and hook validated	DC-1B	80
DC-4	Drone Carriage	Design a physical barrier preventing carriage from completely exiting body (if not already completed)	Implement a design modification that limits how far the carriage can deploy	Successful design of such a feature	DC-4A	9
DC-5	Drone Carriage	Verify washer embedding method will withstand flight loads and preserve LV structural integrity	Research maximum loads of embedding material and, if possible, the effects of embedding using that material in the LV body material, then compare to expected loads found by LV team	Embedding design found to withstand flight loads and preserve structural integrity	DC-1C, DC-2B	54
DC-6	Drone Carriage	Design feature of winch reel that prevents it from moving freely when idle (if such a lock is not built into the step motor)	Implement a design modification that prevents the reel from freely spinning when not being powered	Successful design of such a feature	DC-1A	60
DR-1	Drone Retention System	Design restraint arrangement and verify hook materials will withstand flight loads	After determining locations of hooks, research maximum loads of materials used in system and calculated expected hook loads using expected flight loads found by LV team	Materials and hook arrangement found to withstand expected flight loads	DR-1A	81
DR-2	Drone Retention System	Design passive position locking system for servos and verify materials and setup will withstand flight loads	After designing mechanism to lock servos until commanded, research maximum loads of materials used in system and calculate expected loads using expected flight loads found by LV team	Passive locking system found to withstand expected flight loads	DR-1B, DR-1C	74
EP-1	LV Comms/Control	Verify range of antenna is sufficient for flight operations	Calculate range of antenna based on link budgets and compare with maximum projected altitude and downrange distance predicted by LV team	Antenna range found to be within expected flight range	EP-1A	15
EP-2	LV Comms/Control	Ensure GPS saturation does not affect telemetry	Design and implement a code solution to the risk of GPS module saturation (such as delayed activation)	Successful design and implementation of such a feature	EP-3A, EP-3B	200
EP-3	LV Comms/Control	Ensure drone signaling and monitoring wires disconnect when drone deployment initiates	Design a disconnection system for wires between E/P bay and drone that remains in place during flight yet disconnects easily when carriage deploys	Successful design of such a feature	EP-5	9
SR-1	Sample Retrieval System	Ensure interfaces between system components withstand flight loads	Design interfaces between electric motors, brush rotor, brush cover, and drone body that withstand flight loads and keep components secure (if not already completed)	Successful design of such interfaces	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3, SR-4	312
SR-2	Sample Retrieval System	Prevent collected samples from being lost during flight of MV	Design and implement physical features into the collection bay that prevent collected samples from exiting MV during flight (if not already completed)	Successful design of such features	SR-2C, SR-3, SR-4	73
MV-1	Mission Vehicle	Verify ranges of antennas are sufficient for flight operations	Calculate ranges of telemetry antennas and flight controller antennas based on link budgets and compare with maximum projected altitude and downrange distance predicted by LV team	Antenna ranges found to be within expected flight range	MV-1A, MV-1B, MV-1C, MV-1E, MV-1F	32
MV-2	Mission Vehicle	Ensure GPS saturation does not affect telemetry	Design and implement a code solution to the risk of GPS module saturation during launch (such as delayed activation)	Successful design and implementation of such a feature	MV-3A, MV-3B	135
MV-3	Mission Vehicle	Ensure booms deploy and lock into place properly	Design a boom actuation system that restrains the booms until commanded to deploy and locks them into their deployed position, accounting for maximum loads of materials used and expected loads found by LV team	Successful design and implementation of such a system	MV-4A, MV-4B, MV-6B	57
MV-4	Mission Vehicle	Verify that the MV body, booms, propellers, and boom retention system will withstand flight loads	Research maximum loads of materials used in system and durability of propellers used, then check against expected loads found by LV team	Materials found to withstand expected flight loads	MV-4C, MV-6A, MV-6B	245
MV-5	Mission Vehicle	Verify that CoG location is conducive to vehicle stability	Find location of CoG of completed MV, compare to CoT (equidistant from all propellers), and adjust mass distribution as required so centers lie on same vertical axis	CoG found to be in stable region	MV-6B	15
GS-1	Ground Station	Verify ranges of antennas are sufficient for flight operations	Calculate ranges of all antennas attached to router and RC controller antenna based on link budgets and compare with maximum projected altitude and downrange distance predicted by LV team	Antenna ranges found to be within expected flight range	GS-1B, GS-1C, GS-1D, GS-1E, GS-2	32
LL-1	Landing Leg	Verify landing leg fits properly into LV body	Calculate dimensions of foot of LV and the interface, calculate friction between leg foot and LV body, then verify that clearance and frictional forces on leg are such that leg can be deployed but is still held snugly when retracted	Clearance between foot and LV is found to be satisfactory	LL-1A, LL-1B, LL-1C, LL-1D	30
LL-2	Landing Leg	Verify servos will be able to deploy leg	Find force exerted by each servo and verify that combined force is sufficient to overcome frictional forces and mass of leg for deployment	Servos found to exert sufficient force	LL-1A, LL-1D	21
LL-3	Landing Leg	Verify aerodynamic forces will not cause premature deployment	Using expected Max-Q calculated by LV team, pressure inside LV, and area of leg foot, calculate approximate aeroynamic force on leg and verify it will be mitigated by servos or friction	Leg found to remain secure under aerodynamic loads	LL-1B	75
LL-4	Landing Leg	Verify materials used in landing leg will withstand touchdown loads	Using touchdown velocity found by LV team, calculate force on landing leg on touchdown and compare with researched maximum loads of materials used in landing leg	Materials found to withstand expected touchdown loads	LL-2A	8
AV-1	Avionics Bay	Verify amount of black powder is optimal for each staging event	Find necessary ejection force for each primary altimeter to separate the LV components without causing structural failure, then find corresponding amount of black powder	Calculation of an ideal black powder quantity	AV-1F, AV-1G, AV-2G, AV-2H, AV-3	38
AV-2	Avionics Bay	Verify avionics bay materials with withstand flight loads and e-match forces will not damage LV	Research maximum loads of materials used in system and check against expected loads found by LV team, then calculate force of e-matches involved in each staging event and verify avionics bay and LV will withstand load	Materials found to withstand expected flight loads	AV-3	60
UL-1	Upper Launch Vehicle	Verify materials will withstand flight loads	Research maximum loads of materials used in nosecone and shock cord and check against maximum expected flight loads	Materials found to withstand expected flight loads	UL-1A, UL-3B	35
UL-2	Upper Launch Vehicle	Verify drogue chute can support vehicle	Calculate expected maximum force on chute (considering weight of entire dry LV and aerodynamic force) and check against maximum acceptable loads on chute canvas and lines	Chute found to withstand expected flight loads	UL-2, UL-3A	15
UL-3	Upper Launch Vehicle	Verify GPS tag range is sufficient for flight operations	Calculate effective range of tag using range of ground receiver, range of tag antenna, and the link budget method, then compare with maximum projected altitude and downrange distance	Range found to be within expected flight range	UL-4	8
LV-1	Lower Launch Vehicle	Verify TWR of vehicle (if not already completed)	Using either simulation software or hand calculations, verify that TWR is 3 or greater to ensure vehicle clears launch area	TWR found to be 3 or greater	LV-1C	5
LV-2	Lower Launch Vehicle	Verify motor will propel vehicle to targeted altitude (if not already completed)	Using simulation software, verify that selected motor will achieve targeted altitude for ideal conditions and fall between 3,500-5,500 ft for all realistic unideal conditions	Target altitude/range met for all reasonable flight conditions	LV-1D	3
LV-3	Lower Launch Vehicle	Verify all materials used will withstand flight loads	Research maximum loads of materials used in all lower LV components and check against expected loads from propulsion and aerodynamics	Materials found to withstand expected flight loads	LV-2A, LV-2B, LV-2C, LV-4B	273
LV-4	Lower Launch Vehicle	Verify CoG throughout flight is conducive to vehicle stability	Locate the wet and dry CoG of the entire vehicle using masses and locations from other subteams, and verify that they both lie on the same vertical axis as the CoT	CoG found to be in stable location throughout flight	LV-2C	10
LV-5	Lower Launch Vehicle	Verify shear pins' required breakage force is greater than flight loads but less than staging loads	Find maximum expected flight forces and maximum main staging force, then compare with force of breakage of shear pins	Shear pin breakage force found to lie within specified region	LV-3A, LV-3B	60
LV-6	Lower Launch Vehicle	Verify main chute can support lower LV	Calculate expected maximum force on chute (considering weight of dry lower LV with MV aboard and aerodynamic force) and check against maximum acceptable loads on chute canvas and lines	Chute found to withstand expected flight loads	LV-3D, LV-4A, LV-4B	76

Table 8.9: Design analysis plan for the 2019-2020 ARC competition vehicle.

The analyses with the highest priority are the implementation of a software workaround for GPS saturation, verification of the strength of sample retrieval system component interfaces, and verification of the material properties of the mission vehicle, carriage system, and lower launch vehicle components. These analyses will ensure accurate GPS data, ensure the sample retrieval system remains intact when exposed to flight loads, and mitigate the risk of structural failures that can lead to stability loss, damage to or loss of the LV and MV, and the loss of the mission.

8.2.7 DESIGN VERIFICATION PLAN

Similarly, several failure causes found in the DFMEA require testing to mitigate. These required tests, a general description of their procedures, and their acceptance criteria are found in the Design Verification Plan (DVP) found in Tables 8.7 and 8.8. A higher resolution version of the DVP can be found in the team DFMEA depository, which is located at:

https://drive.google.com/drive/u/1/folders/1Kc8U2xoarTPptHXaBHjlSp58PHiyLw9K

As with the DAP, the priority values given for each test are the sum of the RPNs of all failure causes mitigated by the test.

DVP Item #	Subsystem	Test Summary	Objectives	Test Description	Acceptance Criteria	Associated Failure Modes	Priority
DC-1	Drone Carriage	Ground deployment test of prototype carriage setup (may be waved if prototype phase is skipped)	Validate motor specs/washer configuration and verify that the system functions as designed	Fully integrated test of deployment, beginning with restraint of carriage, releasing the carriage, and observing the deployment sequence	Carriage does not deploy prematurely, deploys when commanded at expected velocity, and provides clearance for simulated drone	DC-2A, DC-2B, DC-3, DC-4A, DC-4B	203
DC-2	Drone Carriage	Repeated deployment tests of prototype carriage setup	Analyze effect of wear and tear on deployment	Repeatedly deploy and reset the system, observing any changes in deployment sequence	Effects of wear and tear found to be negligible	DC-2A, DC-2B, DC-4A, DC-4B	6
DC-3	Drone Carriage	Vibration testing of carriage prototype or final carriage	Analyze effect of vibrations on structural integrity and deployment	Place carriage system onto vibration table, observe effects of vibration, and attempt deployment sequence following vibration test	Carriage maintains integrity during vibration and is fully functional following test	DC-1A, DC-1B, DC-1C, DC-2A, DC-2B, DC-4A, DC-4B	450
DC-4	Drone Carriage	Drop test of prototype or final carriage assembly	Observe effect of touchdown impact on structural integrity and deployment	Drop carriage system from height such that it contacts ground at expected touchdown velocity, observe effect of impact, and attempt deployment sequence following drop test	Carriage maintains integrity following drop and is fully functional following test	DC-1A, DC-1B, DC-1C, DC-2A, DC-2B, DC-4A, DC-4B	398
DC-5	Drone Carriage	Ground deployment test of carriage flight hardware	Ensure flight hardware functions as designed and detect any build errors	Fully integrated test of deployment, beginning with restraint of carriage, releasing the carriage, and observing the deployment sequence (may be done concurrently with DR-5)	Carriage does not deploy prematurely, deploys when commanded at expected velocity, and provides clearance for simulated drone	DC-2A, DC-2B, DC-4A, DC-4B	46
DC-6	Drone Carriage	Ground test of failsafe to prevent complete separation of carriage from LV	Ensure carriage cannot separate from LV and that the failsafe works as designed	Using body tube segment with failsafe installed, install prototype carriage with drone mass simulator and tip full assembly vertical to ensure carriage does not separate	Carriage does not fall out of body tube segment	DC-4A	9
DR-1	Drone Retention System	Ground test of actuation of prototype retention system setup and verification of total restraint (may be waived if prototype phase is skipped)	Verify that the system functions as designed	Rotate, position, and shake setup in various ways to ensure drone simulator remains attached, then initiate and observe release sequence	Drone simulator remains attached to carriage simulator, and total release occurs when commanded and not prematurely	DR-1A, DR-1B, DR-1C	104
DR-2	Drone Retention System	Repeated tests of actuation of prototype retention system setup and observation of impact on restraint effectiveness	Analyze effect of wear and tear on release and restraint effectiveness	Repeatedly release and reset the restraint system, observing any changes in deployment sequence, then rotate/position/shake setup in various ways to ensure drone simulator remains attached	Effects of wear and tear found to be negligible	DR-1B, DR-1C, DR-2A, DR-2B	25
DR-3	Drone Retention System	Vibration testing of drone retention system prototype or final system	Analyze effect of vibrations on structural integrity, release actuation, and restraint effectiveness	Place drone retention system onto vibration table, observe effects of vibration, rotate/position/shake setup following vibration test, and attempt release sequence	Drone retention system maintains integrity during vibration and is fully functional following test	DR-All	264
DR-4	Drone Retention System	Drop test of prototype or final drone retention system assembly	Observe effect of touchdown impact on structural integrity, release actuation, and restraint effectiveness	Drop drone retention system from height such that it contacts ground at expected touchdown velocity, observe effect of impact, rotate/position/shake setup and attempt release sequence after drop test	Drone retention system maintains integrity following drop and is fully functional following test	DR-All	270
DR-5	Drone Retention System	Ground test of drone retention system flight hardware	Ensure flight hardware functions as designed and detect any build errors	Rotation/position/shake test of flight hardware prior to installation in LV followed by fully integrated test of release of drone (may be done concurrently with DC-5)	Drone remains attached to carriage, and total release occurs when commanded and not prematurely	DR-All	196
EP-1	LV Comms/Control	Range test of E/P bay antenna	Verify that antenna range is acceptable for flight	In large, open area (approx. 1 sq. mi.), move active E/P electronic setup away from active ground station to the maximum expected distance from the ground station and verify that connection is maintained	Connection maintained at maximum distance	EP-1A	15
EP-2	LV Comms/Control	Ground test of LV comm/control system prototype (may be waived if prototype phase is skipped)	Verify that the system functions as designed	With prototype ground station and LV comm/control system starting from full battery charge, leave idle for max expected launch delay time, monitor battery levels, walk vehicle around to test GPS coord transmission, and actuate simulated TALL, drone carriage, and drone retention servos	All elements of system function as designed	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	287
EP-3	LV Comms/Control	Vibration testing of prototype or final LV comm/control system	Analyze effect of vibrations on structural integrity and connections of components	Place LV comms/control system onto vibration table, observe effects of vibration, and initialize/validate circuit following test using ground station and simulated servos	System maintains integrity during vibration and is fully functional following test	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	748
EP-4	LV Comms/Control	Drop test of prototype or final LV comm/control system	Observe effect of touchdown impact on structural integrity and connections of components	Drop LV comms/control system (mounted to a base plate or inside a body tube segment) from height such that it contacts ground at expected touchdown velocity, observe effect of impact, and initialize/validate circuit following test using ground station and simulated servos	System maintains integrity during drop and is fully functional following test	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	748
EP-5	LV Comms/Control	Ground test of final LV comm/control system	Verify that the system functions as designed	With final ground station and installed flight LV comm/control system starting from full battery charge, leave idle for max expected launch delay time, monitor battery levels, walk vehicle around to test GPS coord transmission, awaken drone, and actuate TALL, carriage, and retention hooks	All elements of system function as designed	EP-1A, EP-1B, EP-1C, EP-2A, EP-2B, EP-3A, EP-3B, EP-4A, EP-4B, EP-4C	324
EP-6	LV Comms/Control	Ground test of interface connecting drone to LV comms/control system	Verify that all wires disconnect when drone deployment begins	With prototype or final carriage/drone setup and prototype or final LV comms/control system, actuate the carriage and ensure all wires/connections between drone disconnect properly	Wire disconnects when deployment occurs	EP-5	9
SR-1	Sample Retrieval System	Proof-of-concept ground test of sample retrieval system	Verify that the system will collect appropriate amount of sample material without mechanical issues	With plastic pellets and prototype bin/motor/brush/cover setup, attempt to fill bin with sample material while observing system behavior, measure time taken to fill, and find actual volume of sample collected	System collects 150 mL of sample material without encountering mechanical issues	SR-2A, SR-2B, SR-2C, SR-3, SR-4	97
SR-2	Sample Retrieval System	Repeated and extended testing of sample retrieval system	Analyze effect of wear and tear on system effectiveness	With plastic pellets and prototype bin/motor/brush/cover setup, perform numerous mission length collections and observe changes in system behavior, and perform extended run of system directly in pellets (without bin attached) to observe effect of prolonged operation	Effects of wear and tear found to be negligible	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3	74
SR-3	Sample Retrieval System	Vibration testing of prototype sample retrieval system or final system	Analyze effect of vibrations on structural integrity and sample collection ability	Place sample retrieval system onto vibration table, observe effects of vibration, and attempt mission length sample collection following test using plastic pellets	System maintains integrity during vibration and is fully functional following test	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3, SR-4	354
SR-4	Sample Retrieval System	Drop test of prototype or final sample retrieval system	Observe effect of touchdown impact on structural integrity, connection of components, and sample collection ability	Drop sample retrieval system from height such that it contacts ground at expected touchdown velocity, observe effect of impact, and attempt mission length sample collection following test using plastic pellets	System maintains integrity during drop and is fully functional following test	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3, SR-4	354
SR-5	Sample Retrieval System	Ground test of sample retrieval system flight hardware	Verify that system functions as designed	With plastic pellets and final sample retrieval system integrated into mission vehicle, attempt mission length sample collection sequence while observing system behavior, measure time taken to fill, and find actual volume of sample collected	System collects 150 mL of sample material as designed	SR-1A, SR-1D, SR-2A, SR-2B, SR-2C, SR-3, SR-4	196
SR-6	Sample Retrieval System	Flight test of sample retrieval system	Verify that system functions as designed in simulated mission scenario	With operational mission vehicle, attempt collection of plastic pellets while either hovering over or landed on sample material, observe system behavior, measure time taken to fill, fly MV away and watch for sample fragments exiting retrieval system, and find actual volume of sample collected	System collects 150 mL of sample material as designed with no material lost in flight	SR-2B, SR-3, SR-4	98
MV-1	Mission Vehicle	Range test of telemetry and flight controller antennas	Verify that antenna ranges are acceptable for flight	In large, open area (approx. 1 sq. mi.), move active drone comm setup away from active ground station to the maximum expected distance from the ground station and verify that all connections are maintained	All connections maintained at maximum distance	MV-1A, MV-1B, MV-1C, MV-1E, MV-1F	32
MV-2	Mission Vehicle	Ground test of MV comm/control system, boom retention and actuation, and sample retrieval system operation	Verify that the system functions as designed	With prototype drone system (no motor-related systems or FPV) starting from full charge, awaken drone via simulated E/P bay signal, deploy booms and observe behavior, engage and disengage the sample retrieval system, move vehicle to test GPS coord transmission, and verify all comms	All elements of system function as designed	MV-1A, MV-1B, MV-1C, MV-1D, MV-1E, MV-1F, MV-2, MV-3A, MV-3B, MV-4A, MV-4B, MV-4C, MV-4D, MV-5, MV-6B, MV-6C	546
MV-3	Mission Vehicle	Vibration testing of final MV	Analyze effect of vibrations on structural integrity and connections of components	Place final MV system onto vibration table, observe effects of vibration, and initialize/validate all MV systems following test, including one motor on test stand	System maintains integrity during vibration and is fully functional following test	MV-All	1,388
MV-4	Mission Vehicle	Drop testing of prototype or final MV	Observe effect of touchdown impact on structural integrity and connections of components	Drop MV from height such that it contacts ground at expected touchdown velocity, observe effect of impact, and initialize/validate all MV systems following test, including one motor on test stand	System maintains integrity during drop and is fully functional following test	MV-All	1,388
MV-5	Mission Vehicle	Ground test of final MV	Verify that the system functions as designed	With complete MV and LV setup starting from full charge, awaken drone via E/P bay signal, engage GPS and verify coordinates, deploy carriage and release restraints, deploy booms and observe behavior, engage and disengage the sample retrieval system, and verify all comms and FPV system	All elements of system function as designed	MV-1A, MV-1B, MV-1C, MV-1D, MV-1E, MV-1F, MV-2, MV-3A, MV-3B, MV-4A, MV-4C, MV-4D, MV-5, MV-6B, MV-6C	595
MV-6	Mission Vehicle	Repeated tests of boom deployment	Analyze effect of wear and tear on boom deployment	Repeatedly deploy and reset booms while observing any changes in the deployment sequence	Effects of wear and tear found to be negligible	MV-4A, MV-4B	9
MV-7	Mission Vehicle	Load test of rotor booms	Ensure booms can withstand flight loads	Using MV mass simulator attached to booms (which are clamped down), add weights on top of mass simulator until boom fails, record weight resulting in failure, and analytically verify that maximum motor power will not produce a critical load	Booms found to withstand expected flight loads	MV-6A	45
MV-8	Mission Vehicle	Repeated and extended duration prop tests	Analyze effect of wear and tear on propulsion system	Using a motor and prop assembly on test stand, perform numerous mission duration runs (with appropriate throttle changes), perform extended run to observe effect of prolonged operation, and perform visual inspections following each run	Effects of wear and tear found to be negligible	MV-6A, MV-6B	35
MV-9	Mission Vehicle	Flight test of MV	Verify system functions and handles as designed	With operational MV and ground station/controller, activate/verify all systems, engage motors, perform a hover to ensure vehicle stability, test vehicle's ability to maneuver in all 9 degrees of freedom, and perform controlled touchdown	Vehicle flies as expected	MV-3B, MV-6B, MV-6C	70

Table 8.10: The first half of the design verification plan for the 2019-2020 ARC vehicle.

The tests with the highest priority are vibration/drop tests of all systems, parachute deployment tests, comprehensive prototype communication/control system tests, and prototype carriage deployment and retention system release tests. These tests will minimize the risk of unknown effects from the flight environment, ensure the LV recovery systems will deploy as

DVP Item #	Subsystem	Test Summary	Objectives	Test Description	Acceptance Criteria	Associated Failure Modes	Priority
GS-1	Ground Station	Range test of telemetry and RC controller antennas	Verify that antenna ranges are acceptable for flight	In large, open area (approx. 1 sq. mi.), move active LV and MV comm setups away from active ground station to the maximum expected distance from the ground station and verify that all connections are maintained	All connections maintained at maximum distance	GS-1B, GS-1C, GS-1D, GS-1E, GS-2	32
GS-2	Ground Station	Integrated test of ground station network	Verify that the system functions as designed	With final ground station and active LV/MV, initialize ground station computer and RC controller, create the required network and connections, and verify that all connections are stable and transmitting req'd information	System functions as designed	GS-1A, GS-1B, GS-1C, GS-1D, GS-1E	158
LL-1	Landing Leg	Deployment test of prototype landing leg assembly	Verify that leg clears interface with LV body and deploys as designed	Deploy prototype landing leg from LV body segment using landing leg servos and observe deployment sequence	Leg deploys as designed	LL-1A, LL-1B, LL-1C, LL-1D	51
LL-2	Landing Leg	Repeated deployment tests of prototype landing leg assembly	Analyze effect of wear and tear on deployment	Repeatedly deploy and reset prototype landing leg assembly and observe changes in deployment sequence	Effects of wear and tear found to be negligible	LL-1A, LL-1C, LL-1D	10
LL-3	Landing Leg	Vibration testing of landing leg prototype	Analyze effect of vibrations on structural integrity and system effectiveness	Place landing leg system inside body tube segment on vibration table, observe effects of vibration, and attempt deployment sequence following test	System maintains integrity during vibration and is fully functional following test	LL-1A, LL-1B, LL-1C, LL-1D, LL-2A	244
LL-4	Landing Leg	Drop test of final landing leg assembly	Observe effect of touchdown impact on structural integrity	With landing leg extended from LV body mass/volume simulator, drop from height such that it contacts ground at expected touchdown velocity and observe effect of impact	System maintains integrity on impact	LL-1A, LL-1B, LL-1C, LL-1D, LL-2A	236
LL-5	Landing Leg	Integrated deployment test of final landing leg assembly	Verify leg deploys as designed	With final landing leg assembly integrated into LV, deploy leg and observe deployment sequence	Leg deploys as designed	LL-1A, LL-1C, LL-1D	20
LL-6	Landing Leg	Stability test of LV in landing configuration	Verify leg and fins keep vehicle stable on landing	Using final LV with leg deployed, place vehicle into landing orientation and apply forces and moments using hands to ensure vehicle remains stable	LV remains stable for all applied loads	LL-2B	16
LL-7	Landing Leg	Test of landing legin mission scenario	Verify leg raises MV exit point to be greater than level or level with the horizon in a mission scenario	Using final LV with leg deployed to maximum length and a dirt field with varying terrain, place vehicle in various locations on the ground (especially in hilly or bumpy areas) to ensure vehicle is stable and the MV exit point is level or greater than level	LV is stable and properly oriented for deployment in all locations	LL-2B, LL-3	24
AV-1	Avionics Bay	Vibration testing of avionics bay	Analyze effect of vibrations on structural integrity and connections of components	With all safeties engaged and simulated black powder pellets, place avionics bay setup on vibration table and observe effects of vibration	System maintains integrity during vibration	AV-1A, AV-1B, AV-1C, AV-1D, AV-1E, AV-2A, AV-2B, AV-2C, AV-2D, AV-2E, AV-2F	468
UL-1	Upper Launch Vehicle	Vibration testing of upper launch vehicle/secondary recovery system	Analyze effect of vibrations on structural integrity and connections of components	With simulated avionics bay, simulated LV with properly stowed drogue chute, nosecone with GPS tracker, and shock cord, place upper LV setup on vibration table and observe effects of vibration	System maintains integrity during vibration	UL-1A, UL-2, UL-3A, UL-4	201
UL-2	Upper Launch Vehicle	Load test of drogue chute	Verify drogue chute can support weight of full LV	Attach mass simulator of LV to base of drogue chute and apply additional weight to simulate aerodynamic loads	Chute found to withstand expected flight loads	UL-2, UL-3A	15
UL-3	Upper Launch Vehicle	Stretch test of shock cord	Verify shock cord can withstand expected flight loads	Using expected ejection force as reference, stretch shock cord so it experiences a tension equal to that force and observe the results	Shock cord found to withstand expected flight loads	UL-3B	20
UL-4	Upper Launch Vehicle	Range test of GPS tracker	Verify range of GPS tag is acceptable for flight	In large, open area (approx. 1 sq. mi.), with final ground station and active GPS tag in nosecone, move active GPS tag in nosecone away from ground station to the maximum expected distance from the ground station and verify that all connections are maintained	Connection maintained at maximum distance	UL-4	36
UL-5	Upper Launch Vehicle	Deployment test of drogue chute	Verify drogue chute deploys as designed	Using upper launch vehicle setup with properly stowed drogue chute, quickly pull nosecone from AV bay while in bed of moving pickup truck and observe deployment sequence (ensure all personnel and upper LV setup are properly restrained, and keep speed below 25 mph)	Drogue chute deploys as designed	UL-2, UL-3A	150
UL-6	Upper Launch Vehicle	Ejection test of drogue chute	Verify avionics bay and drogue chute interact as designed	With appropriate precautions in place, test drogue staging sequence using upper LV assembly, properly stowed drogue chute, and armed altimeter bay (only HPR Lvl 2 cert members authorized to conduct test)	Drogue chute ejects as designed	UL-2, UL-3A	150
LV-1	Lower Launch Vehicle	Vibration testing of lower launch vehicle/main recovery system	Analyze effect of vibrations on structural integrity and connections of components	With motor mass simulator (filled with simulated propellant), MV mass simulator, and E/P bay mass simulator, place prototype lower LV setup on vibration table and observe effects of vibration	System maintains integrity during vibration	LV-2A, LV-2B, LV-2C, LV-3C, LV-3D, LV-4A, LV-4B	261
LV-2	Lower Launch Vehicle	Deployment test of main chute	Verify main chute deploys as designed	Using lower LV setup with properly stowed main chute, quickly withdraw main chute from storage location while in bed of moving pickup truck and observe deployment sequence (ensure all personnel and lower LV setup are properly restrained, and keep speed below 25 mph)	Main chute deploys as designed	LV-3C, LV-3D, LV-4A, LV-4B	175
LV-3	Lower Launch Vehicle	Load test of main chute	Verify main chute can support weight of lower LV with MV aboard	Attach mass simulator of dry lower LV with MV aboard to base of chute and apply additional weight to simulate aerodynamic loads	Chute found to withstand expected flight loads	LV-3D, LV-4A	20
LV-4	Lower Launch Vehicle	Drop test of LV simulator	Verify fins will withstand force of touchdown	Drop lower LV mass/volume simulator (with fin prototypes and simulated landing leg) from height such that it contacts ground at expected touchdown velocity and observe effect of impact	Fins maintain structural integrity on drop	LV-4B	8
LV-5	Lower Launch Vehicle	Ejection test of main chute	Verify avionics bay and main chute interact as designed	With appropriate precautions in place, test main staging sequence using upper LV assembly, properly stowed main chute, and armed altimeter bay (only HPR Lvl 2 cert members authorized to conduct test)	Main chute ejects as designed	LV-3C, LV-3D, LV-4A, LV-4B	175

Table 8.11: The second half of the design verification plan for the 2019-2020 ARC vehicle.

designed, ensure that all systems can be monitored and controlled from the ground, and the transition from the flight phase to the mission phase occurs with no issues.

8.3 LAUNCH VEHICLE TESTING

8.3.1 LOWER LAUNCH VEHICLE TESTING

LV-1:

This test is a vibration test of the lower launch vehicle main recovery system. The goal of this test is analyze the effect of vibrations on structural integrity and connections of components. With the motor mass simulated, drone mass simulated, and E/P bay mass simulator, place prototype lower LV setup on vibration table and observe effects of the vibrations on the LV. If the system maintains integrity during the vibration it will be considered a pass. Materials needed:

1. Simulated motor
2. Simulated drone mass
3. Prototype lower LV with stowed main parachute
4. Vibration table
5. Camera

LV-2:

This is a test of the deployment system for the main parachute. It is meant to verify that the main parachute deploys as designed. Using the lower LV setup with a properly stowed main parachute, the main parachute will be quickly deployed from the bed of a moving pickup truck and the deployment sequence will be observed (Ensure all personnel and lower LV setup are properly restrained, and keep speed below 25 mph). If the main parachute deploys as designed, then the test will be a success. Materials needed:

1. Lower LV setup with properly stowed main parachute
2. Pickup Truck
3. Road with little or no traffic
4. Safety restraints
5. Camera

LV-3:

This test is of the load ability of the main parachute. This is to verify that the main parachute can support the weight of the lower LV with the drone aboard. This is done by attaching a mass simulated to the dry weight of the lower LV with the drone aboard to the base of the parachute before applying additional weight to simulate aerodynamic loads. If the parachute withstands these loads, it will be a success. Materials Needed:

1. Main parachute
2. Lower LV Mass Simulated
3. Weights
4. Camera
5. Method of anchoring top of parachute in the deployed position

LV-4:

The drop test of the lower LV is done to make sure the fins will withstand the force of touchdown. This test is done by dropping the LV mass/volume simulator (with fin prototypes attached) from a height such that it contacts the ground at expected touchdown velocity. If none of the fins break or lose straightness then the test will be a success. Materials Needed:

1. Lower LV with mass/volume simulator
2. Fins
3. Ruler
4. Camera

8.3.2 UPPER LAUNCH VEHICLE TESTING

UL-1:

This test is a vibration test of the upper launch vehicle main recovery system. The goal of this test is to analyze the effect of vibrations on the structural integrity and connections of components. This test will be conducted on the simulated avionics bays, simulated LV with properly stowed drogue parachute, nose cone with GPS tracker, and shock chord place the upper LV setup on the vibration table and observe the effects. If the system maintains integrity during vibration the test is a success. Materials Needed:

1. Simulated AV bay
2. Nose Cone
3. Stowed Drogue Chute
4. GPS tag
5. Vibration table
6. Camera

UL-2:

This is a load test of the drogue parachute. This is to verify that the drogue can support the weight of the full LV. This will be done by attaching masses to simulate the weight of the LV to the base of the drogue parachute, before applying additional weights to simulate aerodynamic loads. If the the drogue can withstand these loads then it is a success. Materials Needed:

1. Drogue parachute
2. Simulated LV mass
3. Weights
4. Method of anchoring top of chute in deployed chute
5. Camera

UL-3:

This test focused on the elasticity of the shock cord. This is meant to verify that the shock chord can withstand the expected flight loads. Using ejection force as a reference, the shock chord will be stretched so it experiences a tension equal to that of the force at deployment and observe the results. If the shock chord with stands the load then it will be a success. Materials Needed:

1. Shock Chord
2. Method of anchoring one end
3. Camera

UL-4:
This is a test of the range of the GPS tracker. In large, open area (approx. 1 sq. mi.), with a finalized ground station and active GPS tag in the nosecone, the active GPS tag in nosecone will be walked away from ground station to the maximum expected distance from the ground station and verified that all connections are maintained. If the connection is maintained at the maximum distance then the test is a success. Materials Needed:

1. Activate GPS tag
2. Nose Cone
3. Final Ground Station

UL-5:
The purpose of this test is to see how the drogue parachute will deploy and if it will deploy as designed. Using the upper LV setup with a properly stowed drogue chute, the nose cone will be deployed from the AV in the bed of a moving pickup truck, and deployment sequence will be observed (ensure all personnel and upper LV setup are properly restrained, and the speed is kept below 25 mph). If it deploys as designed then the test is a success. Materials Needed:

1. Upper LV with stowed drogue parachute
2. Pickup Truck
3. Road with minimal traffic
4. Safety restrains
5. Camera

8.3.3 AVIONICS BAY TESTS

AV-1:
This test is a vibration test of the avionics bay. The goal of this test is analyze the effect of vibrations on structural integrity and connections of components. With all safeties engaged and simulated black powder pellets, place avionics bay setup on vibration table and observe effects of vibration. If the system maintains integrity during vibration the test is a success. Materials needed:

1. Avionics Bay with safeties engaged
2. Simulated Black Powder
3. Vibration table
4. Camera

8.3.4 Avionics Bay Analyses

AV-1:

This analysis is meant to verify whether the amount of black powder is optimal for each staging event. The goal of this analysis is find necessary ejection force for each primary altimeter to separate the LV components without causing structural failure, then find corresponding amount of black powder. By running this analysis, the correct amount of black powder for deployment can be determined.

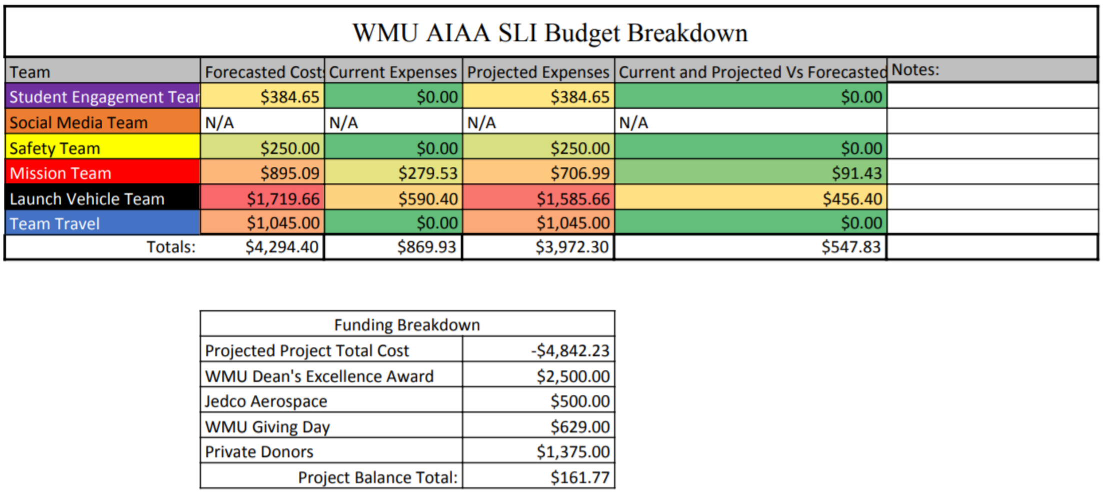
AV-2:

The objective of this analysis is to verify that the avionics bay materials will withstand flight loads and that the e-match forces will not damage the LV. This is done by researching the maximum loads of materials used in system and check against expected loads found by LV team. The force of the e-matches involved in each staging event are then calculated, and the avionics bay and LV are verified whether they will withstand the expected loads.

8.4 Budgeting and Timeline

8.4.1 Budget

The budget for ARC has slipped and exceeded our forecasted costs. This is the result of the failure of our first small scale sounding rocket, and other purchases that have been deemed non-primary design choices. These differences can be seen in Figure 8.10. Fortunately ARC has received donations from private donors, and industry sponsors. This influx of funding is combating the slipping project costs. As a result the Project Balance, including current expenses and projected expenses, is still positive. ARC will continue to search for industry sponsors, and private donors. Detailed lists of current expenses, and projected expenses can be seen in Figure 8.11, 8.12, 8.13 and 8.14 below.

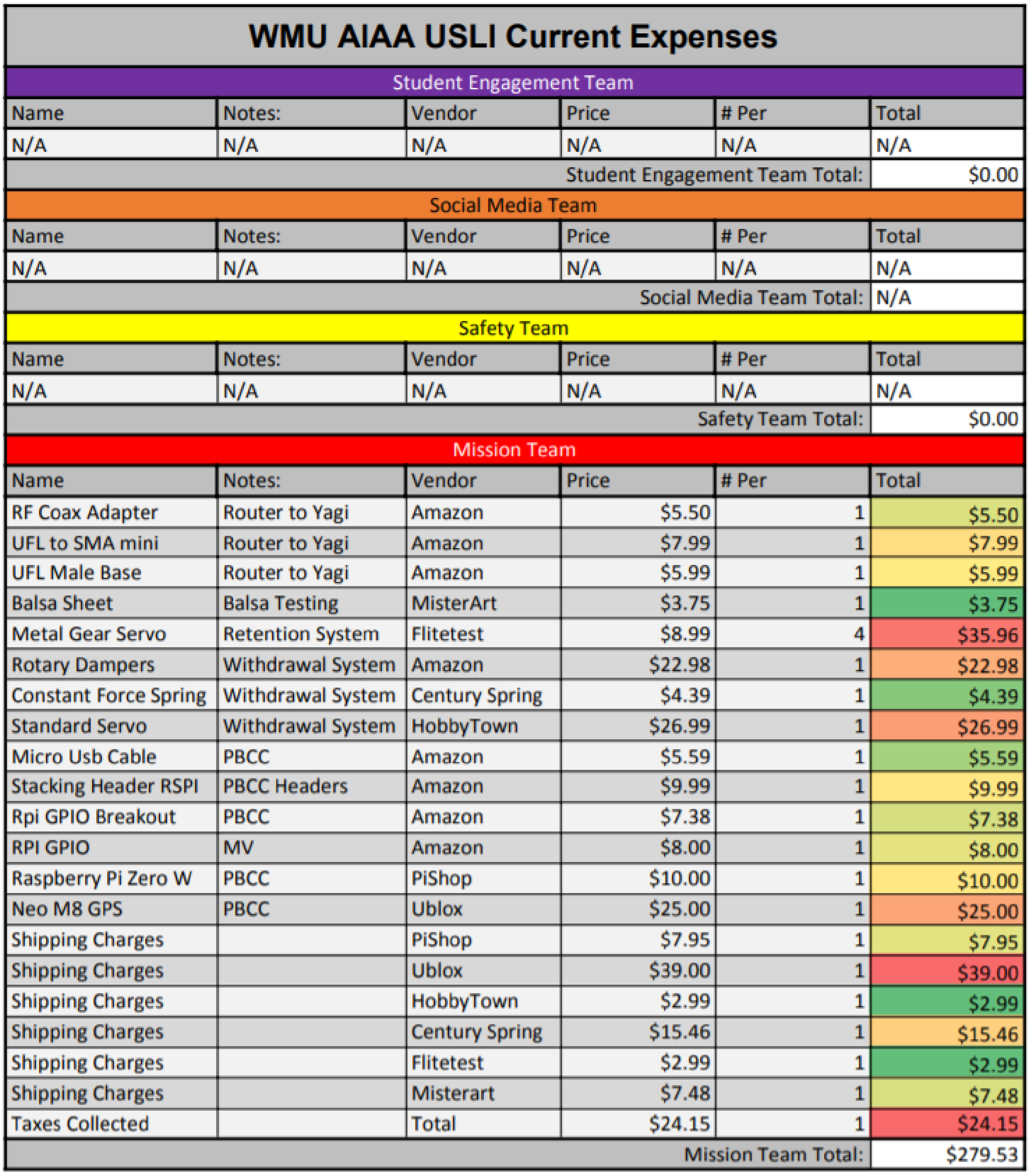


WMU AIAA SLI Budget Breakdown

Team	Forecasted Cost	Current Expenses	Projected Expenses	Current and Projected Vs Forecasted	Notes:
Student Engagement Tear	$384.65	$0.00	$384.65	$0.00	
Social Media Team	N/A	N/A	N/A	N/A	
Safety Team	$250.00	$0.00	$250.00	$0.00	
Mission Team	$895.09	$279.53	$706.99	$91.43	
Launch Vehicle Team	$1,719.66	$590.40	$1,585.66	$456.40	
Team Travel	$1,045.00	$0.00	$1,045.00	$0.00	
Totals:	$4,294.40	$869.93	$3,972.30	$547.83	

Funding Breakdown	
Projected Project Total Cost	-$4,842.23
WMU Dean's Excellence Award	$2,500.00
Jedco Aerospace	$500.00
WMU Giving Day	$629.00
Private Donors	$1,375.00
Project Balance Total:	$161.77

Figure 8.10: Project Totals and Funding Breakdown



WMU AIAA USLI Current Expenses

Student Engagement Team

Name	Notes:	Vendor	Price	# Per	Total
N/A	N/A	N/A	N/A	N/A	N/A
				Student Engagement Team Total:	$0.00

Social Media Team

Name	Notes:	Vendor	Price	# Per	Total
N/A	N/A	N/A	N/A	N/A	N/A
				Social Media Team Total:	N/A

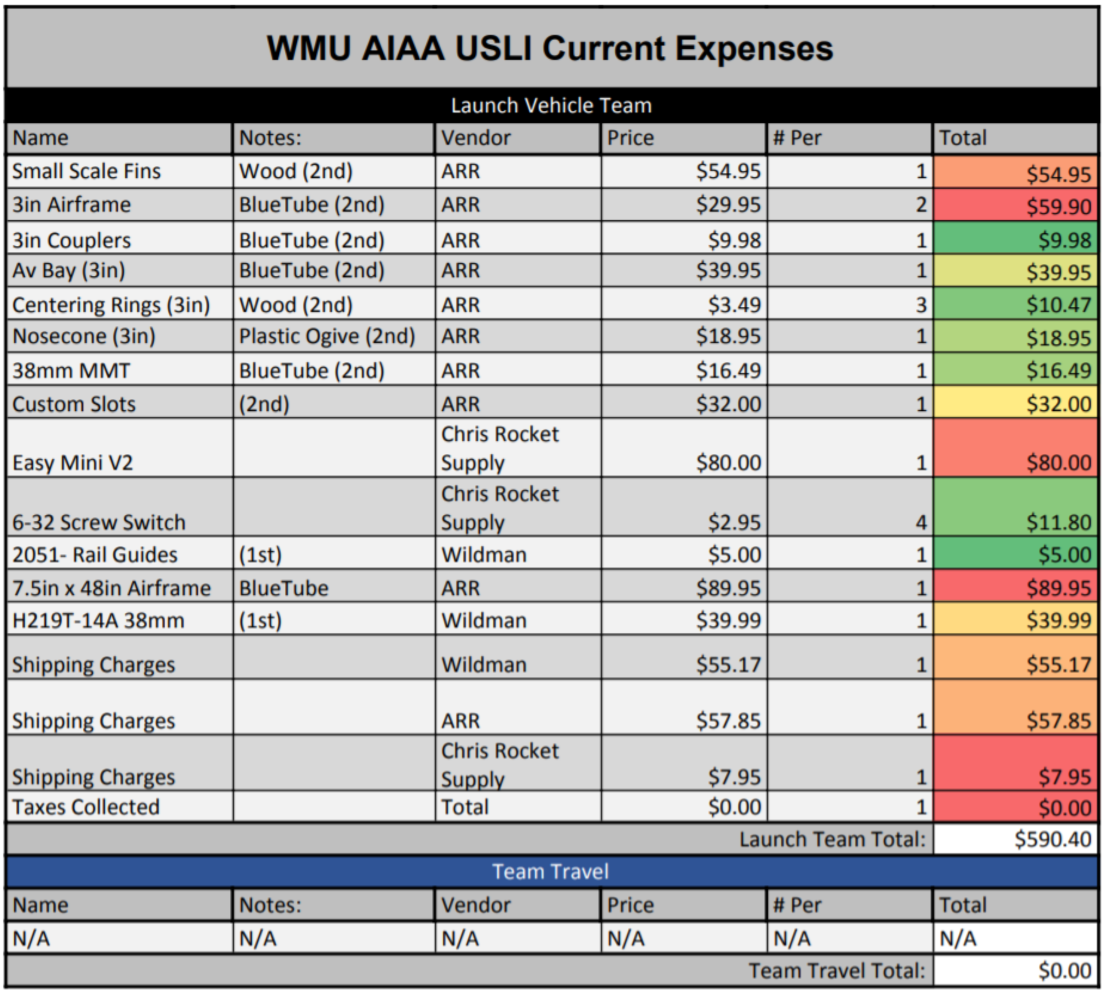
Safety Team

Name	Notes:	Vendor	Price	# Per	Total
N/A	N/A	N/A	N/A	N/A	N/A
				Safety Team Total:	$0.00

Mission Team

Name	Notes:	Vendor	Price	# Per	Total
RF Coax Adapter	Router to Yagi	Amazon	$5.50	1	$5.50
UFL to SMA mini	Router to Yagi	Amazon	$7.99	1	$7.99
UFL Male Base	Router to Yagi	Amazon	$5.99	1	$5.99
Balsa Sheet	Balsa Testing	MisterArt	$3.75	1	$3.75
Metal Gear Servo	Retention System	Flitetest	$8.99	4	$35.96
Rotary Dampers	Withdrawal System	Amazon	$22.98	1	$22.98
Constant Force Spring	Withdrawal System	Century Spring	$4.39	1	$4.39
Standard Servo	Withdrawal System	HobbyTown	$26.99	1	$26.99
Micro Usb Cable	PBCC	Amazon	$5.59	1	$5.59
Stacking Header RSPI	PBCC Headers	Amazon	$9.99	1	$9.99
Rpi GPIO Breakout	PBCC	Amazon	$7.38	1	$7.38
RPI GPIO	MV	Amazon	$8.00	1	$8.00
Raspberry Pi Zero W	PBCC	PiShop	$10.00	1	$10.00
Neo M8 GPS	PBCC	Ublox	$25.00	1	$25.00
Shipping Charges		PiShop	$7.95	1	$7.95
Shipping Charges		Ublox	$39.00	1	$39.00
Shipping Charges		HobbyTown	$2.99	1	$2.99
Shipping Charges		Century Spring	$15.46	1	$15.46
Shipping Charges		Flitetest	$2.99	1	$2.99
Shipping Charges		Misterart	$7.48	1	$7.48
Taxes Collected		Total	$24.15	1	$24.15
				Mission Team Total:	$279.53

Figure 8.11: Current Expenses



WMU AIAA USLI Current Expenses

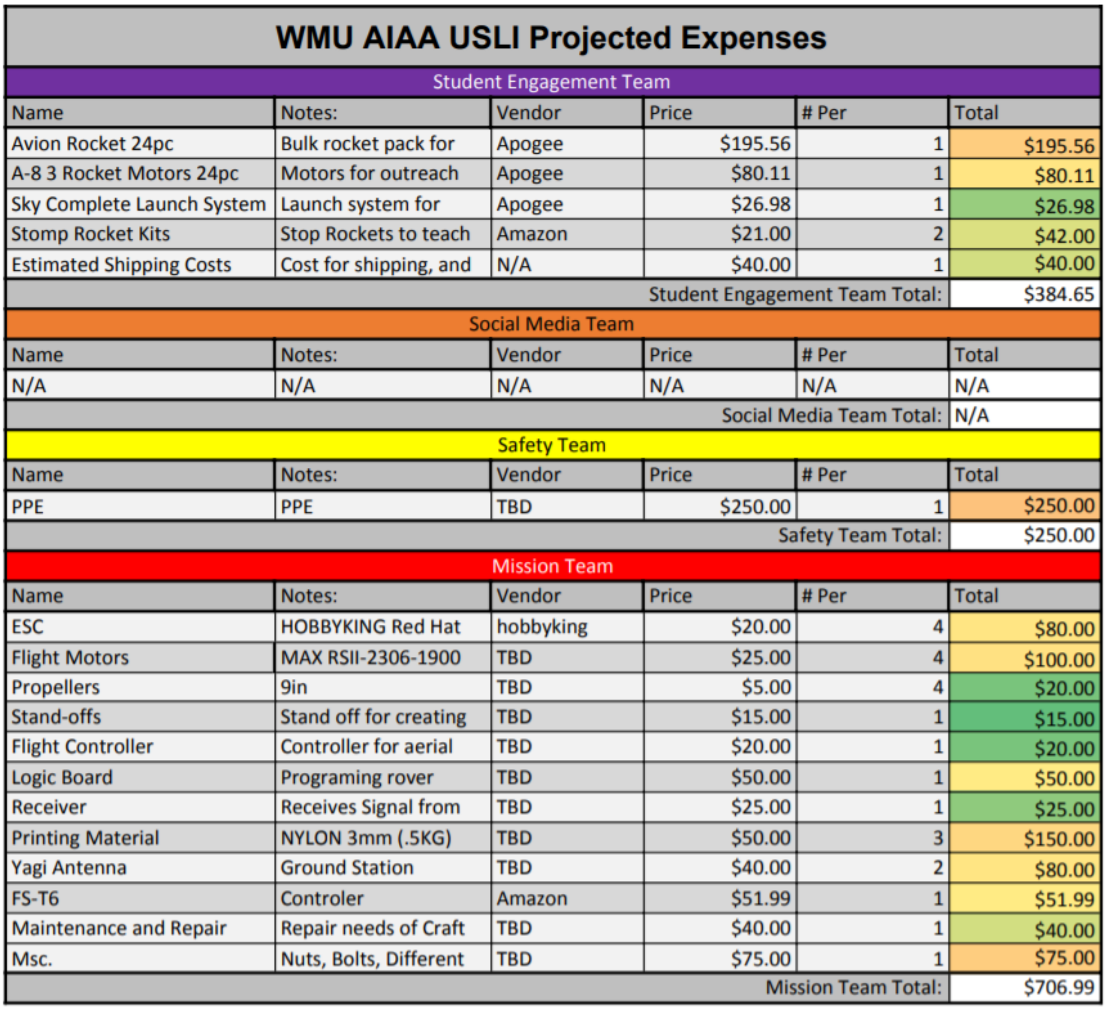
Launch Vehicle Team

Name	Notes:	Vendor	Price	# Per	Total
Small Scale Fins	Wood (2nd)	ARR	$54.95	1	$54.95
3in Airframe	BlueTube (2nd)	ARR	$29.95	2	$59.90
3in Couplers	BlueTube (2nd)	ARR	$9.98	1	$9.98
Av Bay (3in)	BlueTube (2nd)	ARR	$39.95	1	$39.95
Centering Rings (3in)	Wood (2nd)	ARR	$3.49	3	$10.47
Nosecone (3in)	Plastic Ogive (2nd)	ARR	$18.95	1	$18.95
38mm MMT	BlueTube (2nd)	ARR	$16.49	1	$16.49
Custom Slots	(2nd)	ARR	$32.00	1	$32.00
Easy Mini V2		Chris Rocket Supply	$80.00	1	$80.00
6-32 Screw Switch		Chris Rocket Supply	$2.95	4	$11.80
2051- Rail Guides	(1st)	Wildman	$5.00	1	$5.00
7.5in x 48in Airframe	BlueTube	ARR	$89.95	1	$89.95
H219T-14A 38mm	(1st)	Wildman	$39.99	1	$39.99
Shipping Charges		Wildman	$55.17	1	$55.17
Shipping Charges		ARR	$57.85	1	$57.85
Shipping Charges		Chris Rocket Supply	$7.95	1	$7.95
Taxes Collected		Total	$0.00	1	$0.00
				Launch Team Total:	$590.40

Team Travel

Name	Notes:	Vendor	Price	# Per	Total
N/A	N/A	N/A	N/A	N/A	N/A
				Team Travel Total:	$0.00

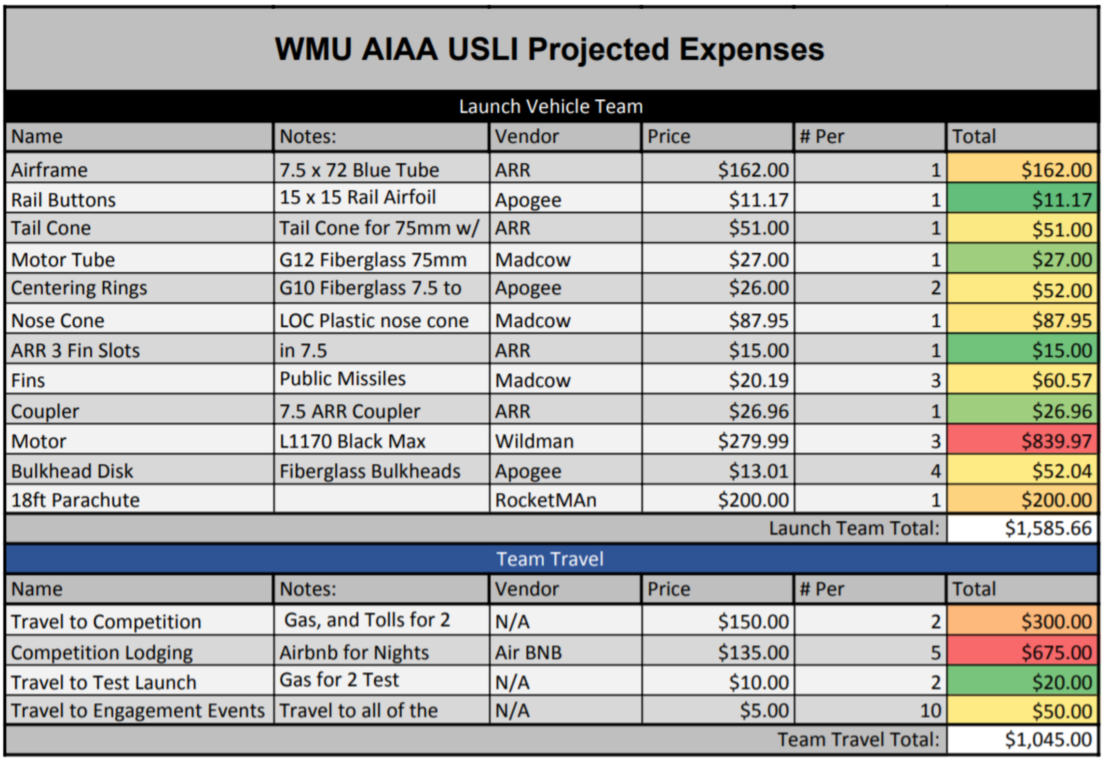
Figure 8.12: Current Expenses



WMU AIAA USLI Projected Expenses

Student Engagement Team					
Name	Notes:	Vendor	Price	# Per	Total
Avion Rocket 24pc	Bulk rocket pack for	Apogee	$195.56	1	$195.56
A-8 3 Rocket Motors 24pc	Motors for outreach	Apogee	$80.11	1	$80.11
Sky Complete Launch System	Launch system for	Apogee	$26.98	1	$26.98
Stomp Rocket Kits	Stop Rockets to teach	Amazon	$21.00	2	$42.00
Estimated Shipping Costs	Cost for shipping, and	N/A	$40.00	1	$40.00
				Student Engagement Team Total:	$384.65
Social Media Team					
Name	Notes:	Vendor	Price	# Per	Total
N/A	N/A	N/A	N/A	N/A	N/A
				Social Media Team Total:	N/A
Safety Team					
Name	Notes:	Vendor	Price	# Per	Total
PPE	PPE	TBD	$250.00	1	$250.00
				Safety Team Total:	$250.00
Mission Team					
Name	Notes:	Vendor	Price	# Per	Total
ESC	HOBBYKING Red Hat	hobbyking	$20.00	4	$80.00
Flight Motors	MAX RSII-2306-1900	TBD	$25.00	4	$100.00
Propellers	9in	TBD	$5.00	4	$20.00
Stand-offs	Stand off for creating	TBD	$15.00	1	$15.00
Flight Controller	Controller for aerial	TBD	$20.00	1	$20.00
Logic Board	Programing rover	TBD	$50.00	1	$50.00
Receiver	Receives Signal from	TBD	$25.00	1	$25.00
Printing Material	NYLON 3mm (.5KG)	TBD	$50.00	3	$150.00
Yagi Antenna	Ground Station	TBD	$40.00	2	$80.00
FS-T6	Controler	Amazon	$51.99	1	$51.99
Maintenance and Repair	Repair needs of Craft	TBD	$40.00	1	$40.00
Msc.	Nuts, Bolts, Different	TBD	$75.00	1	$75.00
				Mission Team Total:	$706.99

Figure 8.13: Projected Cost After CDR



WMU AIAA USLI Projected Expenses

Launch Vehicle Team

Name	Notes:	Vendor	Price	# Per	Total
Airframe	7.5 x 72 Blue Tube	ARR	$162.00	1	$162.00
Rail Buttons	15 x 15 Rail Airfoil	Apogee	$11.17	1	$11.17
Tail Cone	Tail Cone for 75mm w/	ARR	$51.00	1	$51.00
Motor Tube	G12 Fiberglass 75mm	Madcow	$27.00	1	$27.00
Centering Rings	G10 Fiberglass 7.5 to	Apogee	$26.00	2	$52.00
Nose Cone	LOC Plastic nose cone	Madcow	$87.95	1	$87.95
ARR 3 Fin Slots	in 7.5	ARR	$15.00	1	$15.00
Fins	Public Missiles	Madcow	$20.19	3	$60.57
Coupler	7.5 ARR Coupler	ARR	$26.96	1	$26.96
Motor	L1170 Black Max	Wildman	$279.99	3	$839.97
Bulkhead Disk	Fiberglass Bulkheads	Apogee	$13.01	4	$52.04
18ft Parachute		RocketMAn	$200.00	1	$200.00
				Launch Team Total:	$1,585.66

Team Travel

Name	Notes:	Vendor	Price	# Per	Total
Travel to Competition	Gas, and Tolls for 2	N/A	$150.00	2	$300.00
Competition Lodging	Airbnb for Nights	Air BNB	$135.00	5	$675.00
Travel to Test Launch	Gas for 2 Test	N/A	$10.00	2	$20.00
Travel to Engagement Events	Travel to all of the	N/A	$5.00	10	$50.00
				Team Travel Total:	$1,045.00

Figure 8.14: Projected Costs After CDR

8.4.2 TIMELINE

9 APPENDICES

9.1 DFMEA TABLES

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Remains secure during flight	A. Deploys/releases prematurely	Damage to MV	5	Restraint Hook	Structural failure in flight	3	5	75
		Damage to LV	2	Restraint Hook	Structural failure on touchdown	1	1	2
		If in flight, loss of stability of LV	4	Winch Reel	Rotates freely when inactive	3	5	60
		If in flight, loss of mission	5	System Interactions	Launch loads/vibrations damage or trigger system	3	4	60
		Possible loss of LV	5	System Interactions	Early command from Pi	2	N/A	10
	B. Moves in body while restrained	Loss of LV stability	5	Restraint Bolt	Location does not counter flight loads	2	4	40
		Loss of vehicle	5	Restraint Hook	Location does not counter flight loads	2	4	40
		Loss of mission	5	System Interactions	Normal force from body tube does not counter flight loads	1	4	20
	C. Elements structurally fail in flight	Damage to MV	5	Carriage Frame	Material properties insufficient to withstand flight loads	1	4	20
		Damage to LV Loss of stability of LV	5	Restraint Hook	Material properties insufficient to withstand flight loads	3	4	60
		Possible loss of LV Loss of mission	5	Washer (Body)	Embedding method compromises LV structural integrity	2	3	30
2. Deploys drone on command at constant speed	A. Deploys at unsteady speed	Extra wear and tear	2	Carriage Frame	Friction against body tube	2	1	4
			2	Restraint Bolt	Friction against carriage frame	2	1	4
		Increased likelihood of additional deployment failures	2	Restraint Bolt	Does not center frame during deployment	3	1	6
			2	Step Motor	Wear and tear	1	1	2
		Failure of winch system	2	Winch Reel	Improper winding of line on reel	1	1	2
			2	Washers (Both)	Location leads to varying line of action of deployment force	3	1	6
			2	System Interactions	Launch loads/vibrations damage system	3	4	24
	B. Does not deploy when commanded	Loss of mission	4	Actuation Line	Break/snap of line	2	2	16
			4	Actuation Line	Improper tying onto washers	2	1	8
			4	Restraint Servo	Does not fully release hook from carriage	2	2	16
			4	Restraint Servo	Disconnection from Pi	2	N/A	8
			4	Step Motor	Wear and tear	1	1	4
			4	Step Motor	Disconnection from Pi	2	N/A	8
			4	Washers (Both)	Embedding method fails	2	3	24
			4	Washers (Both)	Location leads to varying line of action of deployment force	3	1	12
			4	Winch Reel	Improper winding of line on reel	2	1	8
			4	System Interactions	Launch loads/vibrations damage system	3	4	48
			4	System Interactions	Failure of E/P bay Pi	2	N/A	8
3. Deploys drone for LV landing orientations >= 45 degrees above horizontal	Deployment initiates, but does not complete, when within specified orientation range	Loss of mission	4	Step Motor	Force insufficient for deployment within specified orientations	2	1	8
			4	Washers (Both)	Location leads to varying line of action of deployment force	3	1	12
			4	System Interactions	Landing leg fails	2	N/A	8
			4	System Interactions	Main chute fails to orient vehicle for touchdown	2	N/A	8
4. Extends such that drone has clearance to take off	A. Separates from body on deployment	Damage to MV	3	Actuation Line	Break/snap of line	2	2	12
			3	Actuation Line	Improper tying onto washers	2	1	6
		Possible damage to LV	3	Carriage Frame	Improper installation into body	2	1	6
			3	Step Motor	Rotation speed too rapid	1	1	3
		Possible loss of mission	3	System Interactions	Launch loads/vibrations damage system	3	4	36
			3	System Interactions	No structural failsafe to prevent separation	3	1	9
	B. Incompletely deploys/fails to clear body	Loss of mission	4	Actuation Line	Break/snap of line	2	2	16
			4	Actuation Line	Improper tying onto washers	2	1	8
			4	Carriage Frame	Friction against body tube	2	1	8
			4	Restraint Bolt	Friction against carriage frame	2	1	8
			4	Restraint Bolt	Does not center frame during deployment	3	1	12
			4	Step Motor	Wear and tear	1	1	4
			4	Step Motor	Force insufficient to counter friction	2	1	8
			4	Washers (Both)	Location leads to varying line of action of deployment force	3	1	12
			4	Winch Reel	Improper winding of line on reel	2	1	8
			4	System Interactions	Launch loads/vibrations damage system	3	4	48
			4	System Interactions	Failure of E/P bay Pi	2	N/A	8

Table 9.1: DFMEA results for the drone carriage system.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Secures drone and prevents its movement during entire flight	A. Drone physically breaks free from one or more restraints	Damage to LV	5	Drone Retention Hooks	Structural failure in flight	3	5	75
		Damage to MV	3	Drone Retention Hooks	Structural failure on touchdown	2	1	6
		If only some restraints failed, failure of remaining restraints	5	Drone Retention Hooks	Improper installation	2	1	10
		If in flight, loss of LV stability if more than two restraints fail	5	System Interactions	Launch loads/vibrations damage retention system	3	4	60
		If in flight, loss of vehicle and mission if more than two restraints fail						
	B. Restraints active, but drone shifts during flight	Damage to LV	4	Drone Retention Hooks	Incomplete contact with drone legs when hooks active	3	2	24
		Damage to MV	4	Drone Retention Hooks	Improper installation	2	1	8
		Increased likelihood of restraint failure	4	Drone Retention Hooks	Wear and tear	1	1	4
		If in flight, loss of LV stability	4	Drone Retention Servos	Failure of passive position locking system	3	2	24
			4	System Interactions	Launch loads/vibrations loosen retention hooks or damage servos	3	4	48
	C. One or more restraints release prematurely	Damage to LV	5	Drone Retention Hooks	Improper installation	2	1	10
		Damage to MV	5	Drone Retention Hooks	Wear and tear	1	1	5
		If only some restraints release, failure of remaining restraints	5	Drone Retention Servos	Premature initiation of deployment sequence	2	2	20
		If in flight, loss of LV stability if more than two restraints release	5	Drone Retention Servos	Failure of passive position locking system in flight	3	2	30
		If in flight, loss of vehicle and mission if more than two restraints release	3	Drone Retention Servos	Failure of passive position locking system on touchdown	2	1	6
			5	System Interactions	Launch loads/vibrations release retention hooks or damage servos	3	4	60
2. Completely releases drone upon command from ground	A. One or more restraints only partially release drone	Loss of mission	4	Drone Retention Hooks	Improper installation	2	1	8
			4	Drone Retention Hooks	Wear and tear	1	1	4
			4	Drone Retention Servos	Wear and tear	1	1	4
			4	Drone Retention Servos	Improper installation	2	1	8
			4	System Interactions	Launch loads/vibrations damage retention hooks or servos	3	4	48
			4	System Interactions	Loss of power to LV E/P bay	2	2	16
	B. One or more restraints completely fail to release drone	Loss of mission	4	Drone Retention Hooks	Improper installation	2	1	8
			4	Drone Retention Hooks	Wear and tear	1	1	4
			4	Drone Retention Servos	Wear and tear	1	1	4
			4	Drone Retention Servos	Improper installation	2	1	8
			4	System Interactions	Launch loads/vibrations damage retention hooks or servos	3	4	48
			4	System Interactions	Loss of power to LV E/P bay	2	2	16

Table 9.2: DFMEA results for the drone retention system.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Maintains two way communication with ground station throughout flight and mission	A. All communication lost	Cannot locate vehicle if visual contact lost	5	Antenna	Out of range	3	1	15
		Cannot ascertain whether power levels acceptable for mission	5	Antenna	Disconnection from transceiver or structural failure	2	4	40
			5	Battery	Insufficient charge	3	1	15
		Cannot activate, deploy, and release drone	5	Battery	Disconnection from Pi	2	3	30
			5	Battery	Improper wiring leads to charge depletion	1	1	5
		Loss of vehicle	5	Pi	Unexpected shutdown	2	2	20
			5	WiFi Transceiver	Disconnection from Pi	2	3	30
		Loss of mission	5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
			5	System Interactions	Ground station failure	1	1	5
	B. Uplink observed to be stable, but total telemetry loss	Cannot locate vehicle if visual contact lost	5	Pi	Programming error	2	1	10
		Cannot ascertain whether power levels acceptable for mission	5	System Interactions	Ground station failure	1	1	5
		Loss of vehicle Loss of mission	5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
	C. Downlink observed to be stable, but complete loss of command capability	Cannot activate, deploy, and release drone	4	Pi	Programming error	2	1	8
			4	Pi	Disconnection from servos or drone Pi	2	3	24
		Loss of mission	4	System Interactions	Ground station failure	1	1	4
			4	System Interactions	Launch loads/vibrations damage circuit or components	3	4	48
2. Monitors and relays accurate battery levels of E/P bay in real time throughout flight (and MV until deployment)	A. Uplink observed to be stable, but partial or total loss of battery level telemetry	Cannot ascertain whether power levels acceptable for mission	3	Battery Monitor	Disconnection from Pi, LV battery, or drone batteries	2	3	18
			3	Pi	Programming error	2	1	6
		Loss of mission	3	System Interactions	Ground station failure	1	1	3
			3	System Interactions	Launch loads/vibrations damage circuit or components	3	4	36
	B. Incorrect battery levels relayed	Power levels incorrectly ascertained to be acceptable for mission	3	Battery Monitor	Improper connection to batteries	1	1	3
			3	Pi	Programming error	2	1	6
		Loss of mission	3	System Interactions	Launch loads/vibrations introduce noise into signals	1	3	9
			3	System Interactions	Launch loads/vibrations damage circuit or components	3	4	36
3. Obtains and relays accurate GPS coordinates of LV in real-time throughout flight	A. Uplink observed to be stable, but loss of GPS telemetry	Cannot locate vehicle if visual contact lost	5	GPS Module	Disconnection from Pi	2	3	30
			5	GPS Module	Saturation	4	5	100
		Loss of vehicle	5	GPS Module	Loss of signal to GPS constellation	2	1	10
			5	Pi	Programming error	2	1	10
		Loss of mission	5	System Interactions	Ground station failure	1	1	5
			5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
	B. Incorrect GPS coordinates relayed	If visual contact lost, assumed location of vehicle incorrect	5	GPS Module	Saturation	4	5	100
		Loss of vehicle	5	GPS Module	Unable to obtain proper fix	2	1	10
			5	Pi	Programming error	2	1	10
		Loss of mission	5	System Interactions	Launch loads/vibrations introduce noise into signals	1	3	15
			5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
4. Awakens drone and signals servos (TALL, drone carriage actuation, and drone retention) upon command from ground	A. Failure to command some, but not all, of the servo groups	Drone cannot be placed into position where it can properly take off	4	Pi	Programming error	2	1	8
		Loss of mission	4	System Interactions	Failure of servos	2	N/A	8
			4	System Interactions	Launch loads/vibrations damage circuit or components	3	4	48
	B. Failure to awaken drone	Drone cannot begin mission	4	Pi	Programming error	2	1	8
			4	System Interactions	Loss of power on mission vehicle	2	N/A	8
		Loss of mission	4	System Interactions	Programming error on drone Pi	2	N/A	8
			4	System Interactions	Launch loads/vibrations damage circuit or components	3	4	48
	C. Premature command sent to one or more servos	If in flight, loss of LV stability	5	Pi	Programming error	2	1	10
		If in flight, loss of vehicle	5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
		If in flight, loss of mission	5	System Interactions	Premature command from ground station	1	N/A	5
	D. Drone is awakened prematurely	Increased battery usage by drone	3	Pi	Programming error	2	1	6
		Loss of mission	3	System Interactions	Launch loads/vibrations damage circuit or components	3	4	36
			3	System Interactions	Premature command from ground station	1	N/A	3
5. Wire to drone releases when deployment begins	Failure to disconnect from MV when mission phase begins	Damage to MV Damage to LV Loss of mission	3	System Interactions	Interface between E/P bay and drone does not function properly	3	1	9

Table 9.3: DFMEA results for the LV comms/control system.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Engages and disengages upon command from ground	A. Does not engage on command from ground	Loss of mission	4	Electric Motors	Disconnection from Pi	2	3	24
			4	Electric Motors	Wear and tear	2	1	8
			4	System Interactions	Launch loads/vibrations damage system components	3	4	48
			4	System Interactions	Pi does not relay command to motors	2	N/A	8
			4	System Interactions	MV power loss	3	N/A	12
	B. Does not disengage on command from ground	Increased drone battery consumption Sample loss Loss of mission	4	System Interactions	Pi does not relay command to motors	2	N/A	8
	C. System engages prematurely	Increased drone battery consumption Loss of MV power Loss of mission	4	System Interactions	Early command from Pi	1	N/A	4
	D. System disengages prematurely	Incomplete sample collection	3	Electric Motors	Disconnection from Pi	2	3	18
			3	Electric Motors	Wear and tear	2	1	6
		Partial mission failure	3	System Interactions	Launch loads/vibrations damage system components	3	4	36
			3	System Interactions	Early command from Pi	1	N/A	3
			3	System Interactions	MV power loss	3	N/A	9
2. Smoothly intakes granules that approximate expected sample material	A. Sample intake rate unsteady	Increased likelihood of additional failures	2	Brush Roller	Wear and tear	3	1	6
		Incomplete sample collection	2	Brush Roller	Improper installation	2	2	8
			2	Electric Motors	Wear and tear	2	1	4
		Partial mission failure	2	System Interactions	Launch loads/vibrations damage system components	3	4	24
			3	System Interactions	Unsteady MV power	2	N/A	6
		Damage to system	3	Brush Cover	Improper installation	2	2	12
			3	Brush Roller	Improper installation	2	2	12
	B. System partially jams during intake	Incomplete sample collection	3	Brush Roller	Wear and tear	3	1	9
			3	Brush Roller	Brush force insufficient to move granules	1	1	3
		Partial mission failure	3	Electric Motors	Wear and tear	2	1	6
			3	System Interactions	Launch loads/vibrations damage system components	3	4	36
			3	System Interactions	Insufficient MV power	3	N/A	9
	C. System completely jams during intake	Damage to system	4	Brush Cover	Insufficient clearance for granules	2	2	16
			4	Brush Cover	Improper installation	2	2	16
			4	Brush Roller	Improper installation	2	2	16
		Incomplete sample collection	4	Brush Roller	Wear and tear	3	1	12
			4	Brush Roller	Brush force insufficient to move granules	1	1	4
			4	Collection Bin	Overflow of reservoir into brush roller	4	2	32
		Partial or total mission failure	4	Electric Motors	Wear and tear	2	1	8
			4	System Interactions	Launch loads/vibrations damage system components	3	4	48
			4	System Interactions	Insufficient MV power	3	N/A	12
3. Intakes at least 150 mL of sample granules	System does not collect at least 150 mL of sample material	Partial or total mission failure	3	Brush Cover	Design does not redirect granules toward collection bin	2	1	6
			3	Brush Cover	Vibrations and loads loosen cover	3	4	36
			3	Brush Cover	Improper installation	2	2	12
			3	Brush Roller	Design does not collect granules it contacts	1	1	3
			3	Brush Roller	Wear and tear	3	1	9
			3	Brush Roller	Improper installation	2	2	12
			3	Collection Bin	Opening to brush roller is too small	3	1	9
			3	Electric Motors	Wear and tear	2	1	6
			3	System Interactions	Launch loads/vibrations damage system components	3	4	36
4. Collected sample remains contained in MV during flight	Collected sample does not remain in MV during transport	Partial or total mission failure	4	Collection Bin	Design does not contain sample through entire flight envelope	4	2	32
			4	Collection Bin	Too much sample material collected	4	1	16
			4	System Interactions	Launch loads/vibrations damage system components	3	4	48

Table 9.4: DFMEA results for the sample retrieval system.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Maintains two way communication with ground station computer and controller throughout flight and mission	A. All communication to Pi lost	If drone in mission flight, inability to toggle sample retrieval system	5R	Antennas (LoRa & WiFi)	Simultaneously out of range	1R	1	5
			5R	Antennas (LoRa & WiFi)	Simultaneous disconnections from transceiver or structural failures	1R	3	15
		If drone in E/P bay, inability to engage flight controller and motors	5	Pi	Unexpected shutdown	2	2	20
			5	Battery (Primary)	Insufficiently charged	3	1	15
		If visual contact lost, inability to locate MV	5	Battery (Primary)	Improper wiring leads to charge depletion	1	1	5
			5	Battery (Primary)	Disconnection from battery distributor	2	3	30
		Loss of MV	5	Battery Distributor	Disconnection from Pi	2	3	30
			5R	Transceivers (LoRa & WiFi)	Simultaneous disconnection from Pi	1R	3	15
		Loss of mission	5R	System Interactions	Launch loads/vibrations damage circuit or components	3R	4	60
			5R	System Interactions	Ground station failure	1R	N/A	5
	B. Total loss of primary communication to Pi	Temporary telemetry dropout while switching to secondary	2	Antenna (WiFi)	Out of range	3	1	6
			2	Antenna (WiFi)	Disconnection from transceiver or structural failure	2	3	12
			2	Pi	Programming error	2	1	4
		Loss of communication redundancy	2	Transceiver (WiFi)	Disconnection from Pi	2	3	12
			2	System Interactions	Launch loads/vibrations damage circuit or components	3	4	24
			2	System Interactions	Ground station failure	1	N/A	2
	C. Total loss of secondary communication to Pi	Loss of communication redundancy	1	Antenna (LoRa)	Out of range	1	1	1
			1	Antenna (LoRa)	Disconnection from transceiver or structural failure	2	3	6
			1	Pi	Programming error	2	1	2
			1	Transceiver (LoRa)	Disconnection from Pi	2	3	6
			1	System Interactions	Launch loads/vibrations damage circuit or components	3	4	12
			1	System Interactions	Ground station failure	1	N/A	1
	D. Downlink observed to be stable, but complete loss of command capability to Pi	If drone in mission flight, inability to toggle sample retrieval system	4R	Pi	Programming error	2R	1	8
		If drone in E/P bay, inability to engage flight controller and motors	4R	Pi	Disconnection from sample retrieval and boom retention servos	2R	3	24
		Loss of mission	4R	System Interactions	Ground station failure	1R	N/A	4
			4R	System Interactions	Launch loads/vibrations damage circuit or components	3R	4	48
	E. Loss of flight controller command capability	If drone in mission flight, loss of stability and/or control	5	Flight Controller	Programming error	2	2	20
		If drone in mission flight, uncontrolled impact w/ ground	5	Flight Controller	Disconnection from Pi	2	3	30
		Loss of MV	5	Flight Controller	Out of range of ground controller	1	1	5
			5	Pi	Programming error	2	1	10
		Loss of mission	5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
			5	System Interactions	Ground controller failure	1	N/A	5
	F. Loss of flight controller telemetry	Unable to ensure acceptable battery levels	3	Flight Controller	Programming error	2	2	12
		Loss of MV	3	Flight Controller	Out of range of ground controller	1	1	3
		Loss of mission	3	System Interactions	Launch loads/vibrations damage circuit or components	3	4	36
			3	System Interactions	Ground controller failure	1	N/A	3
2. Awakens upon signal from E/P Bay	Does not awaken upon signal from E/P bay	Loss of mission	4	Battery (Idle)	Insufficiently charged	3	1	12
			4	Battery Distributor	Disconnection from Pi	2	3	24
			4	Pi	Programming error	2	1	8
			4	System Interactions	Launch loads/vibrations damage circuit or components	3	4	48
			4	System Interactions	Ground station failure	1	N/A	4
3. Obtains and relays accurate GPS coordinates of MV in real-time throughout mission	A. Uplink observed to be stable, but loss of GPS telemetry	If visual contact lost, inability to locate MV	4	GPS Module	Disconnection from Pi	2	2	16
			4	GPS Module	Saturation	3	5	60
		Loss of MV	4	GPS Module	Loss of signal to GPS constellation	2	1	8
			4	Pi	Programming error	2	1	8
		Loss of mission	4	System Interactions	Ground station failure	1	N/A	4
			4	System Interactions	Launch loads/vibrations damage circuit or components	3	4	48
	B. Incorrect GPS coordinates relayed	If visual contact lost, assumed location of vehicle incorrect	5	GPS Module	Saturation	3	5	75
		Loss of MV	5	GPS Module	Unable to obtain proper fix	2	1	10
			5	Pi	Programming error	2	1	10
		Loss of mission	5	System Interactions	Mission flight loads/vibrations introduce noise into signals	1	1	5
			5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60

Table 9.5: The first half of the DFMEA results for the mission vehicle.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
4. Deploys rotor booms and toggles sample retrieval system on command from ground	A. Rotor booms do not deploy when commanded	Motors not in position to safely engage	4	Battery (Primary)	Insufficiently charged	3	1	12
			4	Battery (Primary)	Disconnection from battery distributor	2	3	24
			4	Battery (Primary)	Improper wiring leads to charge depletion	1	1	4
			4	Battery Distributor	Disconnection from Pi	2	3	24
		Loss of mission	4	Boom Retention Servos	Disconnection from Pi	2	3	24
			4	Boom Retention Servos	Wear and tear	1	1	4
			4	Booms	Actuation torque insufficient for deployment	3	1	12
			4	Pi	Programming error	2	1	8
			4	System Interactions	Launch loads/vibrations damage circuit or components	3	4	48
	B. Rotor booms deploy incompletely	Motors not in position to safely engage	5	Booms	Actuation torque insufficient for deployment	3	1	15
		If locking fails and vehicle takes off, loss of stability and/or control	5	Booms	Booms do not lock into place	3	1	15
		Loss of MV	5	Booms	Wear and tear	1	1	5
		Loss of mission	5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
	C. Rotor booms deploy prematurely	If prior to drone deployment, damage to MV and LV	5	Boom Retention Servos	Structural failure	2	4	40
		If during launch, loss of LV stability	5	Boom Retention Servos	Material strength of retainer insufficient to oppose deployment actuator	2	1	10
		Loss of vehicle	5	Pi	Programming error	2	1	10
		Loss of mission	5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
			5	System Interactions	Ground station failure	1	N/A	5
	D. Sample retrieval system does not engage when commanded	Loss of mission	4	Battery Distributor	Disconnection from sample retrieval system	2	3	24
			4	Pi	Programming error	2	1	8
			4	Pi	Disconnection from sample retrieval system	2	3	24
			4	System Interactions	Launch loads/vibrations damage circuit or components	3	4	48
			4	System Interactions	Ground station failure	1	N/A	4
5. First person view system relays video to ground station during mission	Loss of FPV capabilities	Increased difficulty in flying MV	2	FPV Camera	Disconnection from Pi	2	3	12
			2	FPV Camera	Debris damage during flight	1	5	10
			2	Pi	Programming error	2	1	4
			2	Transceiver (WiFi)	Connection unable to support video transmission	2	1	4
			2	System Interactions	Launch loads/vibrations damage circuit or components	3	4	24
			2	System Interactions	Ground station failure	1	N/A	2
6. Vehicle maintains stability in flight, remains intact, and executes flight commands from ground controller	A. Vehicle experiences structural failure	If during launch, damage to LV	5	Body	Material cannot withstand launch/landing loads	3	4	60
		If during launch, loss of LV stability	5	Booms	Material cannot withstand launch/landing loads	3	4	60
		Damage to MV	5	Booms	Booms cannot withstand combined forces of weight and propulsion	3	3	45
		Loss of vehicle	5	Props	Debris or wear and tear result in blade shearing	2	1	10
		Loss of mission	5	System Interactions	Launch loads/vibrations damage vehicle structure	3	4	60
	B. Vehicle loses stability during mission flight	Loss of MV	5	Body	CoG not aligned with CoT	3	1	15
			5	Booms	Incomplete deployment	3	1	15
			5	Battery (Primary)	Insufficiently charged	3	1	15
			5	ESCs	Failure or disconnection of one or more units	2	3	30
			5	ESCs	Improper calibration	2	1	10
			5	Flight Controller	Programming error	2	1	10
			5	Flight Controller	Improper calibration	2	1	10
		Loss of mission	5	Motors	Wear and tear	1	1	5
			5	Motors	Failure or disconnection of one or more units	2	3	30
			5	Props	Wear and tear	2	1	10
			5	Props	Structural failure	2	1	10
			5	System Interactions	Launch loads/vibrations damage vehicle structure, circuit, or components	3	4	60
			5	System Interactions	Ground station failure	1	N/A	5
		Loss of stability and/or control	5	ESCs	Improper calibration	2	1	10
	C. Vehicle does not properly respond to flight control signals from ground	Loss of MV	5	Flight Controller	Improper calibration	2	1	10
			5	Flight Controller	Programming error	2	2	20
		Loss of mission	5	System Interactions	Launch loads/vibrations damage circuit or components	3	4	60
			5	System Interactions	Ground station failure	1	N/A	5

Table 9.6: The second half of the DFMEA results for the mission vehicle.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Provides telemetry (GPS, battery levels) from MV and LV throughout mission and sends commands to Pis	A. Loss of all telemetry and Pi command capability for all vehicle components	Inability to locate LV and/or MV	5R	Antennas (All)	Simultaneous failure or disconnection of all antennas	1R	1	5
		Inability to send commands to LV and MV for mission initiation	5	Computer	Unexpected shutdown	2	2	20
			5	Computer	Programming/network configuration error	2	1	10
		Loss of vehicle	5	Power Supply	Loss of power	3	1	15
			5	Power Supply	Disconnection from computer	2	1	10
		Loss of mission	5	Router	Unexpected shutdown	3	2	30
			5	Router	Disconnection from computer	2	1	10
	B. Loss of telemetry and command capability on LV	Inability to locate LV	5	Antenna (WiFi 1)	Disconnection from router	2	1	10
		Inability to deploy TALL, carriage, and drone retention system	5	Antenna (WiFi 1)	Insufficient range	3	1	15
		Inability to monitor LV and MV battery levels	5	Computer	Programming/network configuration error	2	1	10
		Loss of vehicle	5	Router	Network configuration error	2	1	10
		Loss of mission						
	C. Loss of all telemetry and Pi command capability on MV	Inability to locate MV	5R	Antennas (WiFi 2 and LoRa)	Simultaneous failure or disconnection of both antennas	1R	1	5
		Inability to activate flight controller and motors	5R	Antennas (WiFi 2 and LoRa)	Insufficient range on both antennas	1R	1	5
		Inability to engage sample retrieval system	5	Computer	Programming/network configuration error	2	1	10
		Loss of MV	5	Router	Network configuration error	2	1	10
		Loss of mission						
	D. Loss of primary telemetry and Pi command capability on MV	Loss of communication redundancy on MV	2	Antenna (WiFi 2)	Failure or disconnection from router	2	1	4
			2	Antenna (WiFi 2)	Insufficient range	3	1	6
		Temporary communication drop during switch to secondary	2	Computer	Programming/network configuration error	2	1	4
			2	Router	Network configuration error	2	1	4
	E. Loss of secondary telemetry and Pi command capability on MV	Loss of communication redundancy on MV	1	Antenna (LoRa)	Failure or disconnection from router	2	1	2
			1	Antenna (LoRa)	Insufficient range	1	1	1
			1	Computer	Programming/network configuration error	2	1	2
			1	Router	Network configuration error	2	1	2
2. Provides data and RC commands to MV flight controller throughout mission	Loss of flight controller data and command capability on MV	Inability to engage flight of MV	5	RC Controller	Insufficient range	1	1	5
		If in flight, inability to control/stabilize MV						
		Loss of MV	5	RC Controller	Loss of power	3	1	15
		Loss of mission						

Table 9.7: DFMEA results for the ground station.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Deploys upon command from ground within 10 seconds	A. Leg does not deploy when commanded	LV in improper orientation for deployment of carriage	4	Landing Leg	Leg fits too snugly in LV body	2	1	8
			4	Landing Leg Servos	Disconnection from landing leg	2	2	16
			4	Landing Leg Servos	Insufficient force to deploy leg	3	1	12
		Loss of mission	4	Landing Leg Servos	Wear and tear	1	1	4
			4	System Interactions	Launch loads/vibrations damage system	3	4	48
			4	System Interactions	No command from Pi	1	N/A	4
	B. Leg deploys prematurely	Loss of LV stability	5	Landing Leg	Leg fits too loosely in LV body	2	1	10
		Structural failure of leg	5	System Interactions	Launch loads/vibrations damage system	3	4	60
		Loss of vehicle	5	System Interactions	Early command from Pi	1	N/A	5
		Loss of mission	5	System Interactions	Pressure gradient during flight causes deployment	3	5	75
	C. Leg deploys incompletely	LV in improper orientation for deployment of carriage	3	Landing Leg Servos	Wear and tear	1	1	3
		Loss of mission	3	System Interactions	Friction from LV body at interface	2	1	6
			3	System Interactions	Launch loads/vibrations damage system	3	4	36
		If command issued just before touchdown, leg unable to finish deploying	3	Landing Leg Servos	Insufficient force to deploy leg	3	1	9
	D. Leg takes more than 10 seconds to deploy	LV in improper orientation for deployment of carriage	3	Landing Leg Servos	Wear and tear	1	1	3
		Loss of mission	3	System Interactions	Friction from LV body at interface	2	1	6
			3	System Interactions	Launch loads/vibrations damage system	3	4	36
2. Withstands force of landing and stabilizes vehicle on ground	A. Leg structurally fails on landing	Damage to LV	4	Landing Leg	Material properties insufficient to withstand landing force	2	1	8
		LV in improper orientation for deployment of carriage	4	System Interactions	Launch loads/vibrations damage system	3	4	48
		Loss of mission						
	B. Leg does not prevent vehicle from rolling over on touchdown	LV in improper orientation for deployment of carriage	4	Landing Leg	Size of foot too small	2	1	8
		Loss of mission	4	System Interactions	Leg location/deployment length do not create stable tripod when combined with fins	2	1	8
3. Raises MV exit point to be level with the horizon at a minimum	Leg does not raise MV exit point to be level with the horizon when fully deployed	LV in improper orientation for deployment of carriage	4	Landing Leg	Maximum deployment length is too short to level vehicle on terrain within performance specs	2	1	8
		Loss of mission						

Table 9.8: DFMEA results for the landing leg system.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Fires black powder at apogee to separate nose cone and initiate secondary recovery (drogue phase)	A. Primary drogue altimeter does not fire at apogee	Loss of redundancy of drogue altimeters	2	Activation Switch (Drogue 1)	In "off" position	2	1	4
			2	Altimeter (Drogue 1)	Improper setting/timing error	2	2	8
			2	Battery (Drogue 1)	Insufficient charge	3	1	6
			2	Safety Switch (Drogue 1)	In "off" position	2	1	4
			2	System Interactions	Launch loads/vibrations damage system	3	4	24
	B. Secondary drogue altimeter does not fire at apogee	Loss of redundancy of drogue altimeters	1	Activation Switch (Drogue 2)	In "off" position	2	1	2
			1	Altimeter (Drogue 2)	Improper setting/timing error	2	2	4
			1	Battery (Drogue 2)	Insufficient charge	3	1	3
			1	Safety Switch (Drogue 2)	In "off" position	2	1	2
			1	System Interactions	Launch loads/vibrations damage system	3	4	12
	C. Neither drogue altimeter fires	Vehicle unstable during descent	5R	Activation Switches (Both Drogue)	In "off" position	1R	1	5
		Drogue chute does not deploy	5R	Altimeters (Both Drogue)	Improper setting/timing error	1R	2	10
		Descent rate too high for main chute deployment	5R	Battery (Both Drogue)	Insufficient charge	2R	1	10
		Loss of vehicle	5R	Safety Switch (Both Drogue)	In "off" position	1R	1	5
		Loss of mission	5	System Interactions	Launch loads/vibrations damage system	3	4	60
	D. One or both drogue altimeters fire during ascent	Early nosecone separation LV structural failure from aerodynamic forces	5	Altimeter (Any Drogue)	Improper setting/timing error	2	2	20
		Loss of LV stability Loss of vehicle Loss of mission	5	System Interactions	Launch loads/vibrations damage or trigger system	3	4	60
	E. Both drogue altimeters fire after apogee	Descent rate too high for drogue chute deployment Vehicle unstable during descent	4R	Altimeter (Both Drogue)	Improper setting/timing error	2R	2	16
		Loss of vehicle Loss of mission	4	System Interactions	Launch loads/vibrations damage system	3	4	48
	F. Primary drogue altimeter fires, but nosecone does not separate	Loss of redundancy of drogue altimeters	2	E-Match (Drogue 1)	Insufficient quantity of black powder loaded	1	2	4
	G. Both drogue altimeters fire, but nosecone does not separate	Vehicle unstable during descent Drogue chute does not deploy Descent rate too high for drogue chute deployment Loss of vehicle Loss of mission	5R	E-Matches (Both Drogue)	Insufficient quantities of black powder loaded	1R	2	10
2. Fires black powder at 550 ft AGL to separate lower LV and AV bay to initiate primary recovery (main phase)	A. Primary main altimeter does not fire at 550 ft AGL	Loss of redundancy of main altimeters	2	Activation Switch (Main 1)	In "off" position	2	1	4
			2	Altimeter (Main 1)	Improper setting/timing error	2	2	8
			2	Battery (Main 1)	Insufficient charge	3	1	6
			2	Safety Switch (Main 1)	In "off" position	2	1	4
			2	System Interactions	Launch loads/vibrations damage system	3	4	24
	B. Secondary main altimeter does not fire at 550 ft AGL	Loss of redundancy of main altimeters	1	Activation Switch (Main 2)	In "off" position	2	1	2
			1	Altimeter (Main 2)	Improper setting/timing error	2	2	4
			1	Battery (Main 2)	Insufficient charge	3	1	3
			1	Safety Switch (Main 2)	In "off" position	2	1	2
			1	System Interactions	Launch loads/vibrations damage system	3	4	12
	C. Neither main altimeter fires	Main chute does not deploy	5R	Activation Switch (Both Main)	In "off" position	1R	1	5
		Lower and upper LV do not separate	5R	Altimeter (Both Main)	Improper setting/timing error	1R	2	10
		Drone deployment impossible	5R	Battery (Both Main)	Insufficient charge	2R	1	10
		Descent rate too high for safe touchdown	5R	Safety Switch (Both Main)	In "off" position	1R	1	5
		Damage to or loss of vehicle Loss of mission	5	System Interactions	Launch loads/vibrations damage system	3	4	60
	D. One or both main altimeters fire during ascent	Early lower and upper LV separation LV structural failure from aerodynamic forces	5	Altimeter (Any Main)	Improper setting/timing error	2	2	20
		Loss of LV stability Loss of vehicle Loss of mission	5	System Interactions	Launch loads/vibrations damage or trigger system	3	4	60
	E. One or both main altimeters fire between apogee and 550 ft AGL	Early lower and upper LV separation Descent time extended	4	Altimeter (Any Main)	Improper setting/timing error	2	2	16
		Increased drift distance of LV components If GPS and visual contact lost, loss of vehicle If GPS and visual contact lost, loss of mission	4	System Interactions	Launch loads/vibrations damage or trigger system	3	4	48
	F. Both main altimeters fire below 550 ft AGL	Main chute cannot deploy in time to ensure safe touchdown velocity	5R	Altimeter (Any Main)	Improper setting/timing error	1R	2	10
		Damage to or loss of vehicle Loss of mission	5	System Interactions	Launch loads/vibrations damage system	3	4	60
	G. Primary main altimeter fires, but lower LV does not separate	Loss of redundancy of main altimeters	2	E-Match (Main 1)	Insufficient quantity of black powder loaded	1	2	4
	H. Both main altimeters fire, but lower LV does not separate	Main chute does not deploy Lower and upper LV do not separate Drone deployment impossible Descent rate too high for safe touchdown Damage to or loss of vehicle Loss of mission	5R	E-Match (Both Main)	Insufficient quantities of black powder loaded	1R	2	10
3. Detonations do not impact structural integrity of vehicle	Any altimeter firing causes vehicle structural failure	Loss of LV stability	5	Bolts	Material properties or configuration insufficient to withstand ejection loads	1	3	15
		Unexpected separation of vehicle components in midair	5	E-Matches (Any)	Too much black powder loaded	1	2	10
		Damage to or loss of vehicle	5	E-Matches (Any)	Force exerted too great for vehicle structures	2	3	30
		Loss of mission	5	Mounts (Any)	Material properties insufficient to withstand ejection loads	1	3	15

Table 9.9: DFMEA results for the avionics bay.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Shields internal vehicle components and ensures smooth airflow over front of vehicle	A. Forward section of LV exposed to incoming flow	Loss of LV stability	5	Nosecone	Structural failure	1	3	15
		Damage to or loss of vehicle	5	Nosecone	Fit too loose	1	1	5
		Loss of mission	5	System Interactions	Launch loads/vibrations damage or loosen nosecone	2	3	30
	B. Airflow over vehicle nose is turbulent/compromises overall vehicle aerodynamics	Loss of LV stability	5	Nosecone	Incomplete or asymmetrical sanding/refining	2	1	10
		Loss of vehicle						
		Loss of mission						
2. Deploys drogue chute to stabilize vehicle when AV bay fires	Drogue chute does not deploy when AV bay fires	Unstable/uncontrolled vehicle descent	5	Drogue Chute	Improper stowage	3	1	15
		Loss of vehicle	5	Drogue Chute	Line tangling	3	3	45
			5	Drogue Chute	Cannot support full LV	2	1	10
		Loss of mission	5	Nosecone	Fit too tight	2	1	10
			5	System Interactions	Launch or ejection loads/vibrations damage, loosen, or tangle components	3	3	45
3. Safely lowers all upper LV components to touchdown	A. Upper LV descends too rapidly for safe touchdown	Loss of all or part of vehicle	5	Drogue Chute	Damage to chute material	3	2	30
			5	Drogue Chute	Improper stowage	3	1	15
			5	Drogue Chute	Line tangling	3	3	45
			5	Drogue Chute	Separation from shock cord	3	2	30
		If lower LV attached, loss of mission	5	Drogue Chute	Chute cannot support vehicle	1	1	5
			5	Nosecone	Fit too tight	1	1	5
			5	System Interactions	Lower LV does not separate	3	N/A	15
			5	System Interactions	Launch or ejection loads/vibrations damage, loosen, or tangle components	3	3	45
	B. Nosecone or AV bay separates from upper LV assembly	Loss of part of LV	5	Shock Cord	Snap or separation of cord	2	2	20
		Uncontrolled descent of part of LV	5	System Interactions	Launch or ejection loads/vibrations damage, loosen, or tangle components	3	3	45
4. Relays accurate location of upper LV to ground station	Correct GPS location not relayed to ground station	If visual contact lost, inability to locate upper LV	4	COTS Integrated GPS	Loss of power	2	2	16
			4	COTS Integrated GPS	Loss of signal to GPS constellation	2	1	8
			4	COTS Integrated GPS	Out of range of ground station	2	1	8
		Loss of part of LV	4	COTS Integrated GPS	Inability to obtain proper fix	1	1	4
			4	System Interactions	Launch or ejection loads/vibrations damage components	3	3	36
			4	System Interactions	Ground station failure	1	N/A	4

Table 9.10: DFMEA results for the upper launch vehicle and secondary recovery system.

Function	Failure Mode	Possible Effects	Sev	Item	Cause	Occ	Det	RPN
1. Motor ignites when commanded and launches vehicle to target altitude	A. Motor does not ignite when commanded	Delayed ignition of motor	3	Ignition System	Improper wiring	2	1	6
		Failed launch attempt	1	Ignition System	Safety switch not disengaged	1	1	1
		Risk of fire or explosion	3	Motor	Improper propellant loading	2	1	6
	B. Motor ignites prematurely	Launch occurs prior to checklist completion	5	Ignition System	Improper wiring	2	1	10
		Risk of fire or explosion	5	Ignition System	Safety switch accidentally disengaged	1	1	5
			5	Motor	Improper propellant loading	2	1	10
	C. Vehicle fails to clear pad area	Damage to or loss of vehicle	5	Ignition System	Improper wiring	2	1	10
			5	Launch Lugs	Friction against launch rail	1	1	5
		Risk of fire or explosion	5	Launch Lugs	Separation from vehicle	3	2	30
			5	Motor	Improper propellant loading	2	1	10
		Possible loss of mission	5	Motor	Incomplete ignition	2	5	50
			5	Motor	Insufficient TWR	1	1	5
			5	System Interactions	Launch rail improperly oriented	1	1	5
	D. Vehicle fails to reach target altitude	Failure of mission objective	3	Motor	Incorrect type	1	1	3
2. Motor burns normally and vehicle remains stable during flight	A. Motor casing ruptures	Loss of LV stability	5	Ignition System	Improper wiring	2	1	10
		Significant damage to or loss of vehicle	5	Motor	Improper propellant loading	2	1	10
			5	Motor	Mishandling	2	2	20
		Loss of mission	5	Motor Mount	Structural failure	3	3	45
			5	Centering Rings	Structural failure	2	3	30
		Risk of fire or explosion	5	Airframe	Structural failure	1	3	15
			5	System Interactions	Vibrations/launch loads damage motor	1	3	15
	B. Motor explodes	Loss of vehicle	5	Airframe	Structural failure	1	2	10
			5	Ignition System	Improper wiring	2	1	10
			5	Motor	Improper propellant loading	2	1	10
		Loss of mission	5	Motor	Mishandling	2	2	20
			5	Motor Mount	Structural failure	3	3	45
		Risk of fire	5	Centering Rings	Structural failure	2	3	30
			5	System Interactions	Vibrations/launch loads damage motor	2	3	30
	C. LV loses stability during flight	Possible loss of vehicle	5	Airframe	CoG through flight not aligned with CoT	2	1	10
			5	Centering Rings	Structural failure	1	3	15
			5	Centering Rings	Improper installation	3	1	15
			5	Fins	Structural failure	2	3	30
			5	Fins	Separation from vehicle	3	3	45
		Loss of mission	5	Fins	Improper installation	3	1	15
			5	Motor	Asymmetrical burn	1	5	25
			5	Motor Mount	Structural failure	3	3	45
			5	Motor Mount	Improper installation	3	1	15
			5	Nozzle	Asymmetrical contour	1	2	10
			5	System Interactions	Vibrations/launch loads damage system	3	3	45
3. Lower LV separates from upper LV and deploys main parachute at appropriate time	A. Lower LV does not separate from upper LV	Rapid vehicle descent	5	Shear Pins	Necessary break force higher than staging force	2	3	30
		Damage to or loss of vehicle	5	System Interactions	Fit of lower LV to AV bay too tight	1	1	5
		Loss of mission	5	System Interactions	AV bay failure	1	N/A	5
	B. Lower LV separates from upper LV prematurely	Loss of LV stability	5	Shear Pins	Necessary break force less than launch loads	2	3	30
		Damage to or loss of vehicle	5	System Interactions	Fit of lower LV to AV bay too loose	1	1	5
		Loss of mission	5	System Interactions	AV bay failure	1	N/A	5
	C. Main parachute does not deploy	Rapid/uncontrolled vehicle descent	5	Main Parachute	Improper stowage	3	1	15
		Loss of lower LV and MV	5	Main Parachute	Line tangling	2	2	20
		Loss of mission	5	System Interactions	Launch or ejection loads/vibrations damage, loosen, or tangle components	3	3	45
			5	System Interactions	AV bay failure	1	N/A	5
		Rapid/uncontrolled vehicle descent	5	Main Parachute	Damage to chute material or lines	2	2	20
	D. Main parachute separates from LV	Loss of lower LV and MV	5	Main Parachute	Improper attachment to LV	3	1	15
		Loss of mission	5	Main Parachute	Chute cannot support lower LV weight	2	1	10
			5	System Interactions	Launch or ejection loads/vibrations damage, loosen, or tangle components	3	3	45
4. Lands safely and in appropriate orientation for MV deployment	A. Vehicle descent too rapid for safe touchdown	Damage to or loss of lower LV and MV	5	Main Parachute	Damage to chute material or lines	2	2	20
			5	Main Parachute	Improper stowage	3	1	15
			5	Main Parachute	Line tangling	2	1	10
		Loss of mission	5	Main Parachute	Chute cannot support lower LV weight	2	1	10
			5	System Interactions	Launch or ejection loads/vibrations damage, loosen, or tangle components	3	3	45
	B. Vehicle does not land in proper orientation for MV deployment	Damage to LV and/or MV	4	Fins	Structural failure on touchdown	2	1	8
			4	Main Parachute	Damage to chute material or lines	2	2	16
			4	Main Parachute	Line tangling	2	1	8
		Loss of mission	4	Main Parachute	Detachment from one end of LV	3	2	24
			4	Main Parachute	Improper stowage	3	1	12
			4	System Interactions	Landing leg failure	2	N/A	8
			4	System Interactions	Launch or ejection loads/vibrations damage, loosen, or tangle components	3	3	36

Table 9.11: DFMEA results for the lower launch vehicle and main recovery system.

9.2 MV CHASSIS DESIGN AND FEA STUDIES

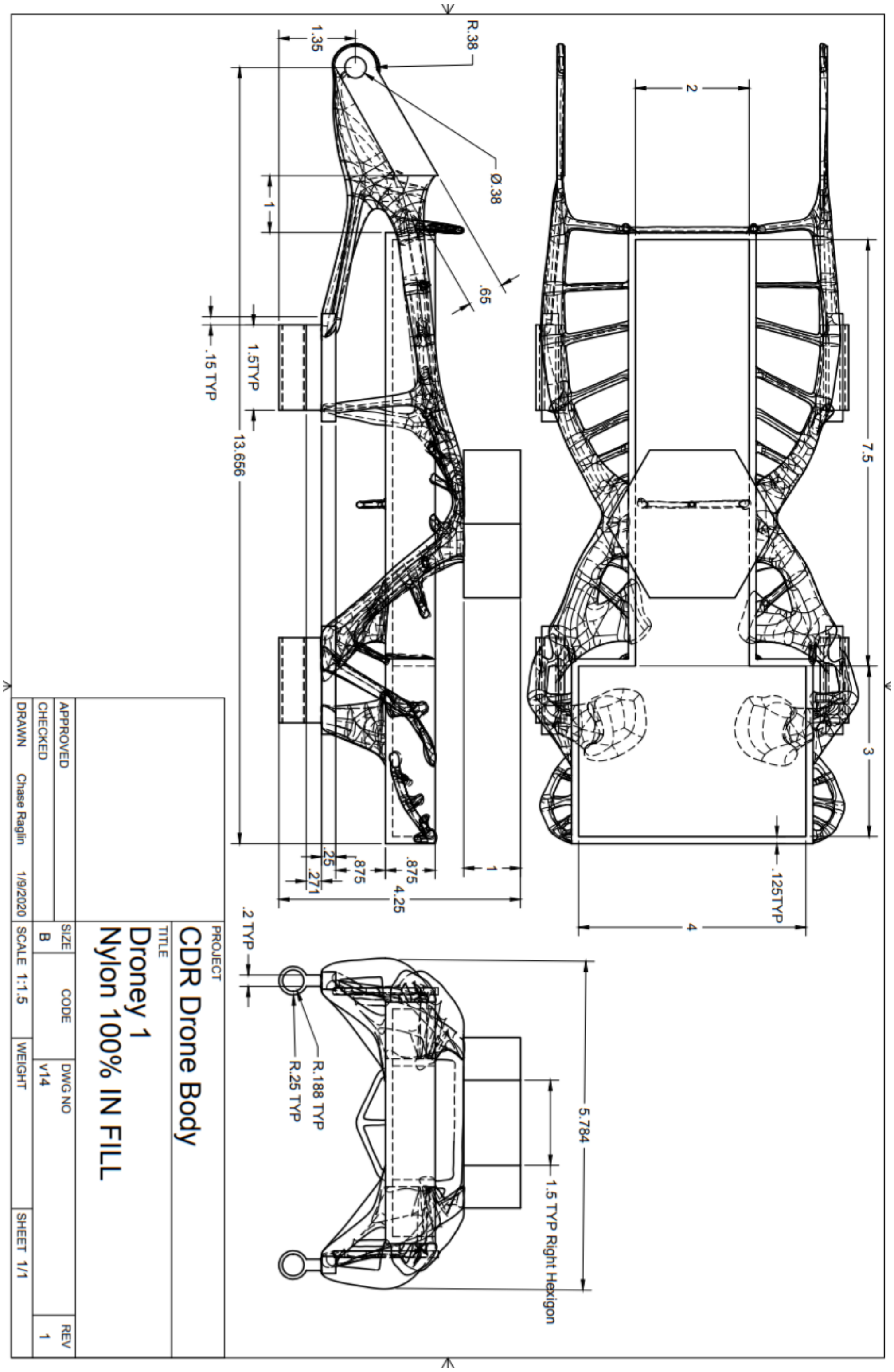


Figure 9.1: MV Chassis(in)

⊟ Simulation Model 1:1

⊟ Study 1 - Static Stress 15lbs Top Surface

⊟ Study Properties

Study Type	Static Stress
Last Modification Date	2020-01-09, 13:43:42

⊟ Settings

⊟ General

Contact Tolerance	0.003937 in
Remove Rigid Body Modes	No

⊟ Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

⊟ Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

⊟ Materials

Component	**Material**	**Safety Factor**
Component1:1	Nylon, molybdenum disulphide	Yield Strength

⊟ Nylon, molybdenum disulphide

Density	0.040824 lbmass / in^3
Young's Modulus	424961 psi
Poisson's Ratio	0.35
Yield Strength	12002 psi
Ultimate Tensile Strength	11992 psi
Thermal Conductivity	3.2099E-06 Btu / (s in F)
Thermal Expansion Coefficient	3.1E-05 / F
Specific Heat	0.32005 Btu / (lbmass F)

⊟ Contacts

⊟ Mesh

Type	**Nodes**	**Elements**

Solids	132609	73310

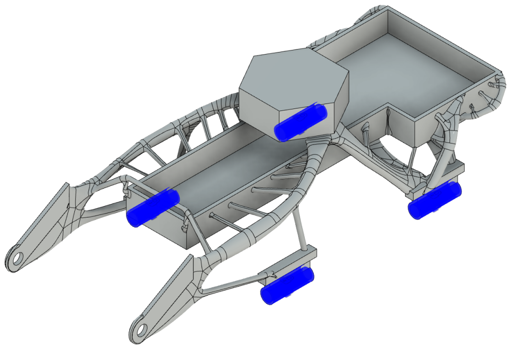
Load Case1

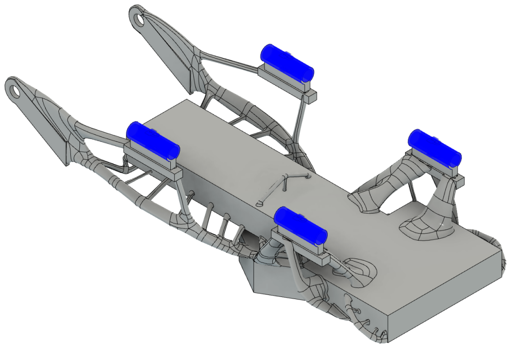
Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities



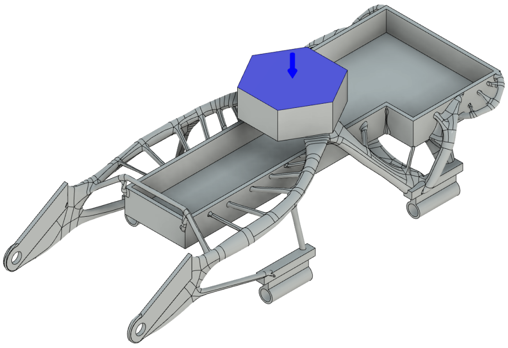


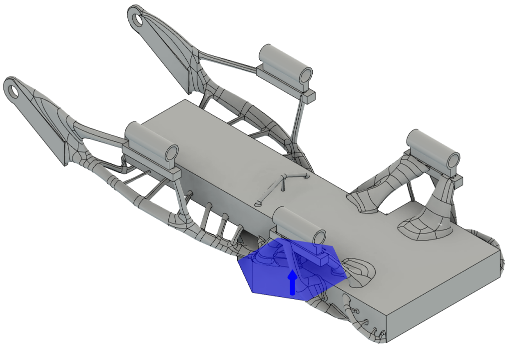
Loads

Force1

Type	Force
Magnitude	15 lbforce
X Value	2.498E-15 lbforce
Y Value	-15 lbforce
Z Value	3.0184E-15 lbforce
Force Per Entity	No

Selected Entities





⊟ Results

⊟ Result Summary

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	8.3073	15
Stress		
Von Mises	2.341E-06 psi	1444.7 psi
1st Principal	-364.23 psi	1233.1 psi
3rd Principal	-1659.7 psi	174.5 psi
Normal XX	-1015.6 psi	1081.8 psi
Normal YY	-943.03 psi	542.91 psi
Normal ZZ	-929.58 psi	362.97 psi
Shear XY	-396.99 psi	500.36 psi
Shear YZ	-292.09 psi	310.06 psi
Shear ZX	-291.85 psi	602.03 psi
Displacement		
Total	0 in	0.01529 in
X	-0.0059838 in	0.0051471 in
Y	-0.014705 in	0.0021855 in
Z	-1.0479E-04 in	0.0056982 in
Reaction Force		
Total	0 lbforce	2.7888 lbforce
X	-0.90648 lbforce	1.6 lbforce
Y	-1.1554 lbforce	2.2347 lbforce
Z	-0.25937 lbforce	0.47256 lbforce
Strain		

Equivalent	8.2411E-12	0.0055545
1st Principal	3.4911E-12	0.0036994
3rd Principal	-0.0058964	-2.9047E-12
Normal XX	-0.001447	0.0021921
Normal YY	-0.0017265	0.0012954
Normal ZZ	-0.001141	6.1034E-04
Shear XY	-0.0025223	0.0031791
Shear YZ	-0.0018558	0.00197
Shear ZX	-0.0018543	0.003825

⊟ Safety Factor

⊟ Safety Factor (Per Body)

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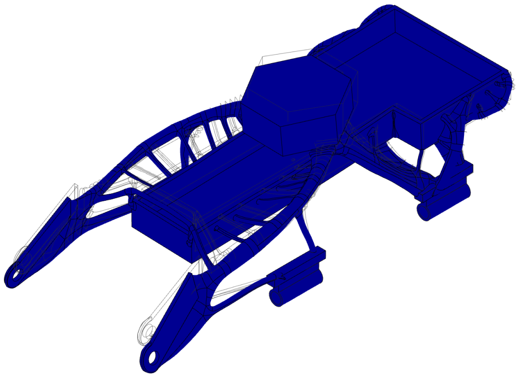

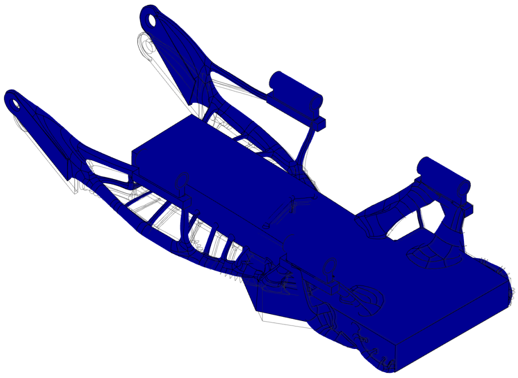

⊟ Stress

⊟ Von Mises

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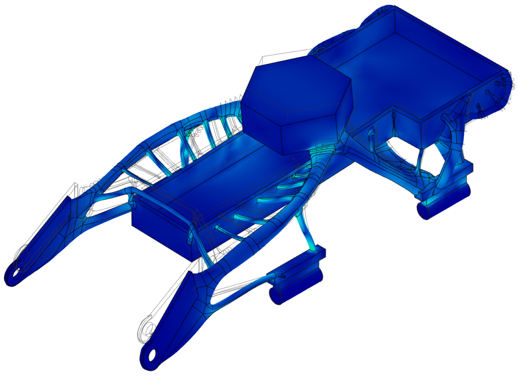

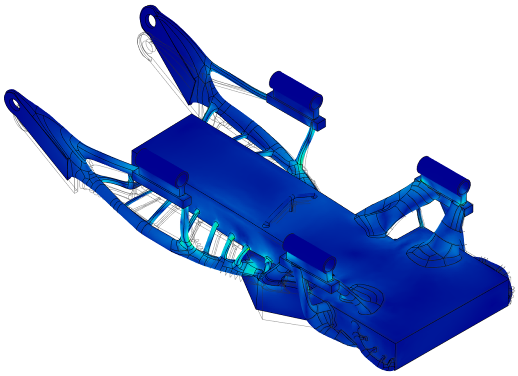

⊟ 1st Principal

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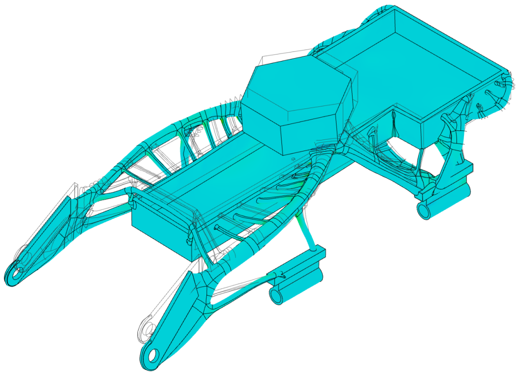

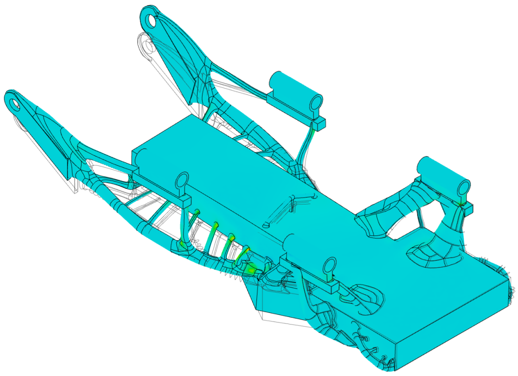

⊟ 3rd Principal

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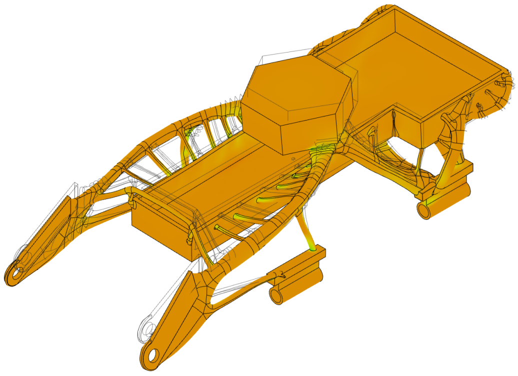
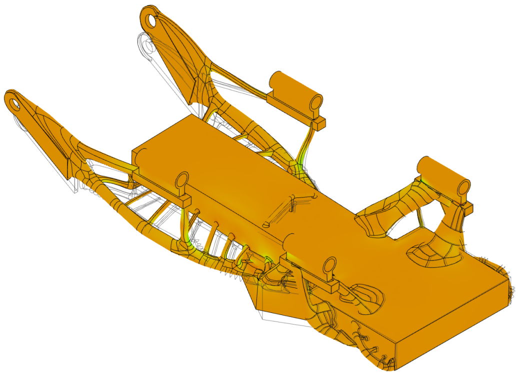
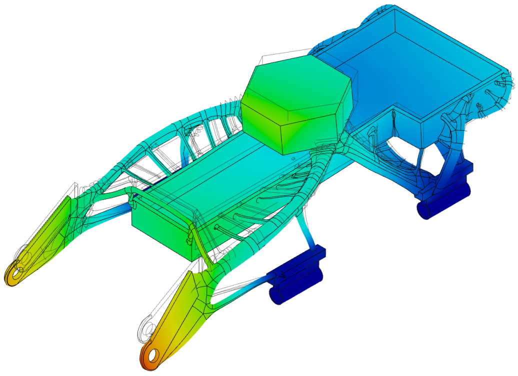


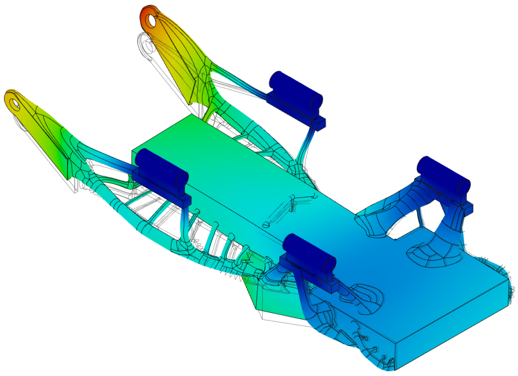


⊟ Displacement

⊟ Total

[in] 0 0.01529





⊟ Study 2 - Static Stress15lb Lift Load

⊟ Study Properties

Study Type	Static Stress
Last Modification Date	2020-01-09, 13:45:34

⊟ Settings

⊟ General

Contact Tolerance	0.003937 in
Remove Rigid Body Modes	No

⊟ Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

⊟ Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

⊟ Materials

Component	**Material**	**Safety Factor**
Component1:1	Nylon, molybdenum disulphide	Yield Strength

⊟ Nylon, molybdenum disulphide

Density	0.040824 lbmass / in^3
Young's Modulus	424961 psi
Poisson's Ratio	0.35
Yield Strength	12002 psi
Ultimate Tensile Strength	11992 psi
Thermal Conductivity	3.2099E-06 Btu / (s in F)
Thermal Expansion Coefficient	3.1E-05 / F
Specific Heat	0.32005 Btu / (lbmass F)

⊟ Contacts

⊟ Mesh

Type	**Nodes**	**Elements**
Solids	132609	73310

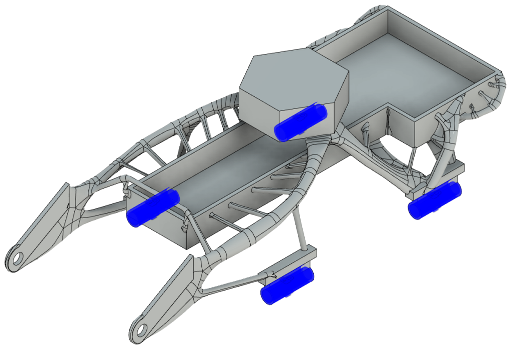
⊟ Load Case1

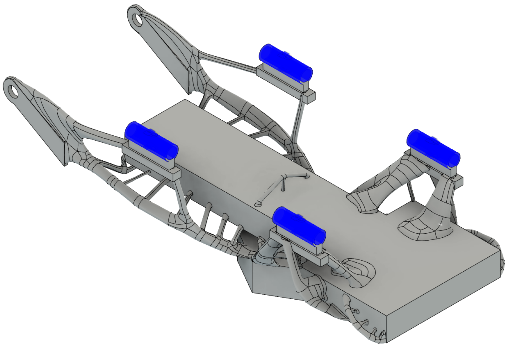
⊟ Constraints

⊟ Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

⊟ Selected Entities



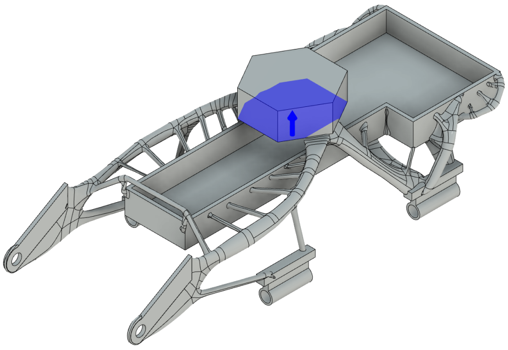


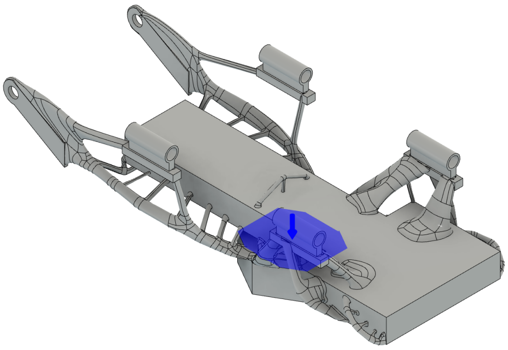
⊟ Loads

⊟ Force1

Type	Force
Magnitude	15 lbforce
X Value	-2.498E-15 lbforce
Y Value	15 lbforce
Z Value	-3.0184E-15 lbforce
Force Per Entity	No

⊟ Selected Entities





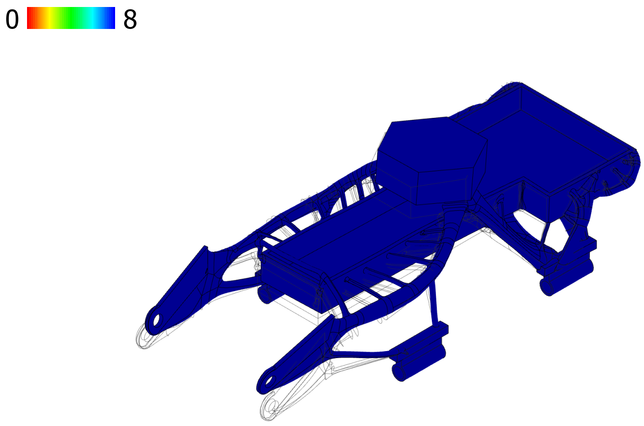
⊟ Results

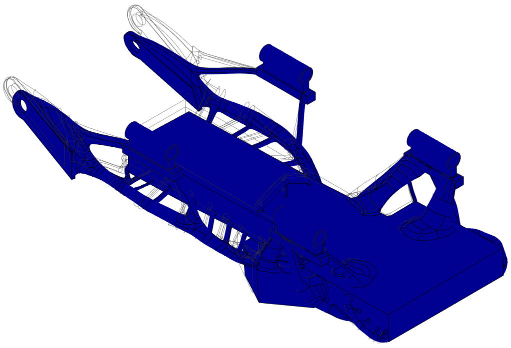
Result Summary

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	8.3147	15
Stress		
Von Mises	1.5233E-06 psi	1443.5 psi
1st Principal	-174.35 psi	1659 psi
3rd Principal	-1233.2 psi	363.77 psi
Normal XX	-1082 psi	1015.3 psi
Normal YY	-543.6 psi	941.66 psi
Normal ZZ	-362.64 psi	928.76 psi
Shear XY	-499.62 psi	397.36 psi
Shear YZ	-310.23 psi	291.58 psi
Shear ZX	-601.46 psi	291.89 psi
Displacement		
Total	0 in	0.015279 in
X	-0.0051597 in	0.005976 in
Y	-0.0021828 in	0.014689 in
Z	-0.0056982 in	1.048E-04 in
Reaction Force		
Total	0 lbforce	2.7905 lbforce
X	-1.6013 lbforce	0.90586 lbforce
Y	-2.2358 lbforce	1.155 lbforce
Z	-0.47345 lbforce	0.25921 lbforce
Strain		
Equivalent	5.4101E-12	0.0055515
1st Principal	-1.7094E-11	0.0058935
3rd Principal	-0.0036989	1.4443E-12
Normal XX	-0.0021928	0.001442
Normal YY	-0.001297	0.0017316
Normal ZZ	-6.0947E-04	0.0011391
Shear XY	-0.0031744	0.0025246
Shear YZ	-0.0019711	0.0018525
Shear ZX	-0.0038214	0.0018545

Safety Factor

Safety Factor (Per Body)

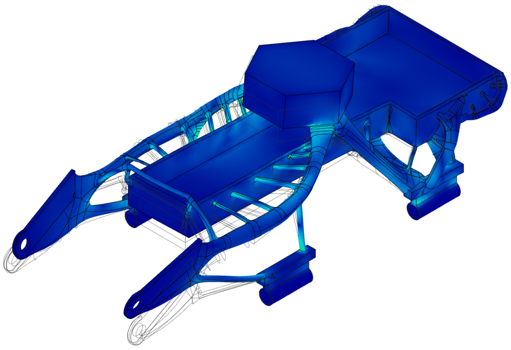


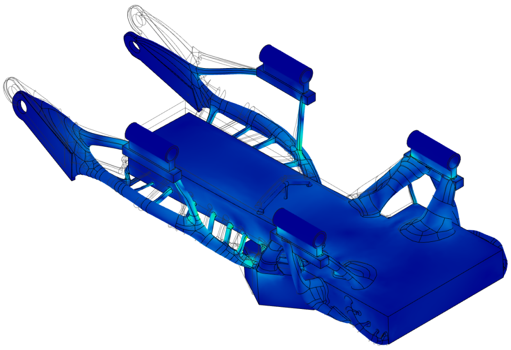


⊟ Stress

⊟ Von Mises

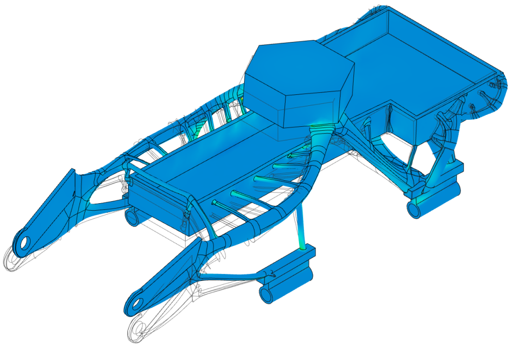
[psi] 0 ▨ 1443.5

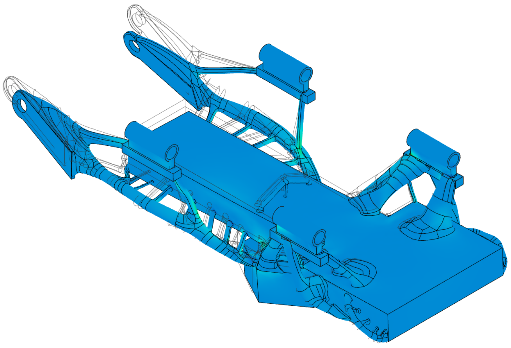




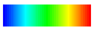
⊟ 1st Principal

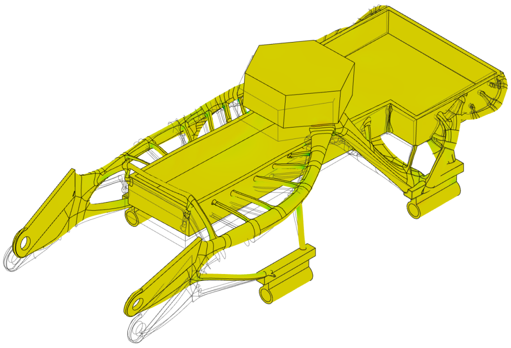
[psi] -174.3 ▨ 1659

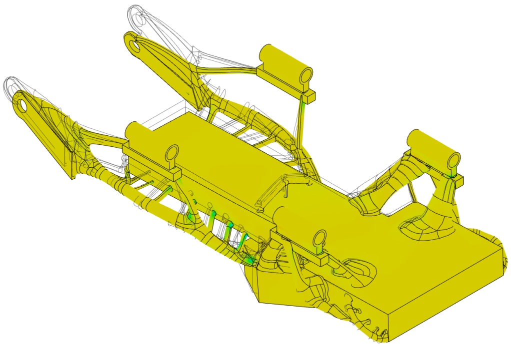




⊟ 3rd Principal

[psi] -1233.2  363.8

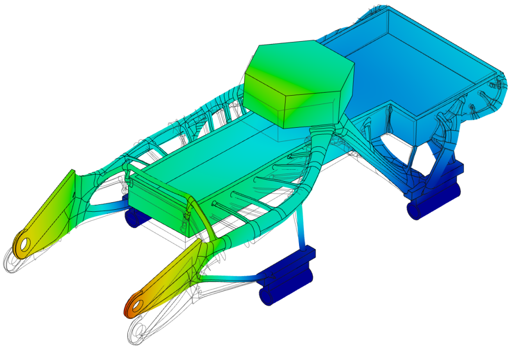


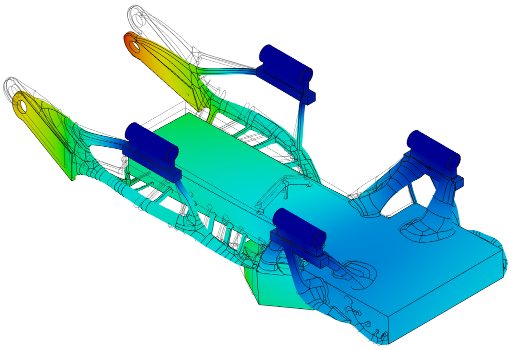


Displacement

Total

[in] 0 0.015279





Study 3 - Static Stress Brush Load 10lbs

Study Properties

Study Type	Static Stress
Last Modification Date	2020-01-09, 13:47:47

Settings

⊟ General

Contact Tolerance	0.003937 in
Remove Rigid Body Modes	No

⊟ Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

⊟ Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

⊟ Materials

Component	Material	Safety Factor
Component1:1	Nylon, molybdenum disulphide	Yield Strength

⊟ Nylon, molybdenum disulphide

Density	0.040824 lbmass / in^3
Young's Modulus	424961 psi
Poisson's Ratio	0.35
Yield Strength	12002 psi
Ultimate Tensile Strength	11992 psi
Thermal Conductivity	3.2099E-06 Btu / (s in F)
Thermal Expansion Coefficient	3.1E-05 / F
Specific Heat	0.32005 Btu / (lbmass F)

⊟ Contacts

⊟ Mesh

Type	Nodes	Elements
Solids	132609	73310

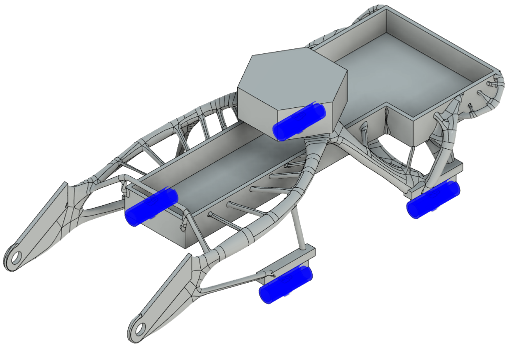
⊟ Load Case1

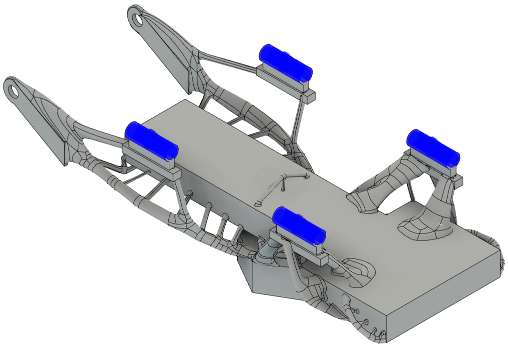
⊟ Constraints

⊟ Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

⊟ Selected Entities



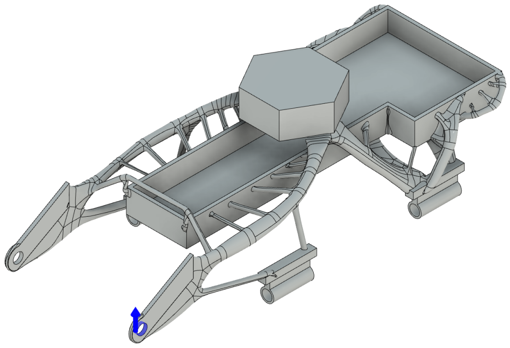


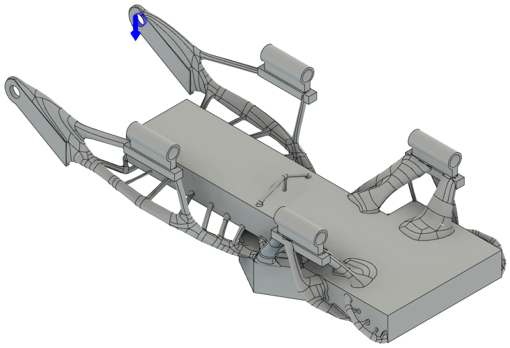
⊟ Loads

⊟ Force1

Type	Force
Magnitude	5 lbforce
X Value	0 lbforce
Y Value	5 lbforce
Z Value	0 lbforce
X Angle	0 deg
Y Angle	90 deg
Z Angle	0 deg
Force Per Entity	No

⊟ Selected Entities

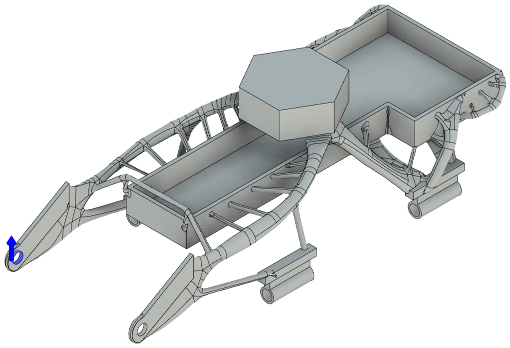


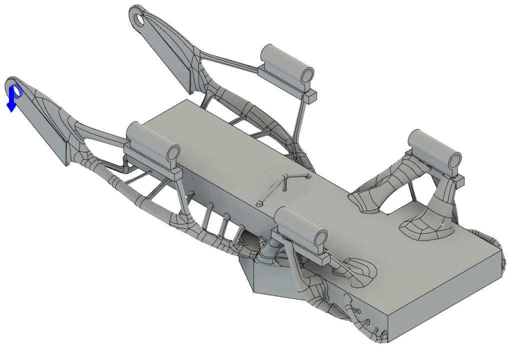


⊟ Force2

Type	Force
Magnitude	5 lbforce
X Value	0 lbforce
Y Value	5 lbforce
Z Value	0 lbforce
X Angle	0 deg
Y Angle	90 deg
Z Angle	0 deg
Force Per Entity	No

⊟ Selected Entities





⊟ Results

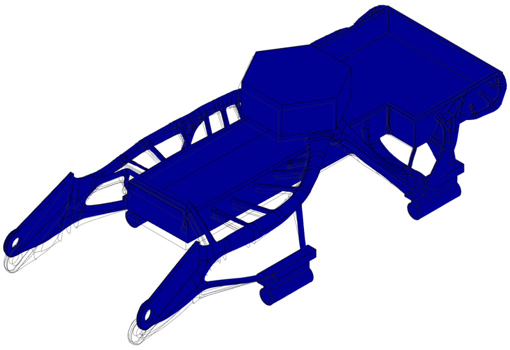
⊟ Result Summary

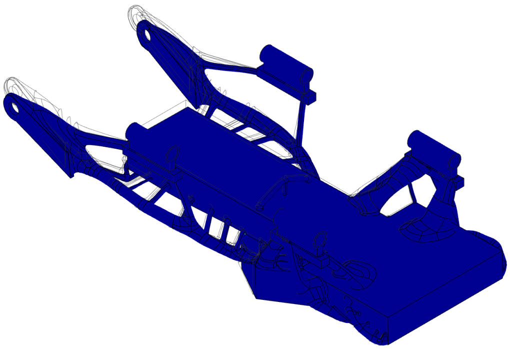
Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	2.7459	15
Stress		
Von Mises	1.0367E-05 psi	4370.9 psi
1st Principal	-444.51 psi	5144.1 psi
3rd Principal	-3059.6 psi	966.01 psi
Normal XX	-2618.1 psi	3180.6 psi
Normal YY	-1828.4 psi	2245 psi
Normal ZZ	-1102.2 psi	2838.2 psi
Shear XY	-847.37 psi	1106.2 psi
Shear YZ	-756.8 psi	852 psi
Shear ZX	-1835.3 psi	845.44 psi
Displacement		
Total	0 in	0.081052 in
X	-0.0052772 in	0.035885 in
Y	-0.0056403 in	0.073298 in
Z	-0.019756 in	0.0069015 in
Reaction Force		
Total	0 lbforce	4.556 lbforce
X	-2.6944 lbforce	2.3342 lbforce
Y	-3.0166 lbforce	3.6448 lbforce
Z	-1.2803 lbforce	1.1412 lbforce
Strain		
Equivalent	5.0344E-11	0.017067
1st Principal	1.8375E-11	0.018132
3rd Principal	-0.0094713	6.9963E-06
Normal XX	-0.0052073	0.0055635
Normal YY	-0.0041489	0.0047945
Normal ZZ	-0.0021601	0.0043021
Shear XY	-0.0053838	0.007028
Shear YZ	-0.0048084	0.0054132
Shear ZX	-0.011661	0.0053715

⊟ Safety Factor

Safety Factor (Per Body)

0 8

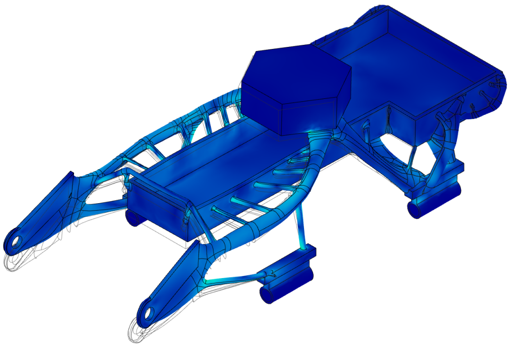


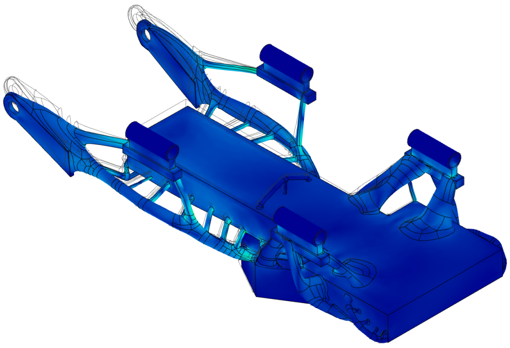


Stress

Von Mises

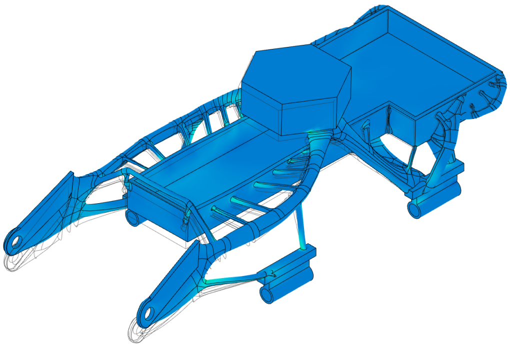
[psi] 0 4370.9

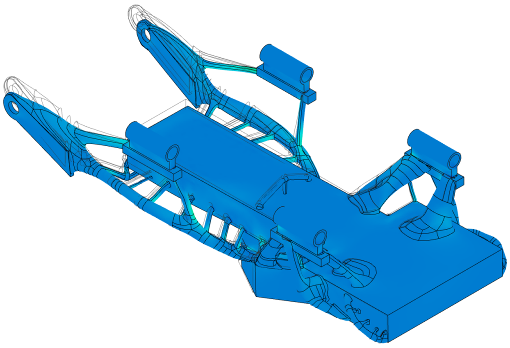




⊟ 1st Principal

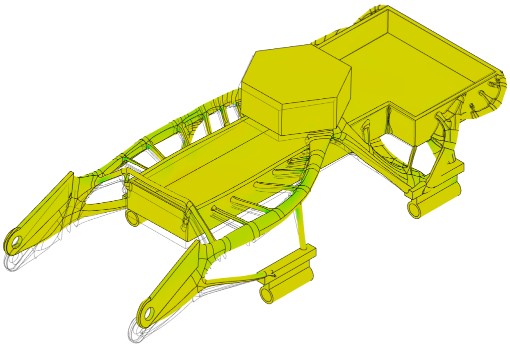
[psi] -444.5 5144.1

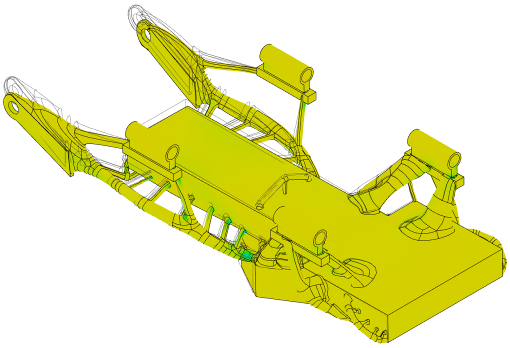




⊟ 3rd Principal

[psi] -3059.6 966

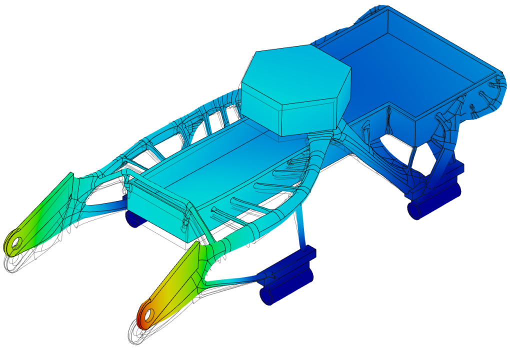


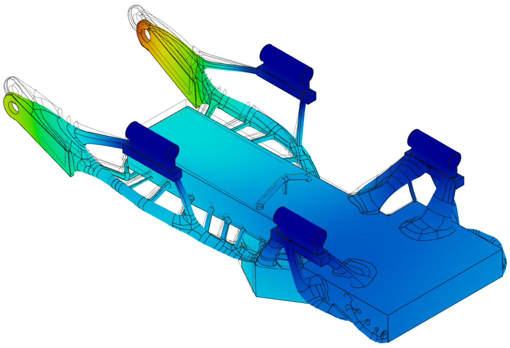


Displacement

Total

[in] 0 0.081052





⊟ Study 4 - Static Stress Brush roller Down 10lbs

⊟ Study Properties

Study Type	Static Stress
Last Modification Date	2020-01-09, 13:50:22

⊟ Settings

⊟ General

Contact Tolerance	0.003937 in
Remove Rigid Body Modes	No

⊟ Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

⊟ Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

⊟ Materials

Component	**Material**	**Safety Factor**
Component1:1	Nylon, molybdenum disulphide	Yield Strength

⊟ Nylon, molybdenum disulphide

Density	0.040824 lbmass / in^3
Young's Modulus	424961 psi
Poisson's Ratio	0.35

Yield Strength	12002 psi
Ultimate Tensile Strength	11992 psi
Thermal Conductivity	3.2099E-06 Btu / (s in F)
Thermal Expansion Coefficient	3.1E-05 / F
Specific Heat	0.32005 Btu / (lbmass F)

Contacts

Mesh

Type	Nodes	Elements
Solids	132609	73310

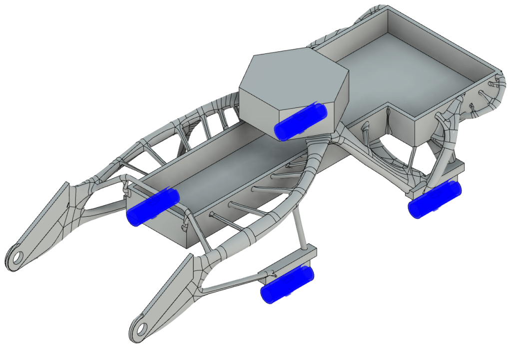
Load Case1

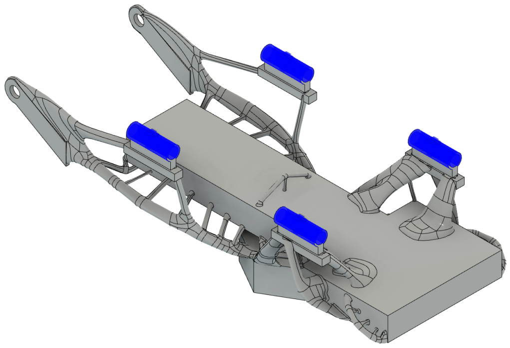
Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities



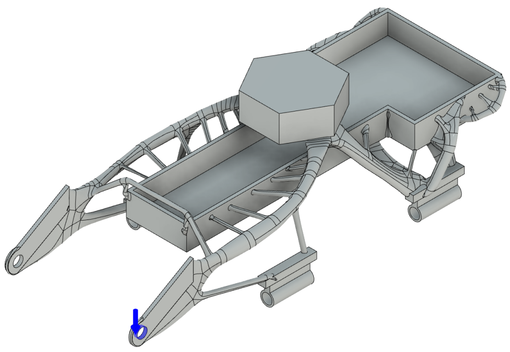


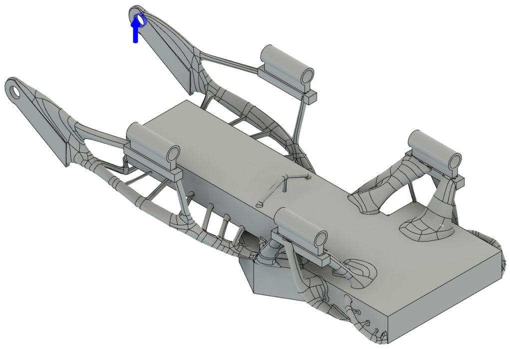
Loads

Force1

Type	Force
Magnitude	5 lbforce
X Value	0 lbforce
Y Value	-5 lbforce
Z Value	0 lbforce
X Angle	0 deg
Y Angle	-90 deg
Z Angle	0 deg
Force Per Entity	No

⊟ Selected Entities

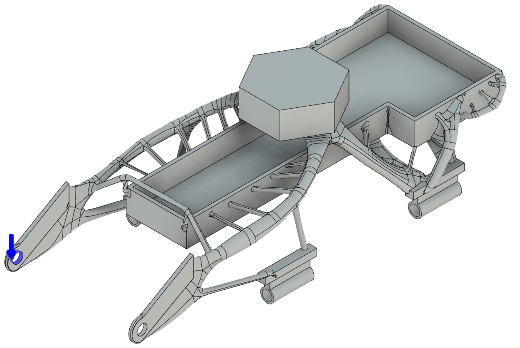


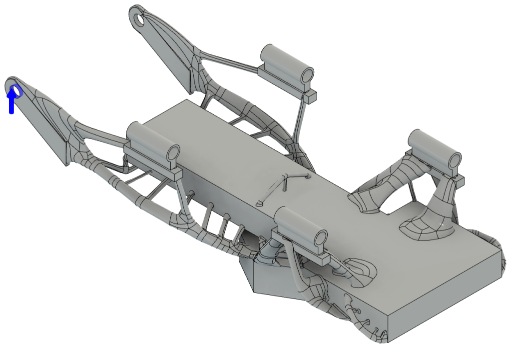


⊟ Force2

Type	Force
Magnitude	5 lbforce
X Value	0 lbforce
Y Value	-5 lbforce
Z Value	0 lbforce
X Angle	0 deg
Y Angle	-90 deg
Z Angle	0 deg
Force Per Entity	No

⊟ Selected Entities





⊟ Results

⊟ Result Summary

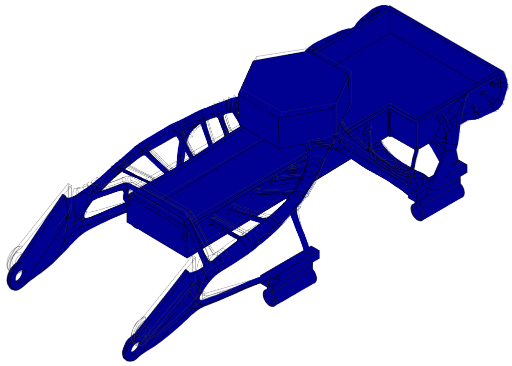
Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	2.7459	15
Stress		
Von Mises	9.7249E-06 psi	4370.8 psi
1st Principal	-966 psi	3059.5 psi
3rd Principal	-5144.1 psi	444.51 psi
Normal XX	-3180.5 psi	2618.1 psi
Normal YY	-2244.9 psi	1828.4 psi
Normal ZZ	-2838.2 psi	1102.2 psi
Shear XY	-1106.1 psi	847.36 psi
Shear YZ	-851.99 psi	756.79 psi
Shear ZX	-845.42 psi	1835.3 psi
Displacement		
Total	0 in	0.081051 in
X	-0.035884 in	0.0052772 in
Y	-0.073297 in	0.0056402 in
Z	-0.0069014 in	0.019756 in
Reaction Force		
Total	0 lbforce	4.5559 lbforce
X	-2.3342 lbforce	2.6944 lbforce
Y	-3.6447 lbforce	3.0165 lbforce
Z	-1.1412 lbforce	1.2803 lbforce
Strain		

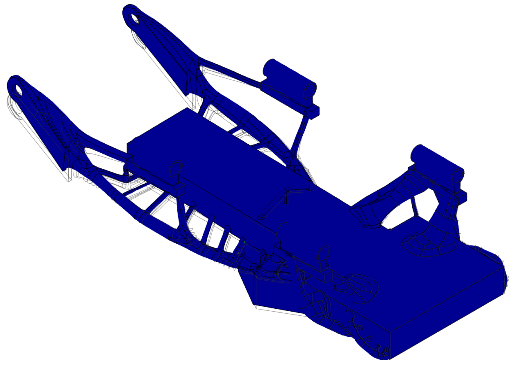
Equivalent	5.1455E-11	0.017067
1st Principal	-6.9963E-06	0.0094712
3rd Principal	-0.018132	-2.4239E-11
Normal XX	-0.0055634	0.0052072
Normal YY	-0.0047945	0.0041489
Normal ZZ	-0.0043021	0.0021601
Shear XY	-0.0070279	0.0053837
Shear YZ	-0.0054131	0.0048083
Shear ZX	-0.0053714	0.011661

Safety Factor

Safety Factor (Per Body)

0 8

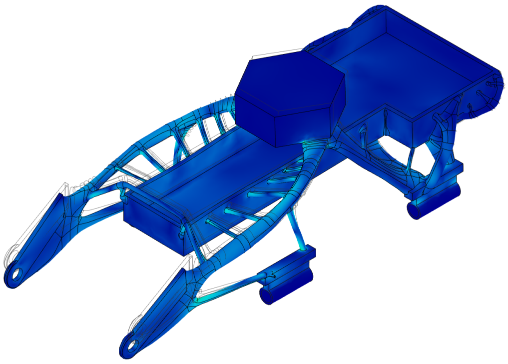


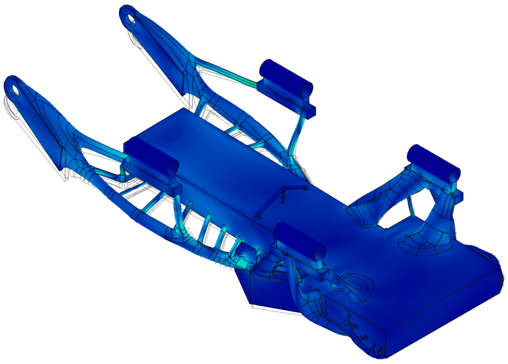


Stress

Von Mises

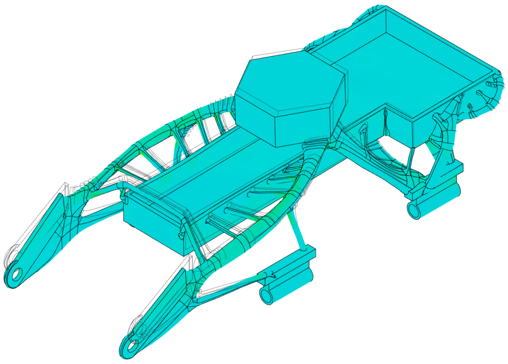
[psi] 0 4370.8

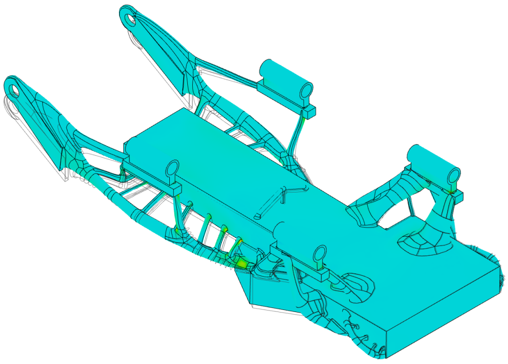




⊟ 1st Principal

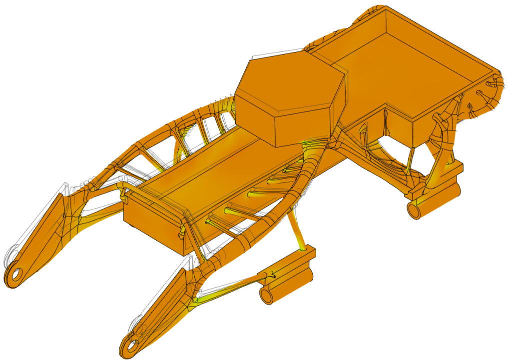
[psi] -966 3059.5

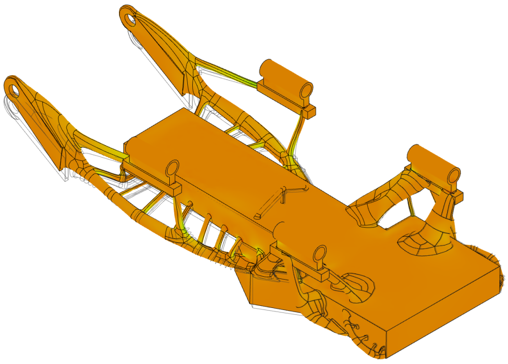




3rd Principal

[psi] -5144.1 444.5

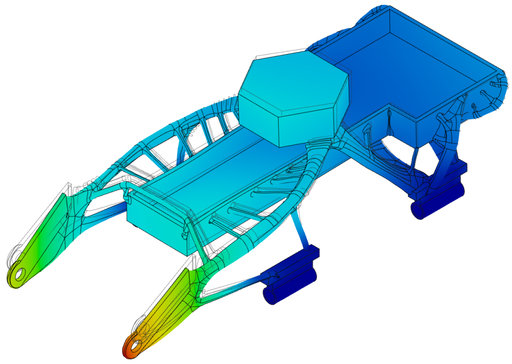


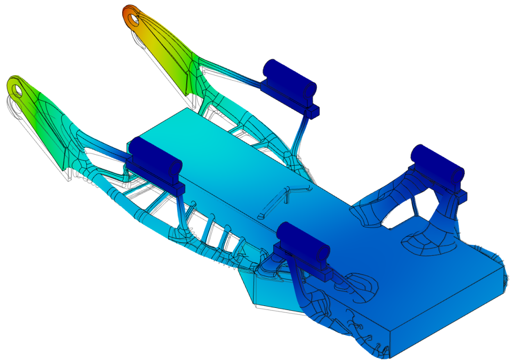


Displacement

Total

[in] 0 0.081051





9.3 ADDITIONAL MV COMPONENT DESIGNS

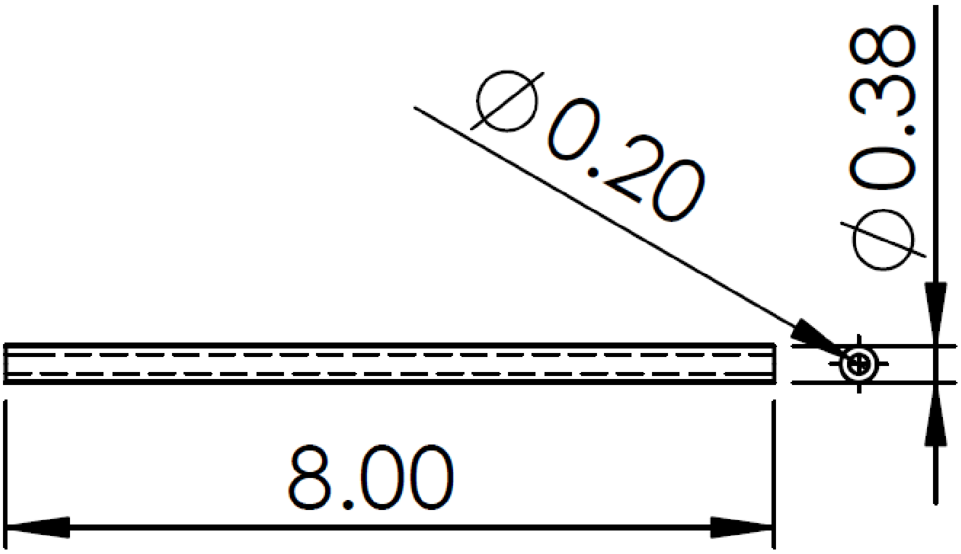


Figure 9.2: MV Boom Arms (in)

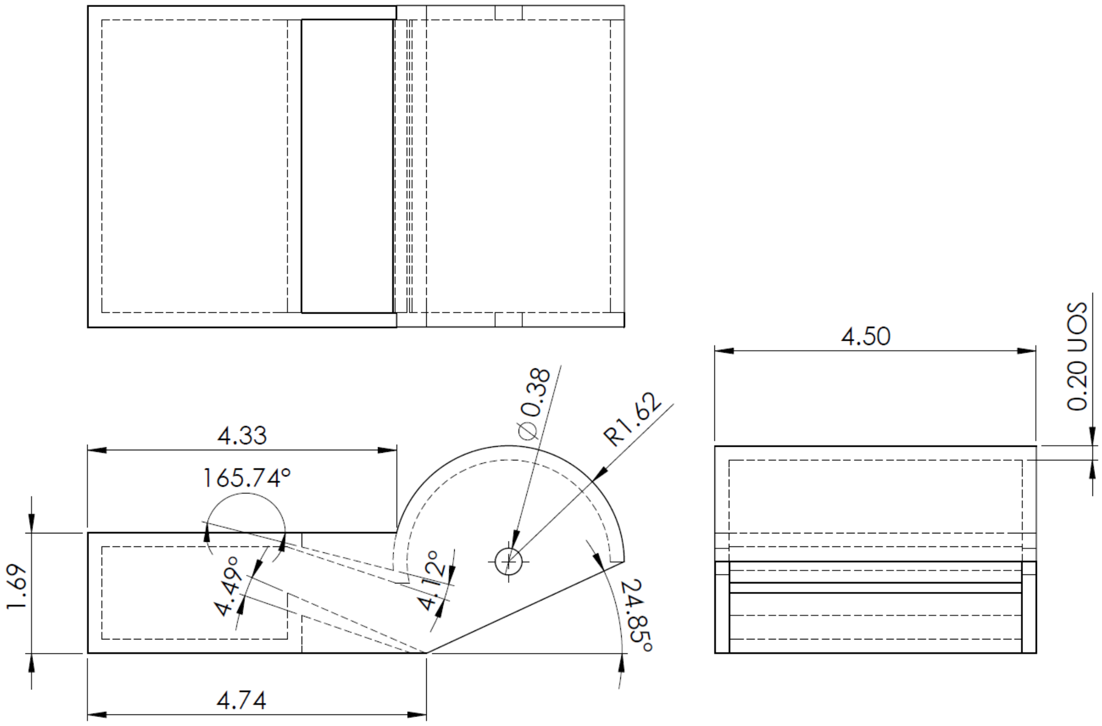


Figure 9.3: MV Objective Collection (in)

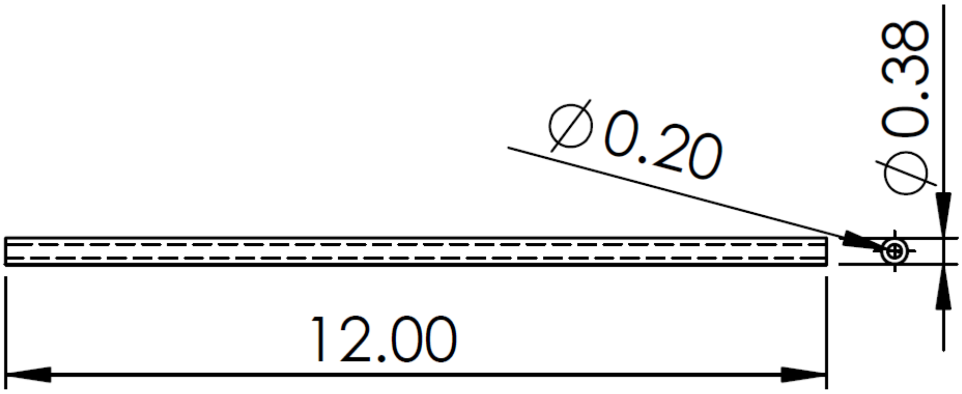


Figure 9.4: MV Legs (in)

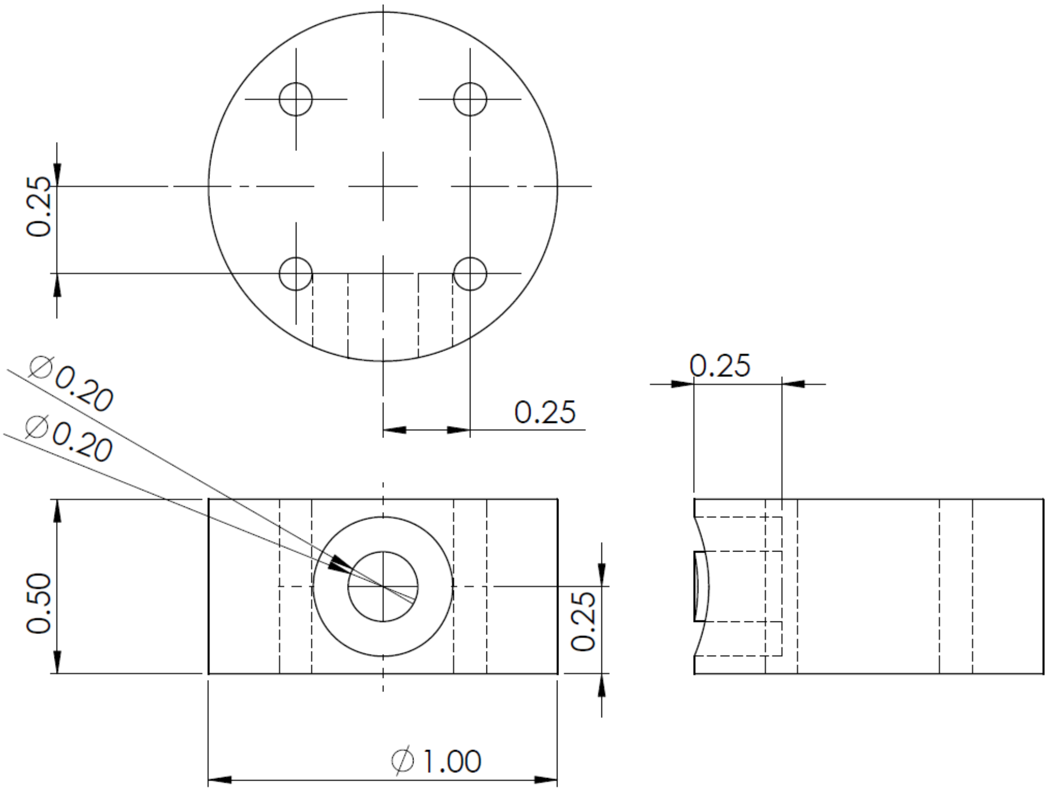


Figure 9.5: MV Motor Mounting Pads (in)

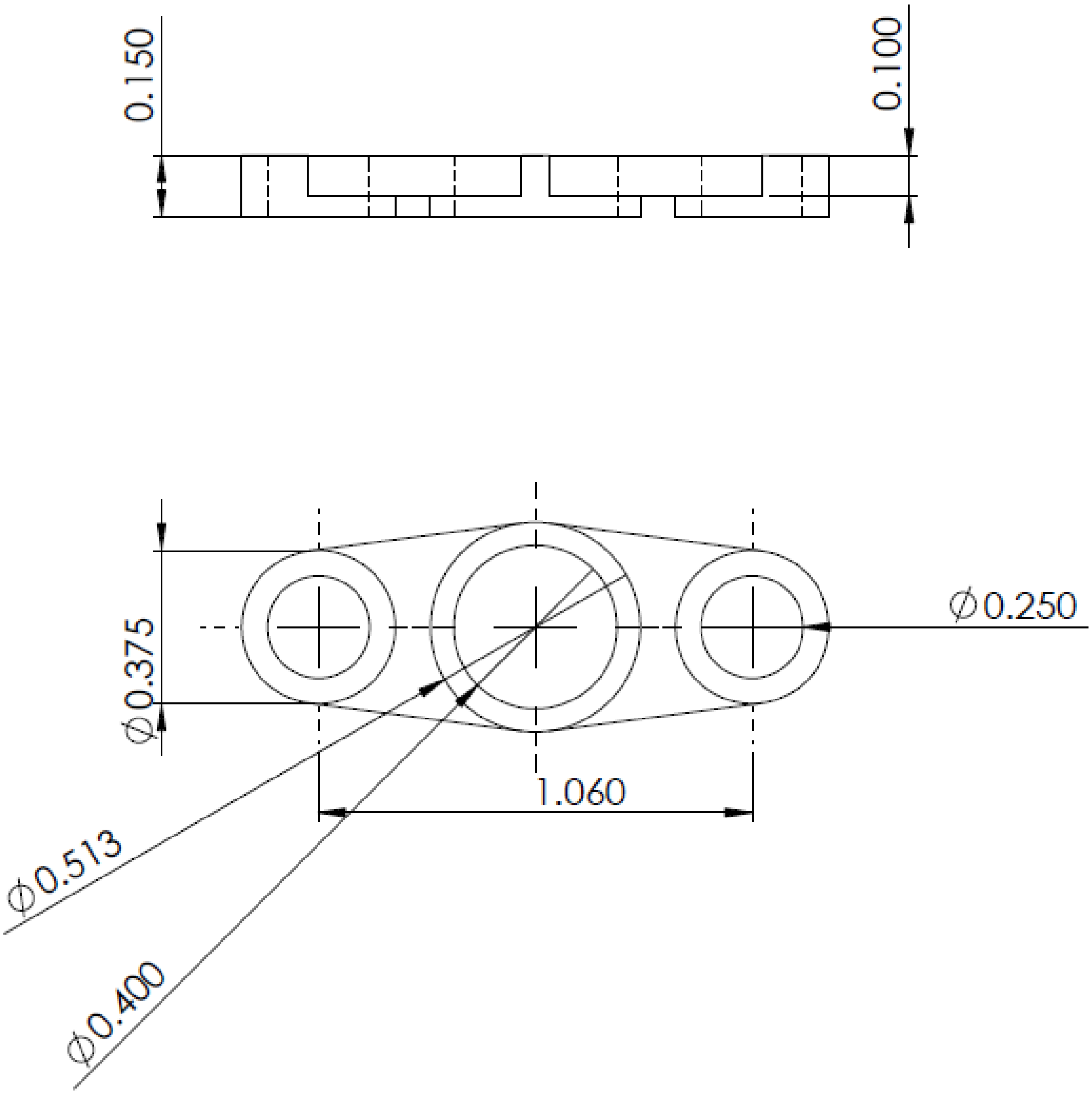
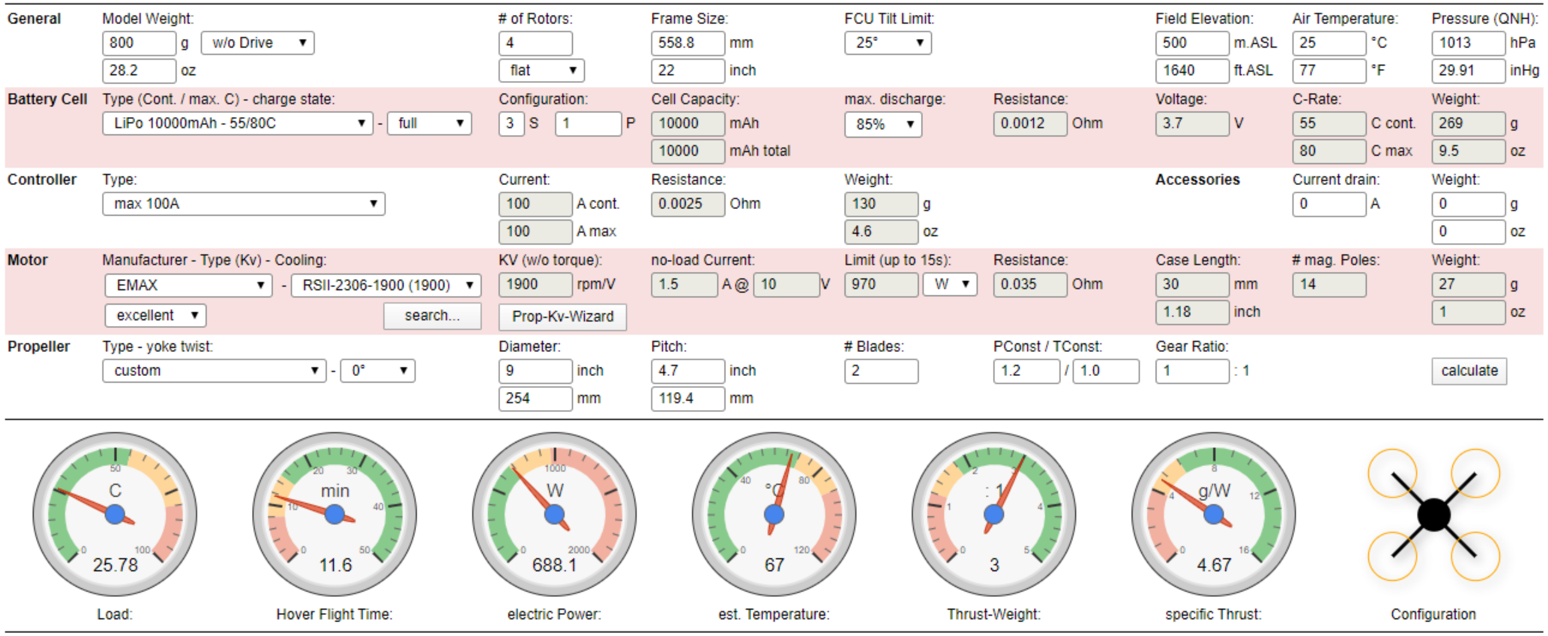


Figure 9.6: MV Stowing Mounts (in)

9.4 MV DRIVETRAIN PERFORMANCE CHARACTERISTICS



General
Model Weight: 800 g w/o Drive; 28.2 oz
# of Rotors: 4 flat
Frame Size: 558.8 mm; 22 inch
FCU Tilt Limit: 25°
Field Elevation: 500 m.ASL; 1640 ft.ASL
Air Temperature: 25 °C; 77 °F
Pressure (QNH): 1013 hPa; 29.91 inHg

Battery Cell
Type (Cont. / max. C) - charge state: LiPo 10000mAh - 55/80C - full
Configuration: 3 S 1 P
Cell Capacity: 10000 mAh; 10000 mAh total
max. discharge: 85%
Resistance: 0.0012 Ohm
Voltage: 3.7 V
C-Rate: 55 C cont.; 80 C max
Weight: 269 g; 9.5 oz

Controller
Type: max 100A
Current: 100 A cont.; 100 A max
Resistance: 0.0025 Ohm
Weight: 130 g; 4.6 oz

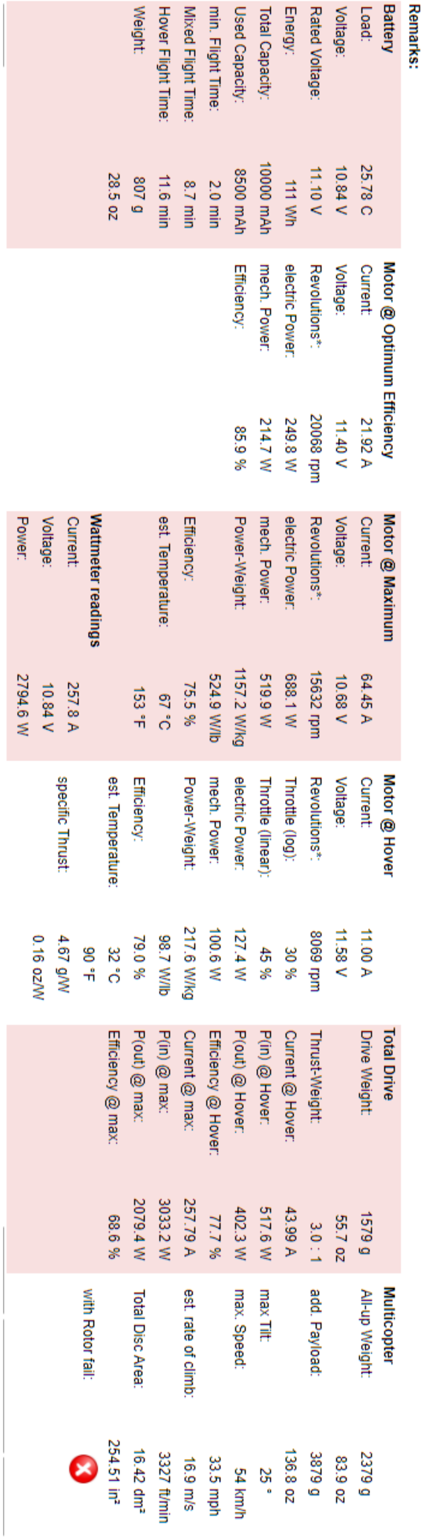
Accessories
Current drain: 0 A
Weight: 0 g; 0 oz

Motor
Manufacturer - Type (Kv) - Cooling: EMAX - RSII-2306-1900 (1900); excellent
KV (w/o torque): 1900 rpm/V
no-load Current: 1.5 A @ 10 V
Limit (up to 15s): 970 W
Resistance: 0.035 Ohm
Case Length: 30 mm; 1.18 inch
mag. Poles: 14
Weight: 27 g; 1 oz

Propeller
Type - yoke twist: custom - 0°
Diameter: 9 inch; 254 mm
Pitch: 4.7 inch; 119.4 mm
Blades: 2
PConst / TConst: 1.2 / 1.0
Gear Ratio: 1 : 1

Load: 25.78
Hover Flight Time: 11.6
electric Power: 688.1
est. Temperature: 67
Thrust-Weight: 3
specific Thrust: 4.67

Figure 9.7: Drivetrain Setup



Remarks:

Battery	
Load:	25.78 C
Voltage:	10.84 V
Rated Voltage:	11.10 V
Energy:	111 Wh
Total Capacity:	10000 mAh
Used Capacity:	8500 mAh
min. Flight Time:	2.0 min
Mixed Flight Time:	8.7 min
Hover Flight Time:	11.6 min
Weight:	807 g 28.5 oz

Motor @ Optimum Efficiency	
Current:	21.92 A
Voltage:	11.40 V
Revolutions*:	20068 rpm
electric Power:	249.8 W
mech. Power:	214.7 W
Efficiency:	85.9 %

Motor @ Maximum	
Current:	64.45 A
Voltage:	10.68 V
Revolutions*:	15632 rpm
electric Power:	688.1 W
mech. Power:	519.9 W
Power-Weight:	1157.2 W/kg 524.9 W/lb
Efficiency:	75.5 %
est. Temperature:	67 °C 153 °F

Wattmeter readings	
Current:	257.8 A
Voltage:	10.84 V
Power:	2794.6 W

Motor @ Hover	
Current:	11.00 A
Voltage:	11.58 V
Revolutions*:	8069 rpm
Throttle (log):	30 %
Throttle (linear):	45 %
electric Power:	127.4 W
mech. Power:	100.6 W
Power-Weight:	217.6 W/kg 98.7 W/lb
Efficiency:	79.0 %
est. Temperature:	32 °C 90 °F
specific Thrust:	4.67 g/W 0.16 oz/W

Total Drive	
Drive Weight:	1579 g 55.7 oz
Thrust-Weight:	3.0 : 1
Current @ Hover:	43.99 A
P(in) @ Hover:	517.6 W
P(out) @ Hover:	402.3 W
Efficiency @ Hover:	77.7 %
Current @ max:	257.79 A
P(in) @ max:	3033.2 W
P(out) @ max:	2079.4 W
Efficiency @ max:	68.6 %

Multicopter	
All-up Weight:	2379 g 83.9 oz
add. Payload:	3879 g 136.8 oz
max Tilt:	25 °
max. Speed:	54 km/h 33.5 mph
est. rate of climb:	16.9 m/s 3327 ft/min
Total Disc Area:	16.42 dm² 254.51 in²
with Rotor fail:	✖

Figure 9.8: Power Consumption Information

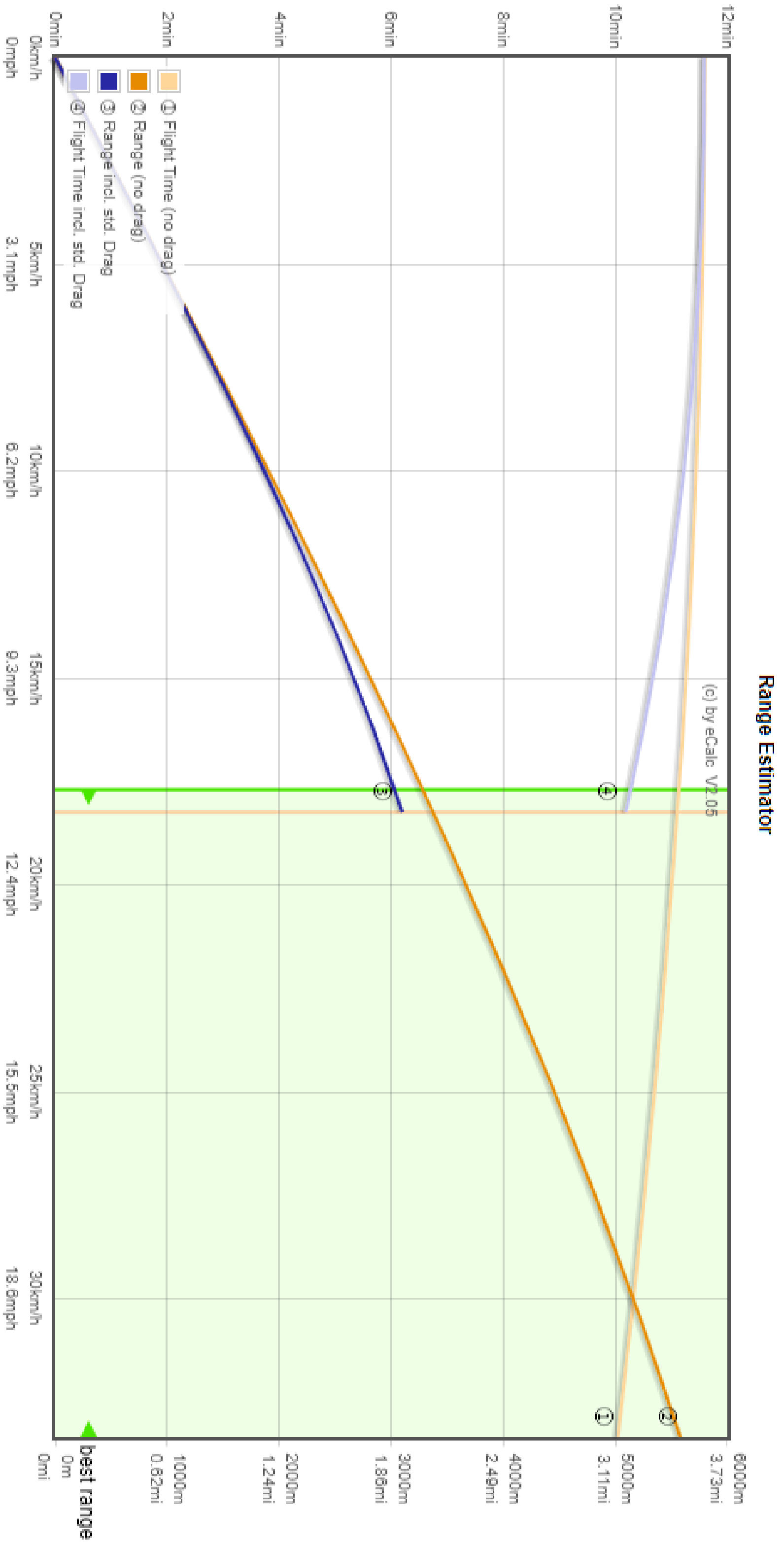


Figure 9.9: Range Estimate