University of Notre Dame
2018-2019

Notre Dame Rocket Team
Critical Design Review

NASA Student Launch 2018
UAV and Air Braking Payloads

Submitted January 11, 2019

365 Fitzpatrick Hall of Engineering
Notre Dame, IN 46556

Contents

List of Tables

List of Figures

Table 1: List of acronyms

Acronym	Meaning
ABS	Air Braking System
ACCST	Advanced Continuous Channel Shifting Technology
AGL	Above Ground Level
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CRAM	Compact Removable Avionics Module
DSM	Digital Spectrum Modulation
ESC	Electronic Speed Controller
FEA	Future Excursion Area
FMEA	Failure Modes and Effects Analysis
FPS	Frames Per Second
FPV	First-Person View
IMU	Inertial Measurement Unit
LED	Light Emitting Diode
LiPo	Lithium Polymer
NDRT	Notre Dame Rocket Team
OpenCV	Open Source Computer Vision Library
OPTO	Optoisolator
PCB	Printed Circuit Board
PDB	Power Distribution Board
PID	Proportional-Integral-Derivative
PLA	Polylactic Acid
PWM	Pulse-Width Modulation
RC	Radio Controlled
RF	Radio Frequency
UAV	Unmanned Aerial Vehicle

1 Summary of CDR Report

1.1 General Information

School Name: University of Notre Dame

Team Name: Notre Dame Rocketry Team

Location: University of Notre Dame
365 Fitzpatrick Hall of Engineering
Notre Dame, IN 46556

Faculty Advisor: Dr. Aleksander Jemcov
Research Assistant Professor
Department of Aerospace and Mechanical Engineering
e: ajemcov@nd.edu
p: (574)631-7576

Graduate Student Advisor: Emma Farnan
PhD Candidate
Department of Aerospace and Mechanical Engineering
e: efarnan@nd.edu
p: (631)572-6091

Team Lead: Patrick Danielson
e: pdaniels@nd.edu
p: (937)760-4366

Safety Officer: James Cole
e: jcole8@nd.edu
p: (347)835-3922

Mentor: Dave Brunsting (NAR/TAR Level 2)
e: dacsmema@gmail.com
p: (269)838-4275.

NAR/TAR Section: TRA #12340, Michiana Rocketry

1.2 Mission Statement

The mission of the Notre Dame Rocketry Team (NDRT) for the 2018-2019 NASA Student Launch competition is to independently design, build, and launch a high power rocket to an altitude of 4,700 feet. The mission shall be successful if the rocket safely descends under a parachute before landing without causing damage to the vehicle, surroundings, or spectators. After landing, a semi-autonomous unmanned aerial vehicle (UAV) will deploy and execute a mission to deliver a beacon to a target area.

In addition, NDRT's mission includes building a program centered around NASA's experiential learning project that will offer 60+ undergraduates opportunities to grow as engineers by developing technical and professional skills not available in a traditional undergraduate curriculum. Finally, the team aims to inspire young minds in the South Bend community through hands on activities promoting STEM education and rocketry.

1.3 Launch Vehicle Summary

1.3.1 Launch Vehicle

For the 2019 Student Launch competition, the launch vehicle's final design is a variable diameter body with fore and aft diameter of 7.71 and 6 inches respectively and a total length of 144 inches. Table 2 gives additional general vehicle dimensions.

The motor selected for this launch vehicle is the Cesaroni L1115. This motor is at the higher end of total impulse for L-class motors. When taking the most conservative estimates for payload and component masses, this motor will exceed the target altitude, as specified below, allowing the effective use of an Air Braking System. More detailed information, including motor thrust curves, can be found in Section 3.1.2. Additionally, the vehicle will utilize a 12 foot 1515 launch rail.

The target altitude selected for this year's competition vehicle is 4,700 ft. This altitude was specified at PDR, and confirmed in this report. Mission performance predictions indicate that the selected motor allows the vehicle to achieve an altitude between 5,000 and 5,100 ft. This range allows for the effective use of drag inducing tabs to reduce the apogee of flight to the targeted altitude.

Table 2: Concise Size and Mass Statement

Characteristic	Dimension
Total Length (in.)	144
Fore Diameter (in.)	7.51
Transition Length (in.)	4
Aft Diameter (in.)	6
Number of Fins	4
Fin Root Chord (in.)	7
Fin Tip Chord (in.)	7
Fin Sweep Angle (°)	30
Fin Height (in.)	6
CG Position from Nose Cone (with motor) (in.)	86.9
Total weight without Motor (oz.)	685
Total weight with Motor (oz.)	840
Stability Margin without Motor	4.24
Stability Margin with Motor	2.85

1.3.2 Recovery System

The recovery system will use a drogue parachute and main parachute which will be ejected simultaneously at apogee. The main parachute will be held tied up until main deployment at 500ft AGL, at which point a system of redundant chute releases will allow for full deployment. The ejection of the main and drogue parachutes will be accomplished through the use of a mechanical deployment system. The deployment system will rely on the energy of 4 pairs of compressed springs for ejection. The springs will be held down using a latch mechanism which can be opened by 2 independent servo motors. The estimated descent time for the launch vehicle is 88.81s, The maximum drift radius in 20mph winds is estimated to be 2441ft. The Eggtimer Model Flight Computer will be used for both the primary and secondary altimeters.

1.4 Payload Summary

1.4.1 Air Braking System Summary

The purpose of the Air Braking System (ABS) is to implement a system to control the apogee of the rocket to reach the target of 4,700 ft. Four drag control surfaces, hereby called drag tabs, will be extended from the side of the vehicle body after motor burnout has occurred to induce a drag force downward due to airflow and control the ascent speed after motor burnout. The drag tabs are controlled by a mechanical system driven by a servo motor and controlled autonomously by on-board avionics. These electronics will implement a closed loop PID control algorithm using feedback from on-board sensors whose data is passed through a Kalman filter to reduce noise. The necessary drag force to bring the vehicle to the designed apogee is calculated, and the drag tab mechanism actuates accordingly until retracting the tabs fully when apogee is detected.

2 Changes Since PDR

2.1 Changes to Vehicle Criteria

Slight alterations have been made to the overall airframe of the launch vehicle. The nose cone has been changed from an external length of 22 inches to a length of 29, to provide consistency with the supplier of the UAV bay, which is directly in contact with that. This same supplier is also providing a fiberglass wrapped phenolic rather than a purely fiberglass body tube. This will allow the overall weight of this section to decrease while increasing the stiffness-to-weight ratio.

2.1.1 Changes to Recovery System

The design of the recovery system was modified to address the action items identified in the Preliminary Design Review. The primary change was the addition of a drogue parachute in order to reduce the descent speed before main deployment. The main parachute also changed from a CERT 3XXL Series to a 14ft Rocketman parachute in order to better satisfy drift and descent time requirements. The ejected couplers shall also now be connected to the launch vehicle (per requirement 3.11.1). The spring used in the deployment mechanism was also changed from a music wire spring to a polyester rubber blend spring in order to increase safety and decrease weight. The design of the latch mechanism used in the deployment system was modified from a rotating latch mechanism to a sliding latch mechanism in order to increase ease of assembly and redundancy. Finally, to prove the success of separation and main deployment, the system shall follow a thorough testing regimen described in section 6.1.3.

2.2 Changes to Payload Criteria

2.2.1 Changes to UAV

The team has made some critical selections regarding the UAV payload. For the Linear Transport Mechanism, the nylon leadscrew was chosen over the rack and pinion due to its lighter weight and an easier assembly. With less components, space in the payload bay is more optimized. Also within the deployment system, the team chose an FS5106R Continuous Rotation Servo motor over a stepper motor for Orientation Correction. The servo motor provides more torque and precision than the stepper motor, which is necessary for accurate rotation of the system.

Additional design decisions have been made for the body of the UAV. For the frame, the team created two main designs: Iteration I and Iteration II. Iteration II was chosen due to its reduction in weight from the previous version. The second iteration also is easier to manufacture and is better equipped to handle the torsion spring deployment. For the arm extension mechanism on the UAV body, the belt and pulley system has been chosen over the sprocket and chain. While the systems are identical in function, the belt and pulley system is lighter which better suits the UAV payload constraints.

The final change affected the FEA detection feature. The team decided on a Hand-Crafted feature over a Data-Driven feature. The Hand-Crafted feature was chosen due to its simplicity and ease of use. It also allows for more options, such as texture and shape, rather than just color detection. The trade-study decisions are discussed more in depth in Table 35.

2.2.2 Changes to ABS

The primary alteration in the design of the Air Braking System since the preliminary design review is changes to the components driving the mechanism. The decision was made to change the ABS servo motor selection to the Hitec D980TW. This motor provides a higher torque of 611 oz-in, a lower weight of 2.76 oz, and an industry standard 25 tooth servo spline. This standard spline allowed a simplification by using a 25 tooth servo spline to shaft coupler to connect to servo motor to the ABS mechanism. Additionally, the drive shaft diameter was changed from 0.375" to 0.3125".

After performing bench testing, the decision was made to use the Freescale MPL3115A2 altimeter for the subscale test launch. Following its successful data collection, the MPL3115A2 was selected over the BMP280 as the full scale ABS altimeter.

2.3 Changes to Project Plan

- Additional funding on the order of $5,000 was secured as a charitable donation from Pratt & Whitney. An additional $250 was allocated to each subsystem design team, $500 allocated to competition travel, and $3,500 reserved for Research and

Development for future years.

- Due to difficulty in scheduling time in the Hessert Research Laboratory, wind tunnel testing was dropped from the vehicle analysis and validation process. This was also driven by a lack of equipment available to collect the desired data.
- Two sub-scale launches were conduced on December 1 to validate the effects of air braking tabs and collect data on flight sensors.
- The timeline for full scale construction slipped from late November to January 14 due to changes necessitated from the Preliminary Design Review and the scheduling of the University's Winter Break. All procurement of components shall conclude during the first week of the spring 2019 semester to begin construction of the vehicle.

3 Launch Vehicle Technical Design

3.1 Design and Verification of Launch Vehicle

3.1.1 Mission Success Criteria

The mission shall be considered a success if the following criteria are met.

Altitude

The team has determined a target altitude range of 4,700 ft - 5,200 ft at apogee, with the success of this criteria being determined by readings from an altimeter on board the rocket.

Stability

The vehicle must remain stable throughout the flight, with an off rail stability of at least 2.0 calipers. The success of this factor is determined theoretically using the simulations provide by OpenRocket and RockSim programs.

Structural Integrity

Each element of the final design must remain structurally intact throughout the duration of the flight and recovery, facilitating the possibility of a relaunch of the vehicle within the same day without any modifications or repairs. This recoverability is predicted by Kinetic Energy calculations of each section upon landing based on terminal velocity, and determined by assessing the condition of each facet of the vehicle upon recovery.

3.1.2 Final Vehicle Design

3.1.2.1 Vehicle Layout

The final vehicle layout can be found below, in Figure 1. The subsections and components are explained in greater detail in Table 3. There is a separation point in the parachute bay to allow access for the recovery system. This will be locked down during flight, and the only separation will occur at the joining of Sections I and II.

Table 3: Vehicle Layout

Section	Sub-Section	Label	Composition	Description
I	Nose Cone	A	Hollow fiberglass ogive nose cone	Foremost component, connected to the UAV payload bay (B)
	UAV Payload Bay	B	Fiberglass-wrapped phenolic body tube	Contains UAV payload and retention mechanism, connects to transition section
	Transition Section	C	Fiberglass transition	Transition piece measuring 4 inches long with fore diameter of 7.708 and aft diameter of 6 inches
	Parachute Bay	D	Carbon fiber body tube	Holds CRAM (Compact Removable Avionics Module), as well as parachute. Measures 6" in diameter and totals 44" in length, with a thickness of 0.08"
II	ABS	E	No airframe components	Houses ABS and physical tabs
	Fin Can	F	Carbon fiber body tube and four fins	Secures four fins, Air Braking System, and motor mounting components to launch vehicle. Measures 45" in length and 6" in diameter

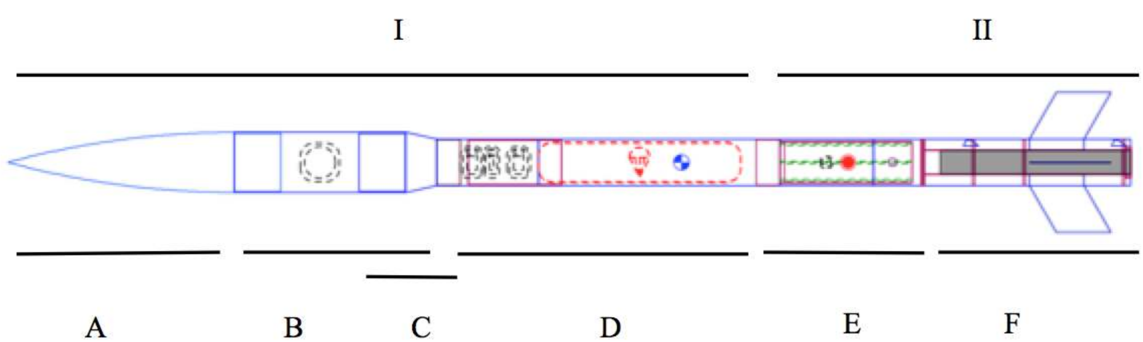


Figure 1: Basic Vehicle Sections

3.1.2.2 Vehicle Dimensions & Mass Statement

A detailed summary of the airframe components contributing to the total length of the launch vehicle is given in Table 4. Additionally, the masses of major components and subsystems for the launch vehicle are listed in Table 5, where the material densities that contributed to these masses are listed in Table 6.

Table 4: Airframe Component Lengths

Component	Exposed Length (in.)	Diameter (in.)
Nose Cone	29	7.708
UAV Payload bay	22	
Transition	4	Variable
Fore Recovery Tube	13	6
Aft Recovery Tube	31	
Fin Can	45	

Table 5: Detailed Mass Statement

Part	Mass (oz)	Material
Nose cone	44	G10 Fiberglass
UAV bay	39.3	Fiberglass-wrapped phenolic
UAV & related systems	100	—-
Transition	35	G10 Fiberglass
Secondary Recovery tube	28.1	Carbon fiber
Bulkhead (each)	8.6	G10 Fiberglass
Tube coupler	3.66	Phenolic
Recovery tube	41.5	Carbon fiber
Parachute	57	—-
Recovery System	120	—-
ABS (total system)	78	—-
Fin can	60.3	Carbon fiber
Fin (each)	6.575	Carbon fiber
Motor mount	16.9	Fiberglass-wrapped phenolic
Motor retainer	5.6	6061 Aluminum
Centering ring (each)	2.07	G10 Fiberglass
Total	840	—-

Table 6: Material Densities

Material	Density (oz/in^3)
G10 Fiberglass	1.51
G12 Fiberglass	1.38
Carbon fiber	0.91
6061 Aluminum	1.56
Kraft Phenolic	0.549
Fiberglassed Phenolic	0.638 (oz/in)

3.1.2.3 Airframe Design

The full scale vehicle has been modeled using CREO Parametric to analyze the interface an mass properties of the rocket. A full CAD drawing of the assembled vehicle can be seen in Figure 2 below.

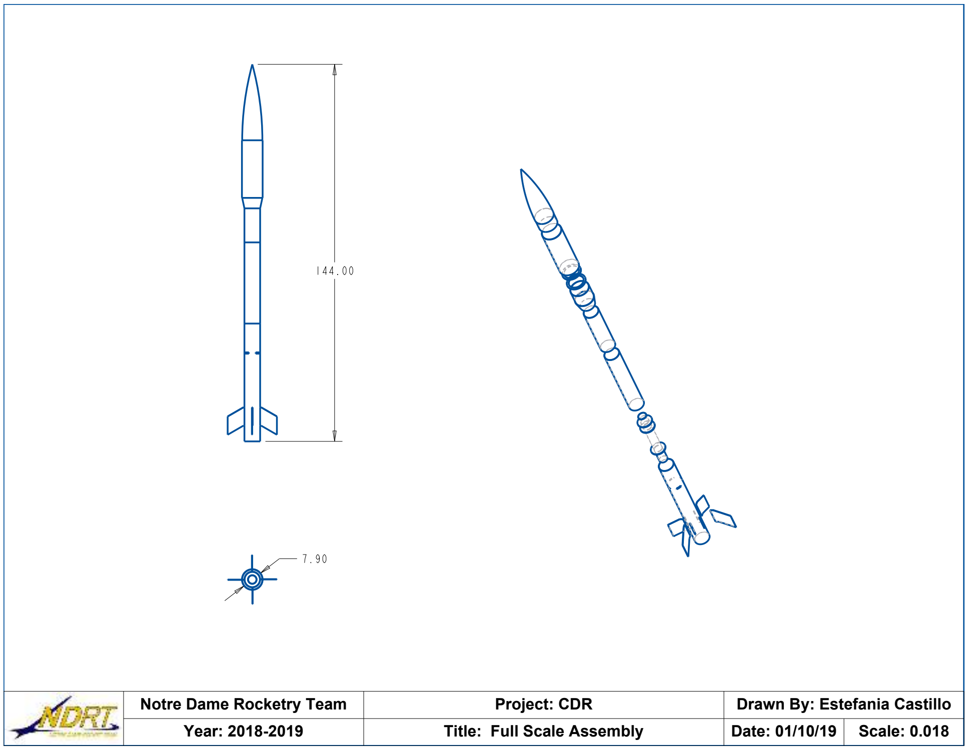


Figure 2: CAD Drawing of the assembled vehicle

Nose Cone

The three major design criteria variables for the nose cone were the material, shape, and size. To ensure that the cone has minimal weight and enough strength to endure in-flight forces, carbon fiber, fiberglass, and polypropylene were among the materials considered. In the past, polypropylene has been used because it fulfills the weight and strength requirements and is inexpensive relative to carbon fiber and fiberglass. However, past nose cones made of polypropylene have shown signs of warping when the shoulders were cut to integrate into the payload bays, adding to the risk of damage during landing. For this reason, a fiberglass nose cone will be used because it offers a higher strength compared to polypropylene while remaining lightweight and inexpensive relative to carbon fiber. Due to possible human error inherent in self-fabrication of the nose cone from fiberglass, there is no advantage to self-fabrication. Therefore, the nose cone will be purchased commercially from a rocket parts supplier.

As for the shape of the nose cone, the dictating factor was the reduction of pressure drag and frictional drag. Because the maximum velocity of the full-scale rocket will be below the transonic region of Mach 0.8, the pressure drag due will be negligible. In order to minimize frictional drag, minimizing wetted area and shape discontinuity became the driving factors in choosing a shape. Therefore, either an elliptical or a tangential ogive shape were considered because both have similar surface area and offer a tangential contact point between the nose cone and payload bay. The tangential ogive shape was ultimately chosen due to its commercial availability in the desired fiberglass material.

Because the pressure drag on the nose cone is negligible, the fineness and bluffness ratios were lesser priorities when determining the nose cone size. The driving dimension, then, was the diameter of the cone such that it will fit the desired payload bay diameter. The length was decided by what was commercially available to yield a sufficient fineness ratio without increasing wetted area. In order to fulfill material, shape, and size requirements, a nose cone was chosen from Public Missiles Limited. The cone is made of fiberglass and has dimensions laid out in Table 7 below.

Table 7: Nose Cone Properties

Property	Value
Exposed Length (in)	29
Shoulder Length (in)	6
Weight (oz)	44
Material	Fiberglassed Phenolic

UAV Payload Bay

The UAV Payload Bay is located directly behind the nose cone and before the transition section. Its main function is to carry the payload experiment, the unmanned aerial vehicle with simulated navigational beacon delivery, as well as contain the retention mechanism. The payload bay will be made out of G12 fiberglass wrapped phenolic, which has a density per unit length of 0.638 oz/in3. This material, along with carbon fiber, was chosen for the construction of the body tube because of its strength. Unlike carbon fiber, fiberglass does not block radio signals which are necessary for the UAV to operate and was therefore chosen for the UAV payload bay. Rather than using a pure fiberglass airframe section, a wrapped phenolic was selected for its stiffness to weight ratio, as the phenolic structure offsets the fiberglass stiffness. The payload bay will be made of a 22” long body tube with a diameter of 7.51” and a thickness of 0.121”. The mass of the unloaded payload bay is 39.3 oz.

Transition Section

The transition sub-section is composed of fiberglass and will have a length of 4 inches, a fore diameter of 7.5 inches, and an aft diameter of 6 inches. Fiberglass is used for the transition section because it is easier to shape into the desired shape than carbon fiber. The transition section is in place to decrease the flow angle across the variable diameter and thereby prevent flow separation. This is important to decrease turbulent flow for altimeter barometer readings, relevant for both Recovery and ABS.

Recovery Body Tube

The main body tube is composed of 2 sections. The section directly attached to the transition section will have an exposed length of 13 inches, and extend through the transition, 4 inches into the UAV bay. There will be 2 centering rings bearing the load, so the transition does not have to be load-bearing. This will have a hard connection point with a coupler to the parachute bay, which is 31 inches long. Both sections are 6 inches in diameter and .08 inches thick. Due to the complexity of the recovery system, a secondary access point was required. Before any flight, the sections will be joined together and secured with a screw lock. The purpose of the main body tube is to hold the recovery subsystem, from the spring release mechanism to the parachute. The fore load bearing bulkhead of the recovery subsystem sits fore of the separation point.

Fin Can

The purpose of the fin can is to secure four fins, the Air Braking System, and the motor mounting components to the launch vehicle. It measures 45 inches in length, and 6 inches in diameter. For the material of the fin can, the team elected to use carbon fiber due to its lightweight but durable composition. Previously proven to be the most effective material for application to the launch vehicle, carbon fiber allows the rocket to withstand greater forces while still maintaining a low weight. Each of the fins will be constructed out of carbon fiber as well, as they are an integral factor of the rocket's flight, providing dynamic stability on the flight path. The motor mount inside of the fin can extends 26.5 inches from the bottom, and is preceded by the ABS bay. On the air frame, this corresponds to slots cut into the body to allow for the ABS drag tabs to extend. A CAD drawing of the fin can can be found below, in Figure 3.

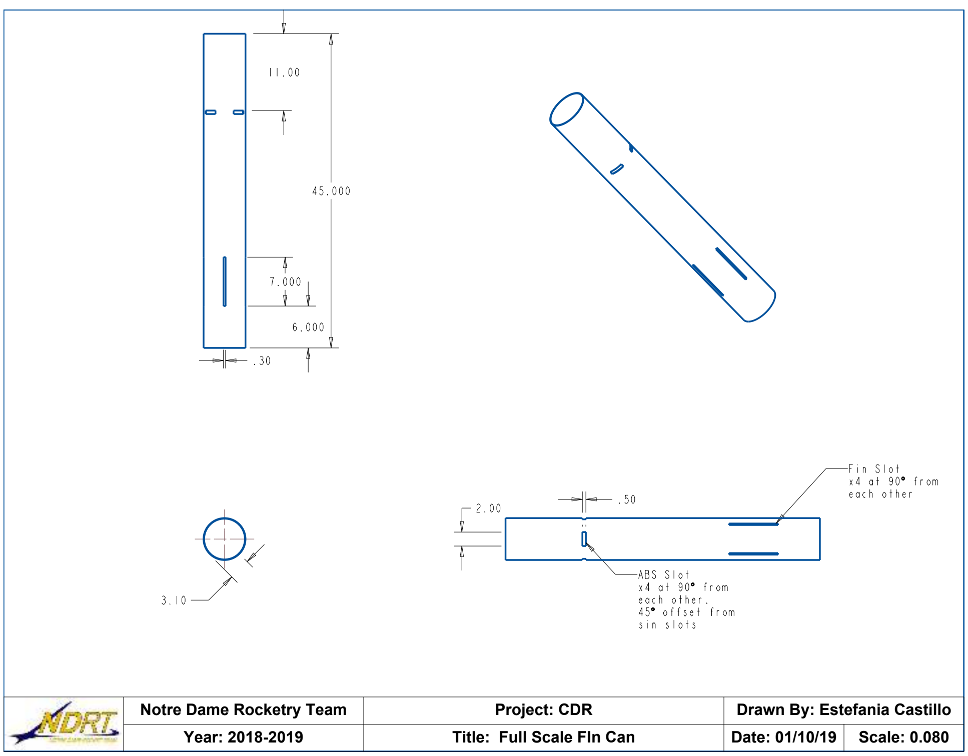


Figure 3: CAD Drawing of unassembled fin can

Fins

In order to retain dynamic stability during flight, fins will be attached at the fin can. Fins serve to position the C_P aft of the C_G, resulting in a stable flight path. Without proper fin placement, resulting moments in flight can compound to induce instabilities, the worst case being rotation about the C_G.

In deciding upon the optimal fin design, factors such as shape, material, and method of attachment were evaluated. The parallelogram will be the planform shape used for the fins as it yields low drag at low Reynolds numbers relative to other possible shapes, and it is simple to construct. Another benefit is the ease with which the design could be changed in order to reposition to the C_P. It is a design criteria that the drag tabs be as close as possible to the center of pressure, and this shape allows the C_P to be easily positioned at this location. The parallelogram was the planform shape used in the Subscale launch, which, after two stable flights, was shown to be effective. The leading edge is rounded and the trailing edge is more pointed, giving a cross section closer to an airfoil than a flat plate to reduce profile drag. Table 8, below, details the specific fin measurements and properties, and a drawing can be found in Figure 4.

Table 8: Fin Properties

Material	Carbon Fiber
Planform shape	Parallelogram
Root chord length	7.0 in.
Tip chord length	7.0 in.
Sweep angle	30°
Tab length	1.0 in.
Thickness	0.125 in.
Number of Fins	4

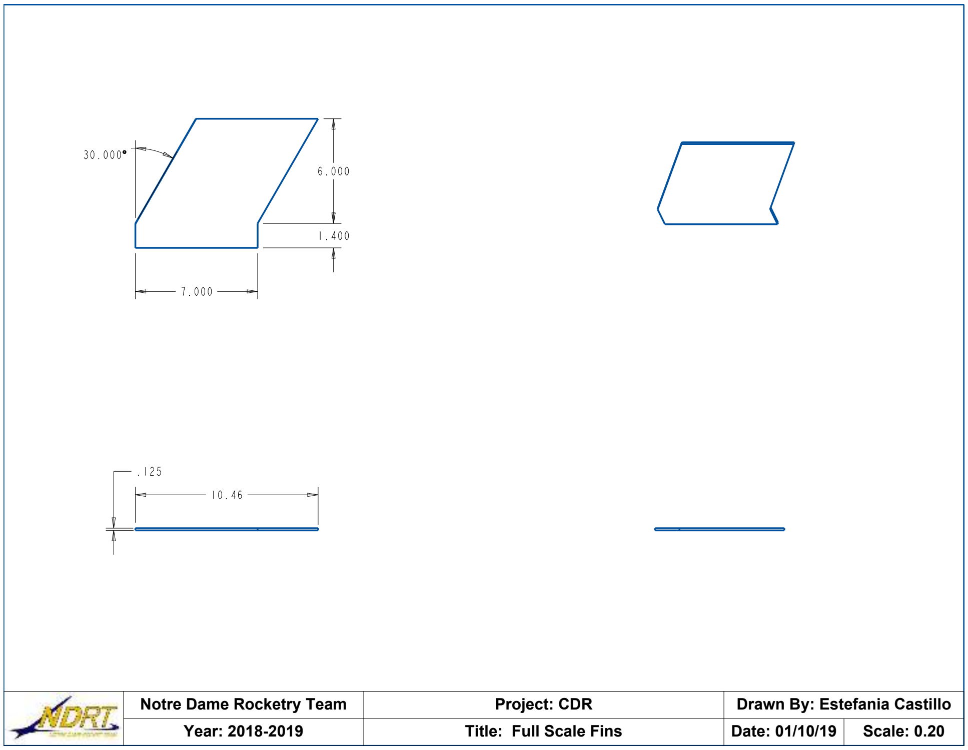


Figure 4: CAD Drawing of Fin design

3.1.2.4 Component Design

Bulkheads

Bulkheads will be used to separate each section on the interior of the rocket and maintain the pressure isolation of the UAV bay, recovery tube, ABS tube, and fin can. In addition, bulkheads, along with centering rings, will serve as the primary points for anchoring electronics and recovery mounts to the frame of the rocket as well as transferring the thrust of the the motor to the frame of the rocket. In previous years, plywood has been used for bulkheads. However, the thickness of the wood required to ensure reliable durability took up a significant volume inside the rocket and added significant weight. This year, fiberglass will be used to make the bulkheads because it offers a higher order of strength while remaining relatively thin. Additionally, fiberglass remains less expensive relative to even stronger carbon fiber. It was determined that the extra strength of a further upgrade to carbon fiber would not justify the additional increase in cost. The final mass of each 6 inch fiberglass bulkhead will be 5.2 oz.

Centering Rings

Centering rings will be used to ensure concentric alignment of thinner tubes within the body of the rocket, most importantly on the motor tube in the fin can where they also act as the primary surface to transfer the thrust of the motor to the frame of the rocket. The other use of the centering rings will be to carry the load through the transition between the 7.5 inch and 6 inch diameter body tubes. The material for the centering rings will be fiberglass because, like the bulkheads, the relative strength and thinness of fiberglass compared to the plywood justifies the slight cost increase of fiberglass. The final mass of each centering ring will be 6.2 oz.

Motor Retention
The motor is secured in the fin can by a 75mm motor retainer. The retainer consists of a body ring and a cap ring. The body ring is secured to the end of the motor mount. Once the motor is inserted into the fin can, the cap ring is screwed onto the body ring, locking the motor into place. This will prevent the separation of the motor from the launch vehicle, and is much more reliable than a friction fit.

Adhesives
The team will also use various adhesives when constructing the full scale rocket. 30 minute epoxy will be used for the attachment of the couplers and the bulkheads in the airframe, as well as the centering rings connecting the fore and aft body tubes. The motor mount centering rings will be attached to the mount with JB weld because of its high heat tolerance, an important factor when choosing motor adhesive.

3.1.2.5 Launch Vehicle Integrity

The total impulse of the Cesaroni L1115 is 4,966 Ns. This is a similar number to motors used in the past with phenolic body tubes. Therefore, since carbon fiber is being used in place of phenolic, the vehicle will have higher structural integrity. In table 9, below, it can be seen that the change to a fiberglass nose cone provides an improvement by a factor of 24, and the change to carbon fiber provides a factor of about 8. In addition, the environmental conditions of launches introduce the hazard of water damage. There materials chosen for this vehicle are resistant to moisture and help mitigate this risk.

Table 9: Material Integrity

Material	Modulus of Elasticity
polypropylene	290 ksi
phenolic	1.5 msi
fiberglass	7 msi
carbon fiber	12 msi

3.1.3 Construction Techniques

Fin Can
The fin can will be constructed in multiple stages, beginning with the motor mount. To ensure a proper mounting of the centering rings on the mount, each centering ring will be attached to the motor mount using JB weld. Once the 3 centering rings are secured to the motor mount, the motor mount will be inserted into the fin can. With the centering rings already aligned to the mount, they can be properly filleted to the fin can. One concern with

this technique is that the middle centering ring will not be accessible, when inserting into the outer fin can. To deal with this, epoxy will be applied to the inside of the fin can prior to sliding the mount in, so that epoxy can fillet itself. The way these fillets will form allows the epoxy to utilize its higher compressive strength, rather than tensile strength. Once the motor mount is affixed to the fin can, the fins will be inserted using a pair of alignment rings. These rings secure the fins in two locations along the axis of the vehicle while epoxy cures. The fins will be epoxied to the motor mount with JB Weld as well as the slots cut into the fin can using RocketPoxy.

ABS Integration
ABS will interface with the fin can via 4 rods attached to a bulkhead at the end of the motor mount tube. The bulkhead will be drilled such that the rods are epoxied in.

Fore Body Tube
The construction of the fore body tube relies mainly on the attachment of the two diameters. 2 centering rings will be epoxied to the 6 inch diameter carbon fiber tube and then that will be inserted into the 22" fiberglass UAV bay. These fiberglass centering rings will be the load bearing features of the transition.

3.1.4 Propulsion

The propulsion system consists of the motor and its corresponding support systems, including a retention system and a centering/mounting system. After several OpenRocket simulations were completed with motors from reliable manufacturers Loki, Cesaroni, and AeroTech, the Cesaroni L1115 was chosen. This motor was selected because it gave the necessary impulse and apogee, which was harder to come by due to the large mass of this rocket. The specifications and the commercially published thrust curve for the L1115 are shown below in Table 10 and Figure 5, respectively.

Table 10: Cesaroni Technologies L1115

Property	Value
Length (in)	24.4
Diameter (in)	2.95
Peak thrust (lbf)	385.1
Average thrust (lbf)	250.9
Total Impulse (lbf*s)	1128
Total weight (oz)	155
Burn time (s)	4.47

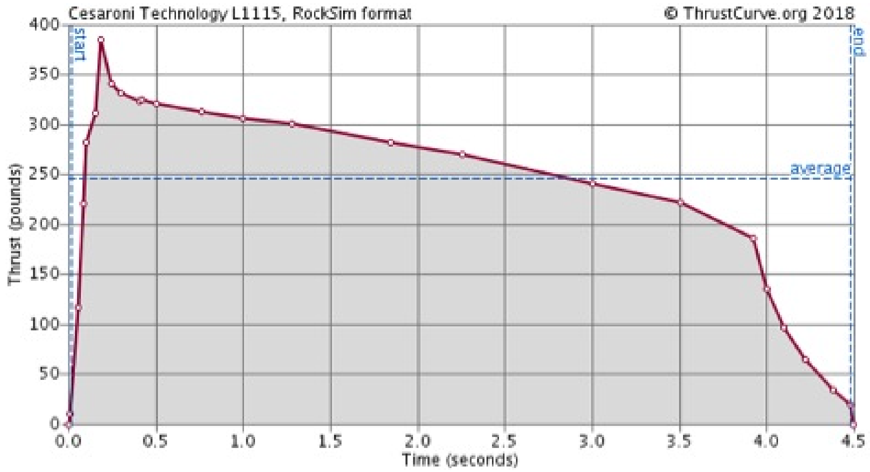


Figure 5: Motor Thrust Curve for Cesaroni 1115

3.2 Subscale Vehicle

3.2.1 Subscale Dimensions

The subscale launch vehicle had a scaling factor of 40% in order to test the vehicle's design as well as to obtain altitude and stability values. The team chose this scaling factor because it was small enough to allow the entire subscale rocket to fit in the wind tunnel, providing the opportunity to carry out testing there prior to the subscale launch. However, the 40% scaling factor also ensured that the size of the air braking systems drag tabs were not too small so as to be negligible. This scaling factor was also chosen based on the size of materials that could be purchased for the subscale model. The length of the subscale model was 52.65 inches, as compared to the full scale vehicle's length of 145 inches. Parts of the subscale vehicle were either ordered or cut to size to fit the scaling model. All parts used were smaller scales of their full scale counterpart with the exception being the motor. For all subscale launches, scaling the impulse by 40% did not allow for a significant difference in altitude to be observed between flights. Therefore, an Aerotech G79-7W motor was used to attain a controlled altitude high enough to see the tabs' effect. The projected apogee for this vehicle was 970 feet in OpenRocket without modeled air braking tabs. A detailed list of the subscale vehicle properties are listed in Table 11 below.

Table 11: Subscale Relevant Values

Property	Value
Length of vehicle (in)	5.27
Fore Diameter (in)	3.1
Aft Diameter (in)	2.26
Transition Length (in)	1.6
Fin root chord (in)	2.5
Fin tip chord (in)	2.5
Fin Sweep angle (degrees)	30
Number of fins	4
Weight without motor (oz)	38.6
Weight with motor (oz)	43.8
Estimated stability without motor	4.99
Estimated stability with motor	3.95

3.2.2 Subscale Results

Two subscale launches were conducted on December 2, 2018 with the goal of observing the overall aerodynamic performance of the design, testing the chute release system, and getting altitude readings. The launch conditions were slightly windy and cold. Subscale was launched to record apogee with and without the 3D printed ABS tabs. Relevant values of each flight are found in Table 12 below. There was a 10% change in apogee betwwen the two launches, with and without the simulated ABS. Even considering varying wind speeds, this is enough of a difference for a proof of concept, that the drag tabs do in fact decrease the apogee.

Table 12: Subscale Results

	Without ABS	With ABS
Center of Pressure	38.5" from tip of nose cone	
Center of Gravity	7.3 inches fore of Cp	
Stability Margin	3.23	
Target Apogee	960'	—
Actual Apogee	1058'	942'

The first launch represented a controlled flight without any tab extension from the body. The flight was stable in 8mph winds and the parachutes deployed as expected however some of the shroud lines became tangled and the parachute did not fully open. This resulted in a harder landing slightly damaging a fin. A repair was made using 5 minute epoxy and a alignment ring to secure the fin.

During the second launch the vehicle displayed a corkscrew flight profile, likely attributed to the cracked fin. Regardless of this motion, the ABS tabs proved to be useful as seen in an almost 10% decrease in altitude. At apogee, the chute properly deployed from the main body for a successful landing.

3.2.3 Full Scale Implications

The subscale launch successfully demonstrated that the drag-inducing tabs can lower an altitude on a launch vehicle. No vehicle design changes were made as a result of the subscale launch. The apogee was reduced more than predicted; however the corkscrew motion that was observed at takeoff is most likely the responsible for this discrepancy. Additionally, the sensors and altimeter flown on the subscale vehicle were able to record data and are therefore viable choices for the full scale vehicle.

3.3 Mission Performance Predictions

3.3.1 Flight Profile Simulations

Simulations were conducted in OpenRocket and RockSim in order to predict flight performance. Simulations were performed with both motors that were considered in the proposal in wind conditions ranging from 0 mph to 20 mph in 5 mph increments. Wind speeds above 20 mph were not considered, as this is the maximum wind speed allowed by NASA at the time of launch. The launch rail length for all simulations was assumed to be 144 in, and atmospheric conditions were set to International Standard Atmosphere. Tables 13 - 17 below shows the results of the OpenRocket and RockSim flight simulations under different wind conditions.

Table 13: Flight Simulation - 0 mph wind

	OpenRocket	RockSim
Apogee (ft.)	4942	5008
Max Velocity (ft/s)	543	549
Max Acceleration (ft/s^2)	204	214
Time to apogee (s)	18.6	18.77

Table 14: Flight Simulation - 5 mph wind

	OpenRocket	RockSim
Apogee (ft.)	4929	4992
Max Velocity (ft/s)	543	549
Max Acceleration (ft/s^2)	204	210
Time to apogee (s)	18.6	18.74

Table 15: Flight Simulation - 10 mph wind

	OpenRocket	RockSim
Apogee (ft.)	4897	4938
Max Velocity (ft/s)	542	548.50
Max Acceleration (ft/s^2)	204	210
Time to apogee (s)	18.6	18.64

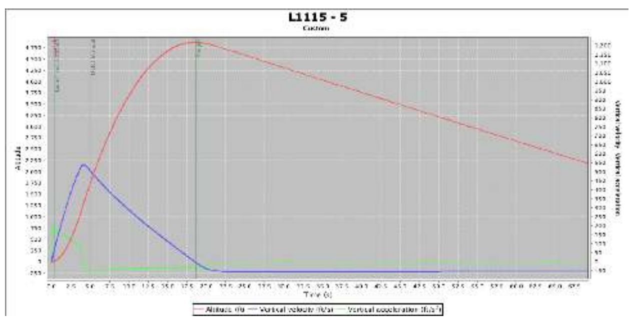
Table 16: Flight Simulation - 15 mph wind

	OpenRocket	RockSim
Apogee (ft.)	4849	4847
Max Velocity (ft/s)	541	548.1
Max Acceleration (ft/s^2)	204	210
Time to apogee (s)	18.5	18.46

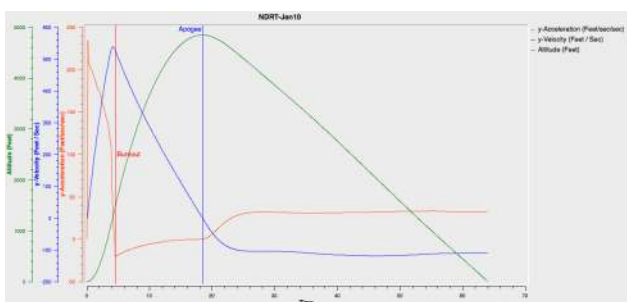
Table 17: Flight Simulation - 20 mph wind

	OpenRocket	RockSim
Apogee (ft.)	4834	4720
Max Velocity (ft/s)	540	547.6
Max Acceleration (ft/s^2)	204	214
Time to apogee (s)	18.5	18.33

Flight profiles from the two simulation packages can be found below, in Figure 6. It can be seen that the flight profiles are very similar, and that flight events are mirrored with the graphs. One such example is where the peak velocity occurs near the motor burnout, and then immediately begins to decrease.



(a) OpenRocket



(b) RockSim

Figure 6: Simulation Flight Profiles

3.3.2 Stability

The stability for the launch vehicle is required to have a margin of at least 2 calipers at rail exit. The vehicle must have a center of pressure aft of the center of gravity to prevent the moments from coupling and creating instability. The goal of the design was to have the stability between 2.2 and 2.7 calipers. However, the stability margin in Table 18 allows the use of ballast in the aft portion of the vehicle to adjust the center of gravity to reduce the stability margin. The value of 2.7 is an acceptable stability margin, but if exceeded by too much, can cause the vehicle to become over-stable, and turning into the small perturbations. The stability was calculated with both CAD modeling, OpenRocket, and RockSim.

Table 18: Stability

	OpenRocket	RockSim
Unloaded	4.11	4.25
Loaded with Motor	2.77	2.84

3.3.3 Simulation Differences

As can be seen from Tables 13 - 18, there are slight differences in the values calculated by the two softwares. Differences between the equations and calculations that the softwares use is the reason for this error. As this is only a design simulation currently, the softwares may use different a density or have round-off errors contributing to the differences. However, currently the maximum apogee error is within 2%, making the current differences acceptable. These models will further be validated through flight testing, as the model is adjusted to reflect the launch vehicle mass and performance.

3.3.4 Kinetic Energy Calculation

The kinetic energy at landing of each section of the vehicle was estimated using the terminal velocity of the vehicle under the main parachute and the mass of each section. The velocity under the main parachute was calculated to be 12.02ft/s from drag calculations found in section 3.6.1.2. The kinetic energy of each section is shown in Table 19.

Table 19: Kinetic Energy of each section of the rocket

Section 1	Section 2
66.91 ft-lb	27.11 ft-lb

3.3.5 Descent Time Calculation

The descent time of the launch vehicle was estimated based on the terminal velocities of the main and drogue parachutes. The worst case scenario implies that the launch vehicle reaches these velocities immediately and descends 500ft at 12.02ft/s and 4250ft at 85.45ft/s. However, due to parachute opening times and acceleration to terminal velocity, this time can be reduced by approximately 5%, and so the descent time was estimated to be 88.81s. OpenRocket calculations predicated a total flight time of approximately 109s, with a time to apogee of 19s, which leaves a descent time of 90s, very similar to that predicted based on terminal velocities.

3.3.6 Drift Calculations

The drift radius of the launch vehicle was calculated based on various wind speeds. The drift distance is simply the wind speed multiplied by the descent time. For wind speeds of 20mph, the drift radius was calculated to be 2678ft, assuming the apogee is directly about the launchpad.

3.4 Air Braking Subsystem

3.4.1 Design Overview

The purpose of the Air Braking System (ABS) is to implement a system to control the apogee of the rocket to reach the target of 4,700 ft. Four drag control surfaces shall be extended from the side of the vehicle body only after motor burnout has occurred to induce additional drag to control the ascent velocity post burnout. The drag tabs are actuated by a mechanical system driven by a servo motor and controlled autonomously by on-board avionics. These electronics will implement a closed loop PID control algorithm using feedback from on-board sensors whose data is passed through a Kalman filter to reduce noise. The necessary drag force to bring the vehicle to the designed apogee is calculated, and the drag tab mechanism actuates accordingly until retracting the tabs fully when apogee is detected.

The Air Braking System will be integrated into the fin can. This was chosen in order to strategically place the drag tabs at the center of pressure of the rocket in order to ensure a stable flight and comply with general requirement 2.24.1.

The results of the system will be evaluated based on the below mission success criteria:

- The vehicle shall achieve an apogee within ± 25 ft of the target apogee.
- Recorded data indicates the drag tabs were actuated.
- The drag tabs shall only be actuated if the vehicle is properly detected to be overshooting the target apogee. That is, if data is accurate and indicates the rocket shall not reach the target apogee the tabs should not actuate.

An important change from previous design iterations is that the Air Braking System forward bulkhead will not be connected to the recovery system shock cords and thus will not be load bearing. The assembly of the full system is shown in Figure 7, and a CAD drawing is shown in Figure 8.

Figure 7: Overall Design of Air Braking System

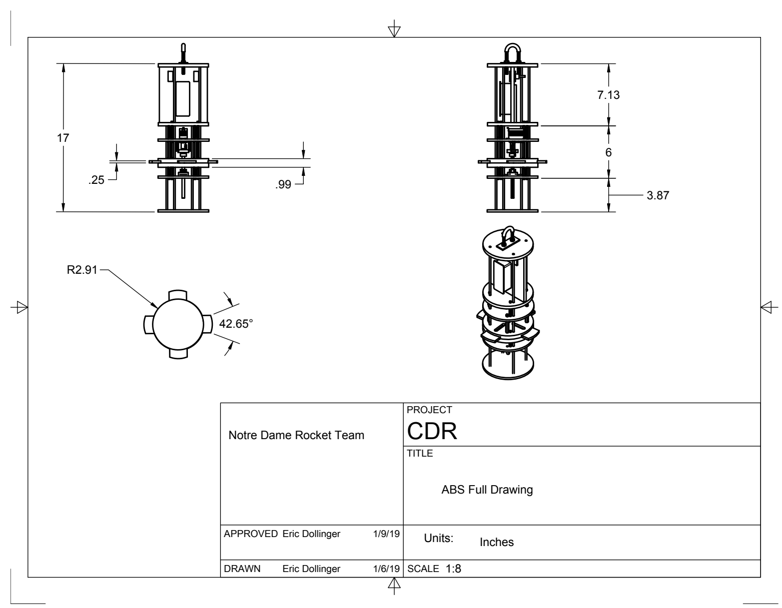


Figure 8: CAD Drawing of Air Braking System

3.4.2 Drag Tabs

The approximate area exposed to airflow of each tab is selected to be $2in^2$. This wetted tab area was calculated by assuming fully extended tabs immediately after motor burnout and lasting until apogee. For vertical flight, the axial summation of forces on the vehicle are given by Eq. 1:

$$m_{rocket} * a = F_{drag,rocket} + F_{gravity} + F_{drag,tabs} \tag{1}$$

where m_{rocket} is the mass of the rocket, a is the net acceleration of the rocket needed to achieve the target apogee of 4,700 ft., $F_{drag,rocket}$ is the force of drag on the rocket, $F_{gravity}$ is the force due to gravity, and $F_{drag,tabs}$ is the force of drag due to the tabs. The drag forces of the rocket and the tabs were calculated using Eq. 2:

$$F_{drag} = 1/2 * \rho * v^2 * A * C_D \tag{2}$$

where ρ is the density of air, v is the velocity, A is the cross sectional area, and C_D is the coefficient of drag. For preliminary approximations, the drag tabs were approximated as a flat plate and the rocket was approximated as a bullet. According to a NASA study, these approximations provide drag coefficients of 1.28 and 0.295 for the drag tab and the rocket body respectively. Using the approximate drag coefficients and the assumption that the tabs are fully extended for the entire flight, the tab area was calculated to be 2 in^2. However, because of variations in air density and rocket velocity, the full extension of the tabs until apogee is not necessary and a closed loop feedback avionics control system has be implemented instead to allow more precise control.

The drag tab is shaped as a rectangle with a rounded edge to match the circumference of the rocket body, allowing the tabs to sit flush when retracted. The back edge of the tab contains an angled edge to allow the tabs to better fit the confines of the rocket body. The dimensions of an individual tab are shown in the CAD drawing of Figure 9 below.

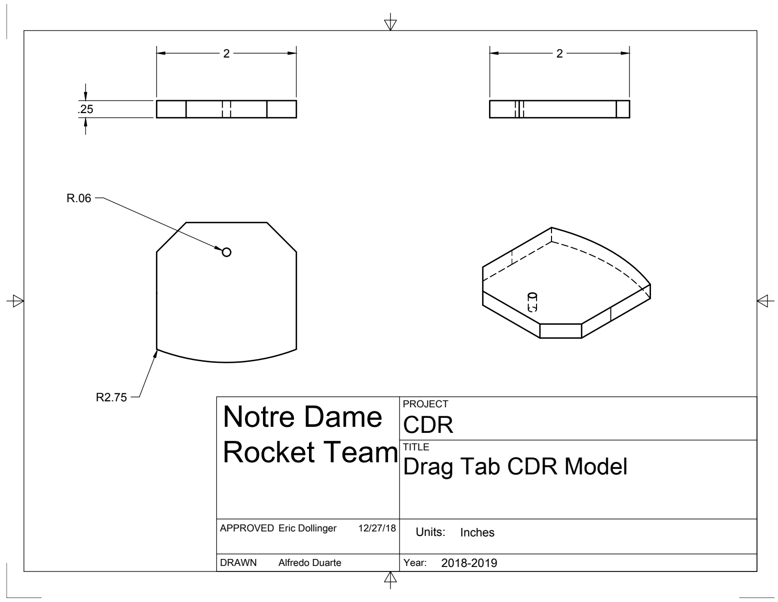


Figure 9: CAD Drawing of ABS Drag Tab

The drag tabs shall each be manufactured from of a sheet of Delrin. Selected properties of Delrin are shown in Table 20. Delrin was selected for several factors that include an affordable cost, easy machinability, a low friction coefficient, and adequate density. The plates that guide the tabs will also be made of Delrin. While Delrin possesses lower yield strength than nylons such as polyamide and alumide, preliminary calculations show that its strength is still more than enough for the loads that the tabs will be subject to. The main advantage of Delrin was its small coefficient of friction compared to the other materials, while still keeping a reasonable price. Polyamide possessed a comparably low coefficient of friction, but its cost was considerably higher. Additionally, Krytox grease will be applied as needed to lubricate the tabs and further reduce friction within the mechanism that may reduce actuation speed.

Table 20: Drag Tab Material Properties

Delrin	
Density (g/in^3)	23.27
Compressive Yield Strength (psi)	5,200
Tensile Yield Strength (psi)	9,000
Coefficient of Friction	0.2
Cost per ft^2 (0.25" thick)	$25.72

3.4.2.1 FEA Analysis of Drag Tab Performance

Finite Element Analysis was performed to ensure the physical integrity of the Delrin drag tabs when under the forces in flight. The pressure forces induced on tabs are estimated to be 8.5 psi. In order to validate the mechanical strength of the tabs, Finite Element Analysis (FEA) was run for pressures of 20 psi on the wetted surface of the tabs. The following constraints were placed on the analysis.

- Sides of the tab that are exposed to air are only permitted to move in the y and z directions.
- Sides of the tab within the mechanism support plates and not exposed to airflow are constrained in the x,y, and z directions.
- The hole for connecting to the tie rod is pinned (constrained nodes in x,y, and z).
- The bottom of the tab within the mechanism support plates which is not exposed to airflow is constrained in the x,y, and z directions.

The results of the analysis are shown below in Figures 10, 11, and 12.

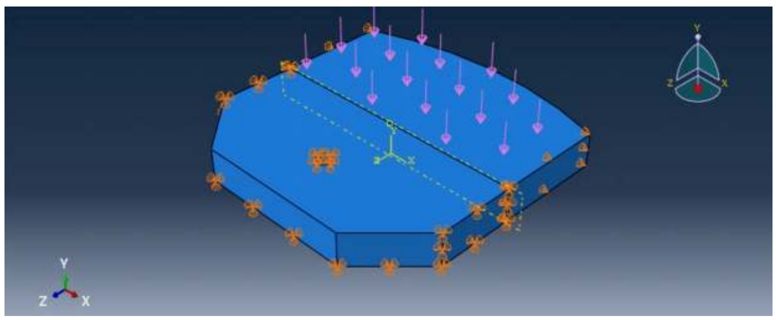


Figure 10: Model of FEA Constraints

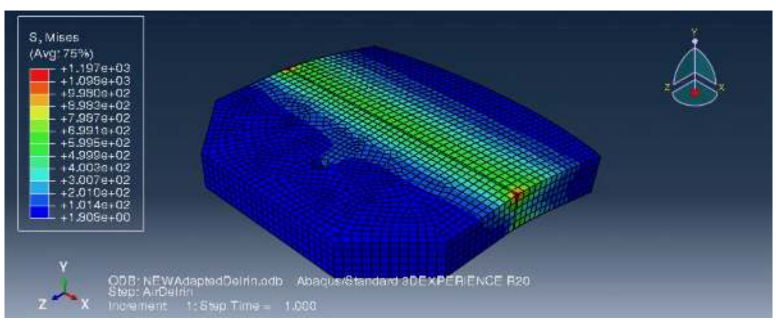


Figure 11: Von Mises Results of Drag Tab FEA at 20 psi

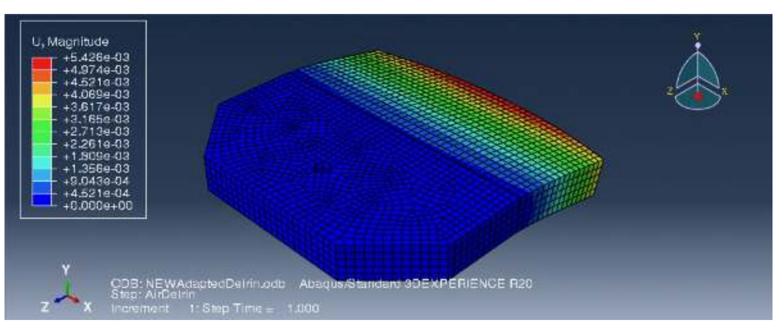


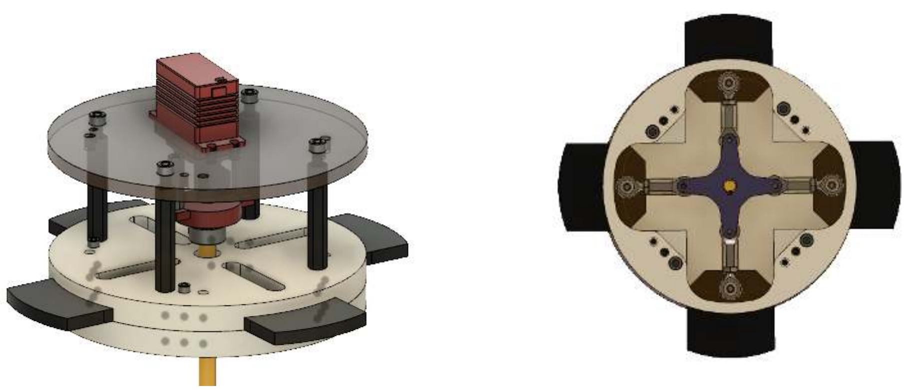
Figure 12: Displacement Results of Drag Tab FEA at 20 psi

The results indicate a max von Mises force of 1,197 psi at full extension and 20 psi acting on the tabs. The compressive yield strength of Delrin is 5,200 psi, providing a factor of safety of 4.3 at the 20 psi estimate. Since expected forces are lower, the Delrin drag tabs are shown to be capable of withstanding flight forces. Additionally, maximum displacement at 20 psi is 0.0054 in. The thickness of the drag tabs is 0.25 in., meaning the maximum displacement represents a displacement of approximately 2% of the tab thickness. Again, since expected flight forces are lower than the 20 psi simulated, the displacement of the tabs is deemed to be negligible and safe for flight.

3.4.3 Mechanical Design

The Air Braking System mechanical system will consist of four drag tabs deployed by a crank-slider mechanism. The system is actuated by a single Hitec D980TW servo motor which will directly connect to the central shaft to transmit power. To connect the motor to the shaft and transmit torque, a 25 tooth servo spline-to-shaft coupler purchased from Servo City will be used. The coupler is rated for up to 1,500 oz-in of torque without slipping, providing a factor of safety of 2.45 for this motor which supplies a maximum of 611 oz-in of torque.

The tabs extend along linear slots in the upper plate of the tab enclosure. The lower plate is a ring around the exterior and as the tabs extend into the flow, they will rack in the slots and slide on the exterior edge of the bottom of the tab and the interior edge on the top of the tab. These tabs are connected to tie rods, which attach to the crosspiece. This crosspiece is connected with a key to the keyed shaft to transmit torque from the servo motor to rotate the mechanism resulting in linear extension of the tabs. The use of a single shaft and crosspiece connecting all four of the tabs was done to ensure that no single tab may be extended into the air independently of the rest. This ensures that all the moments induced by the tabs are balanced, preventing any instabilities to arise during flight. CAD models of the ABS mechanism are shown in Figure 13 below.



(a) Overview (b) Bottom View

Figure 13: ABS Mechanism

3.4.3.1 Drag Tab Support Plates

The drag tab support plates will be constructed using Delrin. Delrin was chosen for its low coefficient of friction and durability despite its low weight. The primary force on the support plates is friction from the drag tabs. The drag tabs will undergo friction and shear forces due to the support plates and the drag that acts on the exposed area of the tabs, respectively. The low coefficient of friction allows the tabs to move sufficiently easy given the torque of the motor. The high yield strength of the drag tab material will prevent the tabs from deforming under the shear forces as a result of the drag and normal forces. The plates can be seen in Figure 13.

3.4.3.2 Crosspiece

The central crosspiece will be custom manufactured in house from Delrin similar to the drag tabs themselves. Delrin was chosen for its low weight, low friction, durability, and to reduce the number of different materials needed. The crosspiece will be under torsional forces. As the crosspiece translates the force generated by the servo motor to the tie rods, there will be shear forces present at the base of each arm as the forces from the tie rods act at an angle at the end of each arm. Delrin has a shear strength of 66 MPa which is much higher than expected shear forces at the base of each arm. Each arm of the crosspiece has a length of 1.05 inches. The dimensions of the crosspiece are shown in the CAD drawing of Figure 14 below.

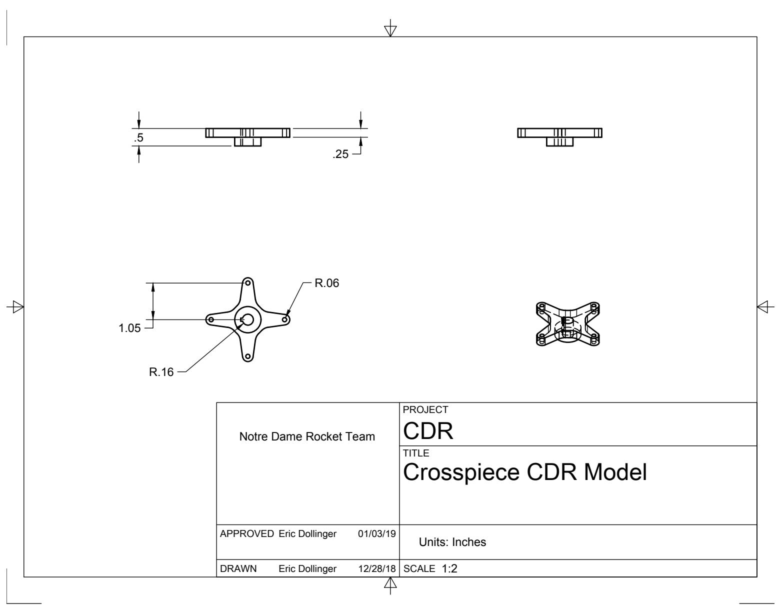


Figure 14: CAD Drawing of ABS Crosspiece

3.4.3.3 Tie Rods

Tie rods connecting the crosspiece to the drag tabs will be constructed using a male and female ball joint rod end with 6-32 threads connected together and secured with a lock nut. These parts will be sourced from McMaster-Carr. The tie rod assembly will have a center-center (major) length of 1.315 inches and are made of zinc-plated carbon steel. The tie rods will be under compressive and tensile forces as the crosspiece rotates to extend and retract the drag tabs, respectively. Carbon steel's typical tensile strength is greater than 50,000 psi which is more than adequate for the forces the tie rods will experience during operation of the ABS.

3.4.3.4 Torque Calculation

Modeling of the ABS mechanism was performed based on the Vector Loop Method (VLM) by assigning a vector to the arm of the crosspiece and tie rod, which sum to a vector pointing along the direction of drag tab extension. By breaking these vectors into their directional components and applying equations for the friction of the system, the torque required for a single tab is calculated and modeled in a Matlab program. By multiplying this torque by 4, the total torque required for the system is acquired.

The Hitec D980TW servo motor can supply 611 oz-in of torque. According to modeling of the system mechanics and frictional forces using Matlab, the system will require a maximum of 202.7 oz-in of torque during tab extension and retraction. This provides a factor of safety of 3.01 for the selected servo motor torque which will be beneficial when dealing with the tolerances of the coefficient of friction for materials, and will ensure that the servo motor does not stall. The servo motor will need to rotate approximately 65 degrees to fully extend the drag tabs.

3.4.3.5 Mounting Approach

Nylon fasteners will be used for most mounting points to reduce weight and cost compared to steel and aluminum options. The servo motor is mounted in a custom polycarbonate mounting plate held above the drag tab enclosure by nylon standoffs to give space for the servo spline to shaft coupler and hollow shaft potentiometer. A polycarbonate plate will also be placed below the drag tab enclosure which will be used to mount the oil embedded mounted sleeve bearing for the bottom end of the motor shaft. Polycarbonate was selected for its transparency which will be beneficial during construction and allow visibility of the mechanism when performing testing.

The avionics portion of the ABS will be mounted on a vertical HDPE plastic deck along the axis of the rocket. HDPE was chosen for its rigidity and electrical insulation. This setup will allow easy access to printed circuit board and associated components and allows for easy modular assembly via the nylon standoffs if the avionics deck needs to be removed for testing. On one side of the vertical deck will be the printed circuit board and sensors, and on the other side the ABS battery will be mounted in a custom case. The vertical avionics deck will have the forward bulkhead attached to the top and a bulkhead below that sits above the motor mounting, with a through-hole allowing for servo motor wiring. These bulkheads will also be made of HDPE. The avionics mounting can be seen in the upper portion of the overall design model in Figure 7.

3.4.4 Electrical Design

3.4.4.1 Servo Motor Selection

The motor selected to run the air braking system is the Hitec D980TW Servo. It provides a maximum torque of 611 oz-in and a lower weight than other options considered. Additionally, it has better technical support through our vendor, Servo City, and has a 25-tooth output spline for easy integration with shaft coupling accessories available from Servo City as well. The servo motor is powered by a 7.4 V battery, provides the programmable interface desired, and has a rating of 0.17 seconds per 60 degrees of rotation which should meet our requirement that the tabs fully extend in under 0.5 seconds. Specifications for the Hitech D980TW are shown below in Table 21.

Table 21: Servo Motor Technical Specifications

Hitec D980TW Servo Motor	
Servo Motor Type	Coreless Metal Brushed
Gear material	Titanium
Stall torque	611 oz-in
Speed	0.17sec/60° at 7.4V
Dimensions	43.8mm x 22.4mm x 40mm
Weight	78.2g
Operating Voltage	6 V - 7.4 V

3.4.4.2 Shaft Potentiometer

A single turn hollow shaft potentiometer was selected as feedback for the control algorithm. This sensor will allow the control algorithm to detect if the drag tabs have jammed by comparing the change in the shaft position measured by the potentiometer with the change expected based on the commands sent to the servo motor. If the shaft is detected to be jammed, the servo motor will be set to fully retract if possible for the safety of the flight.

The selected potentiometer is the RH32PC R5K L2% from P3 America, Inc. This potentiometer has a 5 kilo-Ohm resistance which will ensure the current draw is low and has an 8 mm (0.315") shaft diameter with a spring shim to regulate play which will fit the 0.3125" diameter of the ABS mechanism and be locked to the motor mount bulkhead with nylon standoffs attached to the flange ears on the potentiometer.

3.4.4.3 Battery Selection

The selected battery voltage is 7.4 V to match the required specification for the servo motor. The ABS electronics will be powered by a Tenergy 7.4 V, 2200mAh LiPO battery. This battery provides the advantage of a low weight of 102.06 g and a low cost of $12.99, while still providing sufficient voltage and current rating of 30C for up to a maximum current of 66 A, over ten times the stall current of the motor.

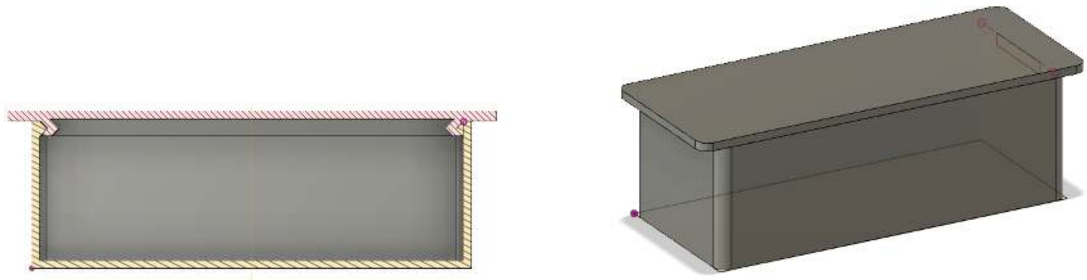
To ensure the selected battery will provide sufficient run time, the current draw of the system is derived. The most important consideration is the current draw of the Hitec D980TW servo motor, which draws 30 mA while idle, and as the servo rotates the current increases from 500 mA with no load to 6.2 A at a max load (stalled). Noting that the majority of the time the system is powered will be idle, the current consumption table shown below is used to calculate that the system can run approximately 9.6 hours while idle, and 14 minutes while stalled.

This provides an idle runtime with a factor of safety > 4 based on a nominal goal of sitting idle for two hours prior to flight. Additionally the system can run for a minimum of 14 minutes while stalled, which is both unlikely to occur and significantly longer than the length of the flight during which a stall would occur. Thus preliminary estimations indicate the battery provides sufficient capacity and maximum current.

Table 22: Electronics Current Draw Derivation

Device	Current Consumption (mA)
D980TW Servo Motor	30 (idle) 500 (no load) 6,200 (stalled)
Arduino MKR Zero	100
LEDs (8)	200
BNO055	12.3
MPL3115A2	2.0
Total Idle Current	344.3
Total Maximum Current	6,514.3

The battery will be enclosed in a 3D printed box which shall be attached to the vertical electronics deck, on the opposite side of the avionics printed circuit board mounting. The battery case shall consist of a snap-on cover for easy assembly and access to the battery. A hole drilled in the case will allow for the battery leads to extend from the case and connect to the printed circuit board. The snap on case is shown in Figure 15 below.



(a) Side View (b) Full View

Figure 15: ABS Battery Case

3.4.4.4 Micro-controller and Primary Sensor Selection

The ABS flight computer will be an Arduino MKR Zero. The Arduino MKR Zero has a 32 bit 48 MHz ARM Cortex M0+ processor and 22 I/O pins providing the speed and connections necessary for operation of the ABS. The Arduino will read the ABS sensors and compute filtered flight characteristics in order to execute the control algorithm while actuating the ABS mechanism.

Based on the trade studies conducted in the preliminary design reveiw report, the following sensors were selected for the full-scale ABS. The ABS altimeter will be a Freescale MPL3115A2 pressure sensor. The MPL3115A2 provides a 20-bit altitude reading with a 1 ft. resolution and provides I2C interface with the Arduino. This altimeter will provide the altitude data used by ABS control algorithms. The second sensor shall be a Bosch BNO055 9-DOF Inertial Measurement Unit (IMU) which provides a 14-bit acceleration measurement up to ±16 g's. This sensor will provide acceleration and orientation data to allow for velocity prediction.

3.4.4.5 Printed Circuit Board Design

A printed circuit board (PCB) was designed using EagleCAD software and produced by OSH Park within the United States. This supplier was chosen for faster processing and shipping and has produced good quality boards for our team in past years. Nominal shipping time for our design in 12 days with a minimum order of three boards. The PCB features two layers of copper traces to minimize the circuit footprint and save cost due to the pricing structure of $5 per square inch. Our board has dimensions of 92.38mm by 31.74mm and a total area of 2932 square millimeters (4.54 square inches), translating to a cost per PCB of $22.70.

The board serves as an interface between all of the electronic components in the Air Braking System. Power is delivered to the board by a 7.4 volt battery, selected to deliver adequate power to the specifications of the motor. The battery clips into the board with a Molex connector for ease of removal in recharging and storage scenarios. It is then routed through a switch directly to the motor. Power is also split off from the battery line and routed through a 5 volt regulator to power the microcontroller which is soldered directly into the board. Traces connect the microcontroller with the on board sensors to relay power, flight data, and control signals. All data from the sensors is written to a removable SD card within the microcontroller.

Eight status LEDs are integrated into the board for an enhanced user interface. The first of theses lights is wired directly across the switch and will illuminate when the battery is providing power to the circuit. The other seven lights are connected to digital output pins of the Arduino MKR Zero. These pins will send high signals to illuminate selected lights as determined by the control code logic. These signals relay information prior to launch about the arming the flight code and data logging status of the system. These LEDs will be a variety of different colors so it is easier to interpret status information when the closely spaced lights are glowing within the payload body. The board is designed for all of the main components to be soldered directly into the board to eliminate the unreliability of excess wires. The motor and battery will be removable for recharging and storage considerations.

The printed circuit board schematic and board layout are shown in Figure 16 below.

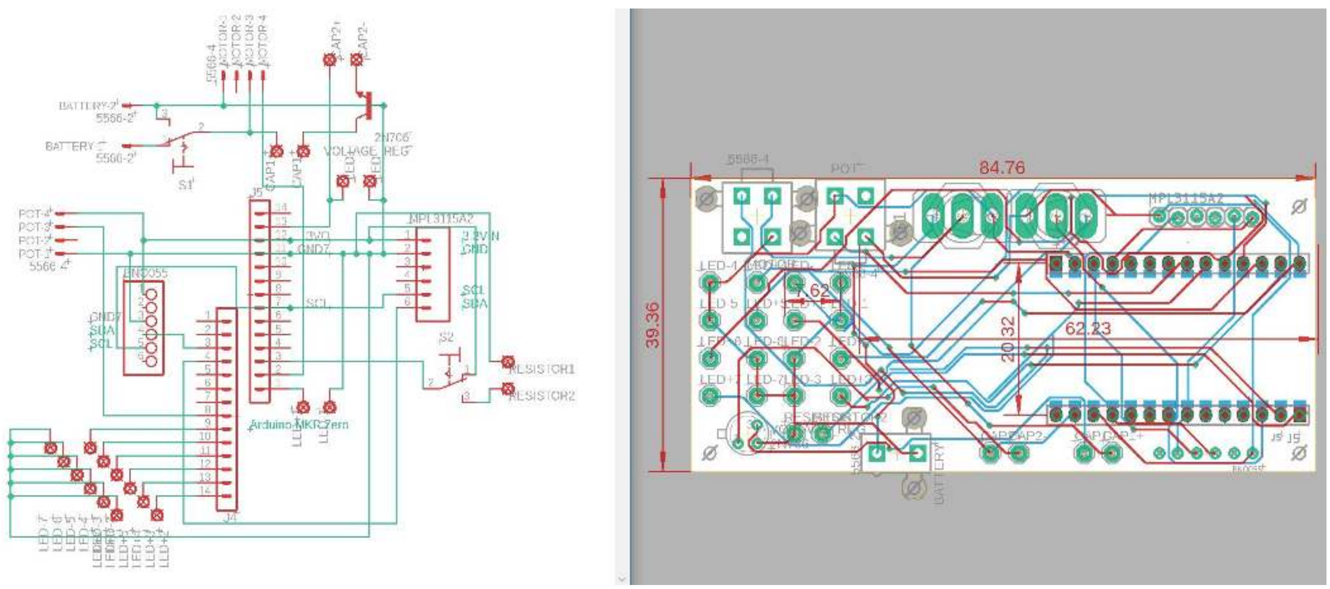


Figure 16: ABS PCB schematic and board layout

3.4.5 Control Software Design

The software for the Air Braking System is structured to run through a sequence of states representing the stages of the flight. A summary of these states are shown in Table 23. The code architecture begins with a startup configuration, which occurs on the launch pad immediately after the payload is powered on. The POWER and ARMED toggle switches will trigger LEDs to confirm that they are switched on. Visual confirmation of successful sensor initialization, proper connection to the SD card, proper connection to the servo motor, and proper connection to the encoder will be provided by distinct LEDs. An ideal flight path is then loaded into the SD card for later use in the PID controller. Once the ARMED switch is activated raw sensor data will begin to be stored onto the SD card and processed by a Kalman filter, which also stores filtered data on the SD card. The rocket's velocity is calculated using a linear regression of a 10-point running buffer of barometer data which is then Kalman filtered. All stage transitions are determined from Kalman filtered data as opposed to raw sensor data to mitigate issues with premature stage transitions due to noise spikes.

Once the ARMED switch is toggled, the code begins to check for liftoff. The drag tab system will not extend until the BURNOUT stage is entered. The control algorithm begins utilizing Kalman provided velocity data, and compares that velocity to a pre-calculated ideal velocity at the given altitude. This error information is then fed to a PID controller which continuously modifies the servo motor's position to change the extension of the drag tabs and achieve the desired change in velocity. The system will act as a closed-loop controller, recursively recalculating a new drag tab extension based on this error and communicating that extension to the servo motor controlling the drag tabs. If apogee is reached or potentiometer data indicates a jam the tabs will retract and remain retracted for the remainder of flight. A flowchart summarizing this process can be found in Figure 17 below.

Table 23: ABS Control System Stage Descriptions

Stage	Transition
ARMED	The control code will initialize in this state.
LAUNCHED	A transition to this state from ARMED occurs if an acceleration threshold or a height threshold is broken.
BURNOUT	A transition from LAUNCHED to this stage occurs when the net acceleration becomes negative.
APOGEE	A transition from BURNOUT to this stage will occur if the altitude is decreasing and the velocity value is negative.
LANDED	A transition from transition from APOGEE to this stage occurs once altitude drops below its initial threshold and velocity is less than a defined threshold.

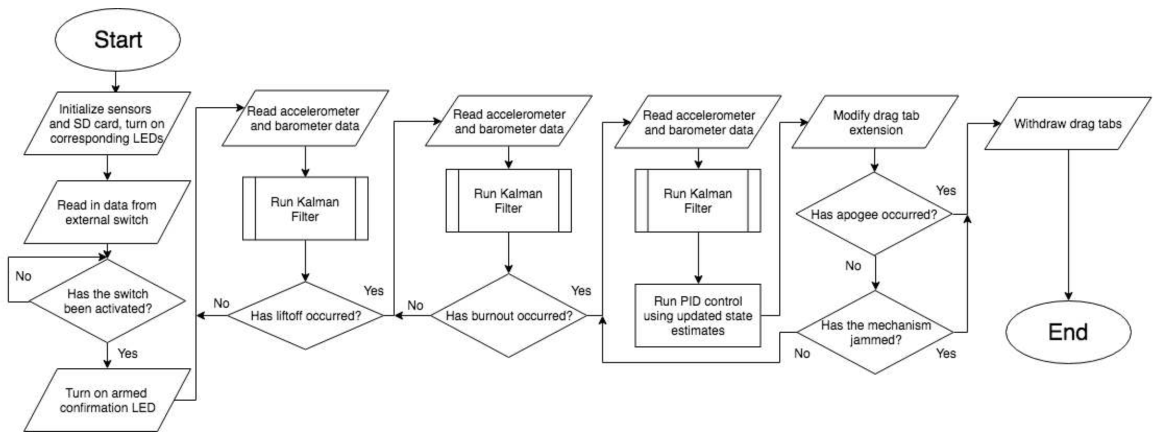


Figure 17: ABS Control System Flowchart

3.4.5.1 Kalman Filter

A Kalman filter will be utilized to dynamically correct sensor noise and error. Prior estimates of position, velocity, and acceleration will be used with sensor data and estimated noise to calculate a Kalman gain. The Kalman gain will be used with the sensor data to estimate the current position, velocity, and acceleration of the rocket. At this point the error covariance matrix is updated based on the Kalman gain factor. Finally, the Kalman filter projects an estimation of the state of the rocket and the associated error covariance into the next time step, to be used in the next iteration of the filter.

3.4.6 ABS User Interface

The user interface of the Air Braking System will consist of status components on the printed circuit board, which will be interfaced with before loading into the fin can, and which is visible when loaded via the barometric vent hole drilled in the rocket body. The panel will have two switches, one to power on the entire payload and another to arm the control code for flight. Both of these switches will have associated LEDs indicating that the switch has been flipped. Along with these two LEDs, there will be 5 status LEDs which will indicate the SD card, sensors, servo, and encoder are functional and communicating with the Arduino microcontroller.

3.4.7 ABS Integration

The Air Braking System will be integrated into the fin can of the vehicle. The ABS shall be installed by permanently mounting four 10-32 threaded steel rods in the fin can which will be run through dedicated holes in the ABS payload. These rods will then be secured with 10-32 low-strength steel lock nuts and #10 washers at top of the forward avionics bulkhead. These rods will provide a secure connection to the fin can while also ensuring proper alignment. A U-bolt on the forward bulkhead will provide a handle for the ABS to be removed from the vehicle by team personnel. The ABS shall weight approximately 72 oz including the steel integration rods.

3.5 Recovery Subsystem

3.5.1 Recovery System Overview

The vehicle will separate into two sections as the result of a spring-based mechanical deployment mechanism. The fore section will contain the UAV and components, the recovery system and components and the nose cone and transition sections. The aft section will contain the ABS and components and the fin can. A ball and latch mechanism will be controlled via a servo motor and will cause the release of a collection of springs which will separate the sections and eject a main and drogue parachute. The main parachute will be held tied up using redundant Jolly Logic Chute Releases until the vehicle reaches an altitude of 500ft AGL.

3.5.1.1 Mission Overview

The launch vehicle separation will be staged in order to comply with both the drift radius and descent time requirements. The recovery details are described in Table 24.

Table 24: Parachute Recovery Staging

Stage	Event	Altitude	Description
1	1.1 Spring Release	4750 ft AGL	The kevlar shock cords used to compress the rubber springs are released by the latch mechanism
1	1.2 Parachute Separation	4750 ft AGL	The released springs push the moveable bulkhead to separate the launch vehicle sections for parachute deployment
1	1.3 Jolly Logic Chute Release	4750 ft AGL	The main parachute is prevented from opening up during and after ejection through the use of a Jolly Logic Chute Release
2	2.1 Parachute Deployment	500 ft AGL	The latch holding the elastic around the main parachute is released, and the originally tethered parachute is opened to its full diameter

The events described above are further demonstrated in Figure 18.

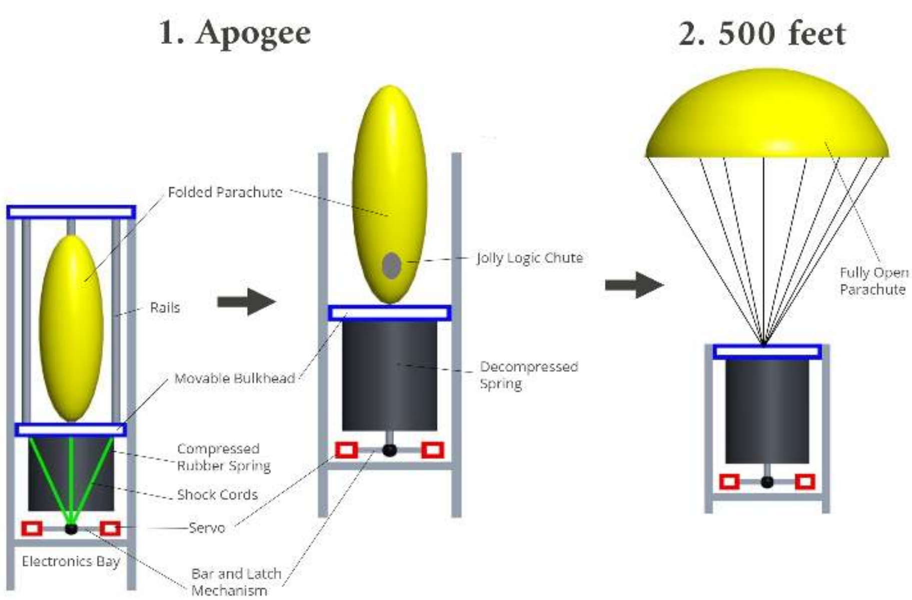


Figure 18: Diagram of Recovery Staging

3.5.1.2 Main Parachute Selection

The size of the main parachute was determined based on the minimum kinetic energy requirement of 75ft-lb as set by Requirement 3.3 in the Student Launch Handbook. The maximum descent velocity was found to be 12.69ft/s using formula 3 where m_s is the mass of the heaviest section of the launch vehicle.

$$V_{descent} = \sqrt{2 * KE * m_s} \tag{3}$$

The minimum diameter of the main parachute was then calculated to be 13.468ft based on equation 4 assuming a drag coefficient C_d of 1.85.

$$D = \frac{8W}{C_d \rho V_{descent}^2 \pi} \tag{4}$$

A 14ft parabolic Rocketman parachute made of low-porosity ripstop nylon was chosen, as it satisfies the kinetic energy requirement, but still produces a swift descent velocity of 96.2% of the maxmimum allowed. This minimizes drift distance and descent time. The Rocketman parachute was also chosen due to its high drag coefficient of 1.85 and its low weight. Characteristics of the Rocketman parachute are shown in Table 25. A picture of the Rocketman parachute is shown in Figure 19.

Table 25: Characteristics of 14 ft Rocketman Nylon Parachute

Characteristic	Value
Nominal Diameter (ft)	14
Drag Coefficient	1.85
Material	ripstop nylon
Maximum descent velocity (ft/s)	12.02
Packing Volume (in^3)	173.3
Weight (oz)	27.2

Figure 19: Rocketman 14ft parachute

3.5.2 Drogue Parachute Selection

The area of the drogue was calculated in order to satisfy the descent time requirement of 90 seconds as set by Requirement 3.10 in the Student Launch Handbook. Assuming a main deployment at an altitude of 500ft, the time required to descend under the main is 41.5628 s. This means that the time to descend to 500ft under the drogue parachute must be less than 48.4371 s. In order to achieve this, a Rocketman 2ft parachute was chosen, as it produces a descent time of 91.22 s, assuming the launch vehicle instantly reaches terminal velocity after parachute deployment. As there is a period of acceleration while the drogue parachute deploys, it can be estimated that the flight only takes 95% of the time of the worst case scenario, and so a descent time of 88.81s was found. The Rocketman parachute was chosen as it is lightweight, has a high drag coefficient, and provides a descent time closest to the required maximum, which allows for the highest terminal velocity, and least force on the launch vehicle when the main parachute deploys. The relevant characteristics of the drogue parachute are shown in Table 26.

Table 26: Characteristics of 2 ft Rocketman Nylon Parachute

Characteristic	Value
Nominal Diameter (ft)	2
Drag Coefficient	1.85
Material	ripstop nylon
Maximum descent velocity (ft/s)	85.45
Packing Volume (in^3)	7.96
Weight (oz)	1.5

From the information on the drogue and main parachutes, the maximum drift radius can be calculated in order to ensure that the flight falls within the 2500ft drift radius as set by Requirement 3.9 in the Student Launch Handbook. Drift radius was calculated by multiplying descent time by the wind speed. A plot of altitude vs. drift distance is shown in Figure 20.

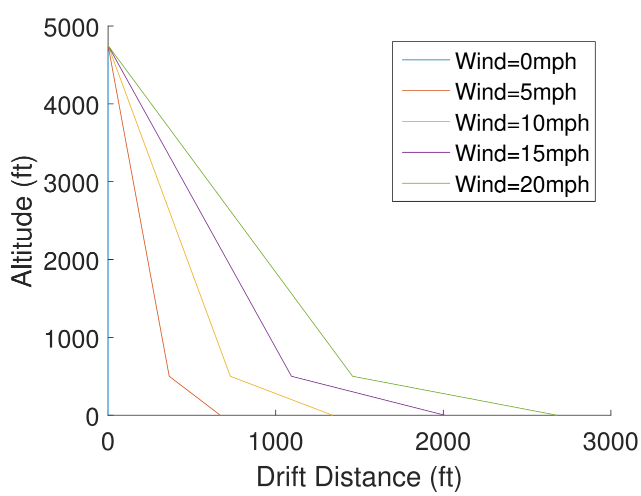


Figure 20: Drift distance vs. altitude for flights under various wind conditions

Figure 21: Jolly Logic Chute Release

The predicted drift distance was calculated for wind speeds ranging from 0 to 20mph, 20mph being the fastest wind speed in which the vehicle could be launched. At a wind speed of 20mph, the maximum drift distance calculated for the flight is 2678ft. This does exceed the max allowed drift radius, but due to weathercock stability, it is predicted that the launch vehicle will turn into the wind during ascent. It is assumed that the turning angle of the launch vehicle in 20mph would be at least .5°, and so the launch vehicle would turn approximately 238ft into the wind during ascent. This would bring the drift radius down to 2441 ft, which is within acceptable limits.

3.5.3 Chute Release

In order to adhere to requirement 3.1 in the NASA Student Launch Handbook, the main and drogue parachutes must deploy at separate times. To limit the number of ejections needed, a chute release was chosen to prevent the main from opening after deployment until the launch vehicle reached an altitude of 500ft AGL. The Jolly Logic Chute Release was chosen for this due to its light weight, ease of testing, and reliability. The Jolly Logic Chute Release consists of a band which wraps around the main parachute. A built-in altimeter triggers the band release at a pre-set altitude which causes the main to deploy. The chute release is shown in Figure 21. Two Jolly Logic Chute Releases will be tied in series around the main parachute in order to ensure redundancy.

3.5.4 Spring System

3.5.4.1 System Overview

The spring system stores and releases the energy needed to separate the sections of the launch vehicle. The main components of the system include: 8 composite compression springs, servo bay, bulkhead, latch mechanism, and other hardware such as eye bolts and shock cords.

3.5.4.2 Spring Selection

The energy will be stored in the recovery system through the use of 8 High-Load Fastener-Mount Compression Springs from McMaster-Carr, shown in Figure 22. These springs are a polyester and rubber blend, and were selected over conventional metal springs based on their reduced weight, decreased length, and increased safety, in the case of ejection from the vehicle during testing. The relevant characteristics of the spring are shown in Table 27

Table 27: Characteristics of High-Load Compression Spring

Characteristic	Value
Uncompressed Length(in)	1.063
Spring constant (lbf/in)	100
Material	Polyester/Rubber Blend
Compressed Length (in)	0.57
Maximum Spring Force (lbf)	49.3
Temperature Range (° F)	-40 to 120
Weight (oz)	0.317

Figure 22: Image of composite compression spring

The exploded view of the overall parachute deployment system is shown in Figure 23.

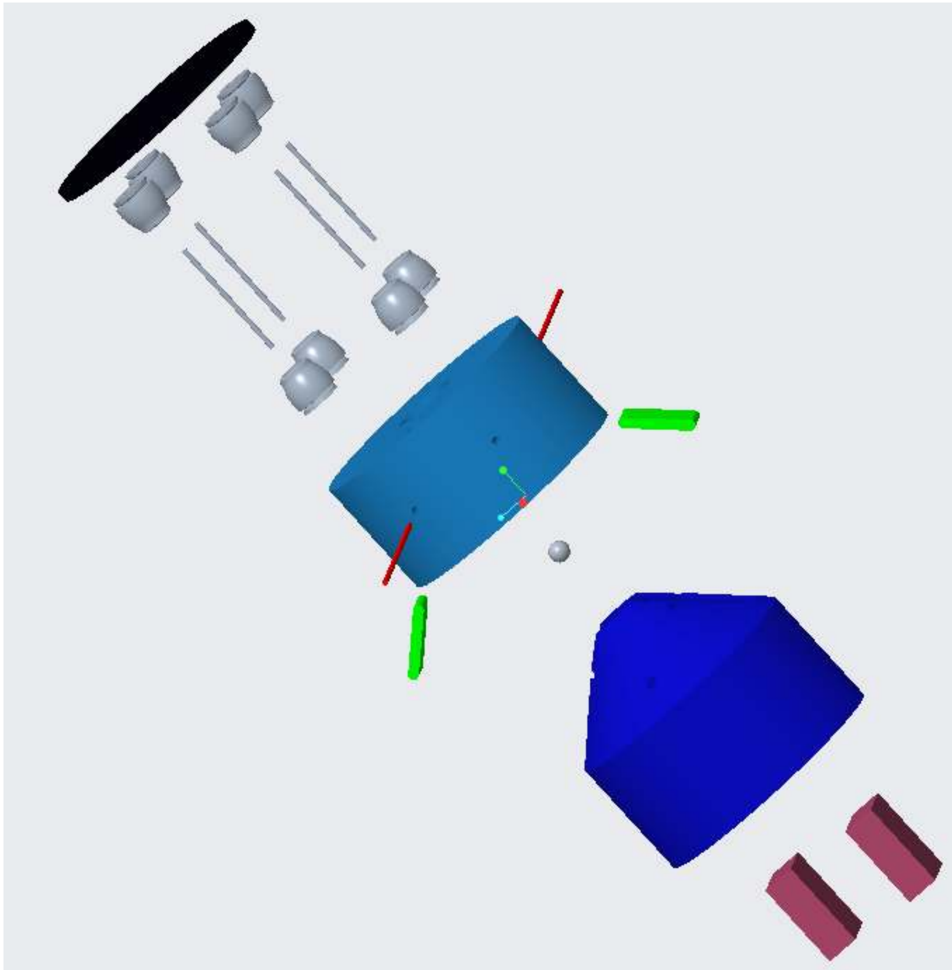


Figure 23: Exploded view of mechanical parachute deployment system

4 pairs of compressed composite springs store and release the energy needed to shear the pins holding the body sections together and eject the parachute into the airstream. The springs will be held in compression between a Garolite G-10 bulkhead plate above it (shown in black in Figure 23), and the top of the servo bay beneath them (shown in light blue). The Garolite bulkhead is held down by Kevlar shock cords which were chosen due to their low weight and the fact that exhibit little to no lengthening under tension. To guard against buckling of the springs, a supporting rod will be placed inside each pair of springs and the base of each spring will be epoxied to the mounting surface. This ensures even vertical compression and expansion.

The Kevlar shock cords attach on their lower end to an aluminum sphere 0.5" in diameter. Together these components link the spring to the mechanical latch mechanism. The sphere is secured by the two angled metal bars shown in green. When extended, these bars prevent the sphere from moving upward, which in turn prevents the expansion of the springs. The bars extend and retract into the servo bay independently and are controlled by two independent servos connected to two independent altimeters. If one bar were to jam, the full retraction of the other bar would allow the aluminum sphere to rotate out of the way of the stalled bar and proceed upward, releasing the energy of the springs. Because the altimeters, batteries, servo motors and latch bars are all independent, the system is one-fault tolerant. A cross sections of the servo bay and latch mechanism are shown in Figure 24. More detail on the latch mechanism, its components, and its mounting inside the servo bay can be found in section 3.5.4.3.

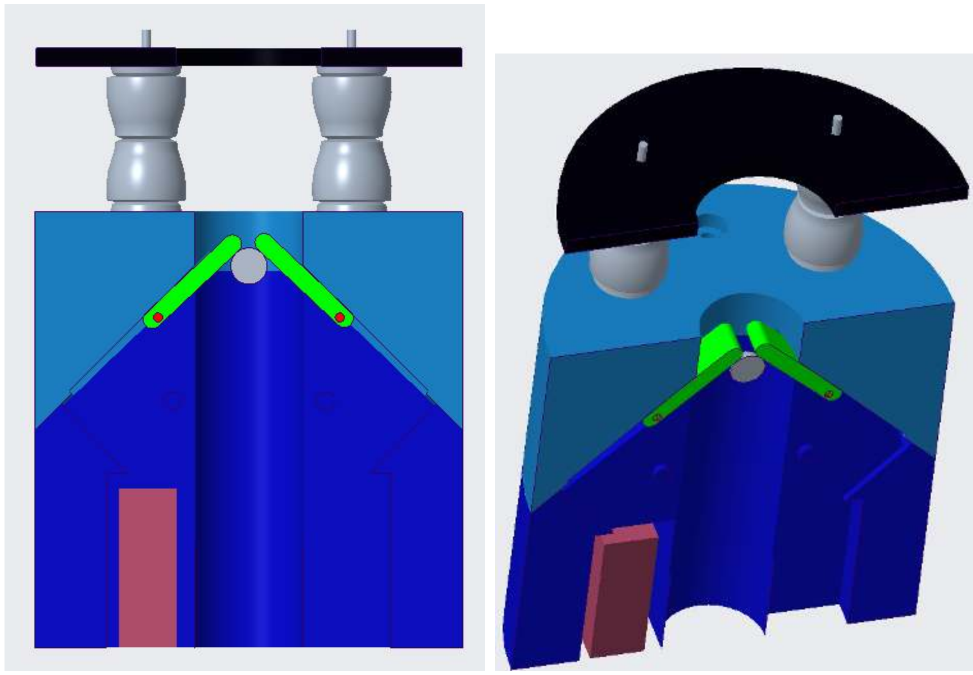


Figure 24: Cross section of the servo bay and latch mechanism

Before launch, the spring will be compressed outside of the launch vehicle. Bar clamps will be used to compress the Garolite bulkhead that sits on top of the springs and the servo bay. Once the springs have been compressed to their minimum length, the bars in the servo bay will be extended and the springs will be held in compression. To ensure the safety of the team, two safety pins, shown in red, will be inserted behind the extended bars, blocking their retraction and preventing the release of the spring. Once the spring-servo bay assembly is inserted into the body tube and the launch vehicle is on the pad, the pins will be pushed out the side of the body tube.

The shock cord that connects the main parachute to the fore section of the launch vehicle will be routed through the spring system. There are 2in diameter holes in both sections of the servo bay and the Garolite bulkhead which allows the shock cord to pass through it. This shock cord passes around the bar mechanism and is secured to the structural bulkhead at the transition section by an eye bolt. The entire path of the shock cord is centered in the body of the launch vehicle, which minimizes the lateral forces on the section and section components upon main parachute deployment.

3.5.4.3 Servo Bay

The servo bay will be 3D printed in three parts using ABS plastic. Two of these components will serve as the bottom half of the bay, and the third will be the top half. The bottom half of the servo bay is shown in Figure 25. The top half of the servo bay is shown in Figure 26, below. Upon assembly, the bottom two pieces of the servo bay will be permanently epoxied together. Then, the top and bottom halves will be bolted together using two 3/16" bolts that are threaded into the CRAM at the bottom of the system.

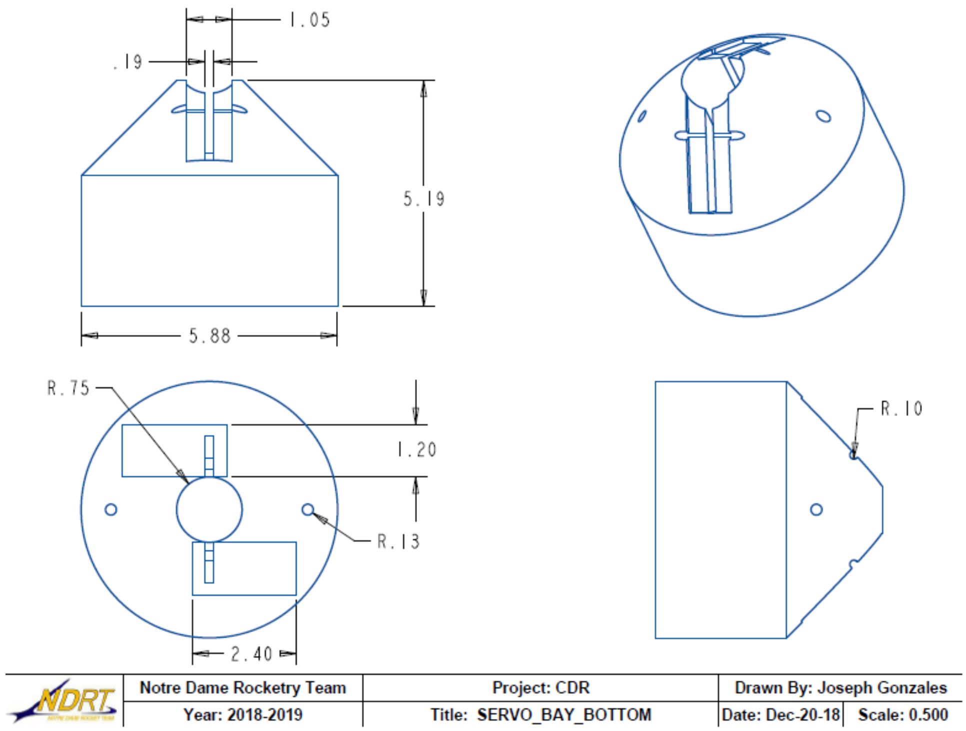


Figure 25: Drawing of bottom half of servo bay

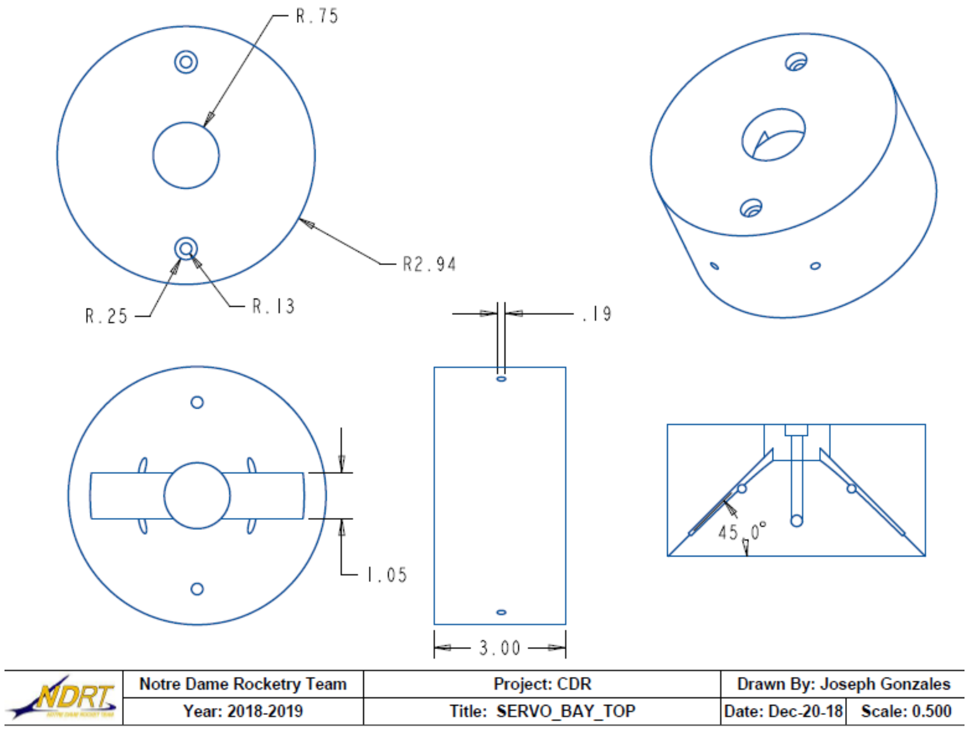


Figure 26: Drawing of top half of servo bay

Construction has begun on the servo bay, and a the two 3D printed sections of the bottom servo bay are shown in Figure 27.

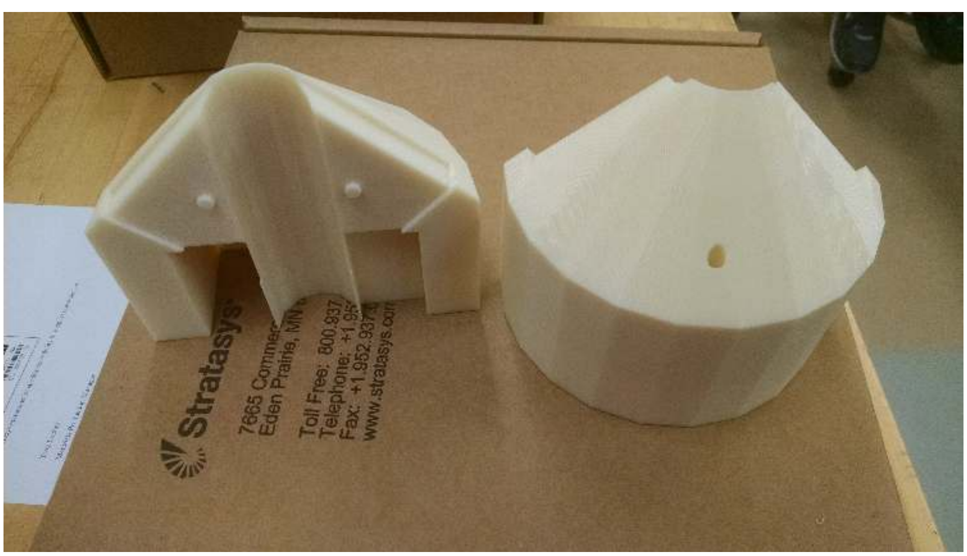


Figure 27: 3D printed bottom of servo bay

The latch mechanism and accompanying mechanics and electronics are all part of the servo bay. The bars slide in slots formed by mirrored cavities at the interface of the top and bottom halves. The retractable bars each have rack strips attached to their undersides, which allows them to be driven by two idler gears. The idler gears are permanently mounted in the bottom half of the servo bay and are driven by pinions attached to the servo output shaft. The servos are removable, and are slotted into the vertical rectangular slots in Figure 27. The servos are secured with screws in threaded holes in the servo bay. As stated above, the bars, the parts that drive them, and the signals that govern this driving are all independent between the two systems, yielding a redundant system. Figure 28 shows the servo bay with all latch mechanism components in place and with both halves of the servo bay bolted together.

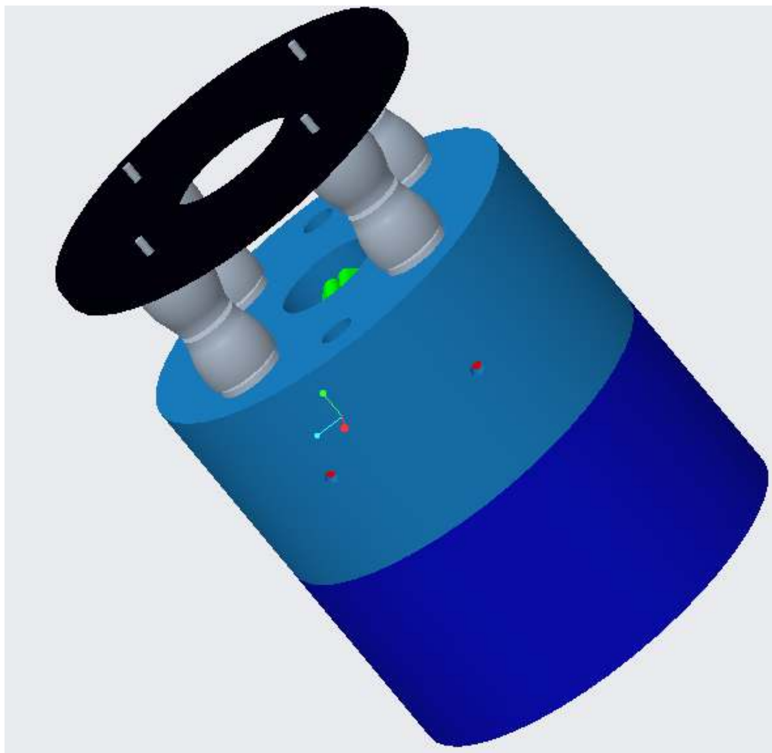


Figure 28: Computer rendered model of assembled servo bay with attached springs and Garolite bulkhead

3.5.5 Altimeter Choice

The Eggtimer altimeter will be used for the recovery system moving forward. As shown in Figure 29, it can be seen that the Eggtimer altimeter provided constant and accurate data. The altimeter collected data 33 times per second during both subscale launches. This data demonstrates that the Eggtimer performed as expected and collected accurate data for use in the recovery system of the full-scale launch vehicle.The Eggtimer altimeter was chosen due to its low cost, high accuracy, and ability to actuate servo motors using a pulse-width modulation signal, which is vital for the success of a mechanical recovery system.

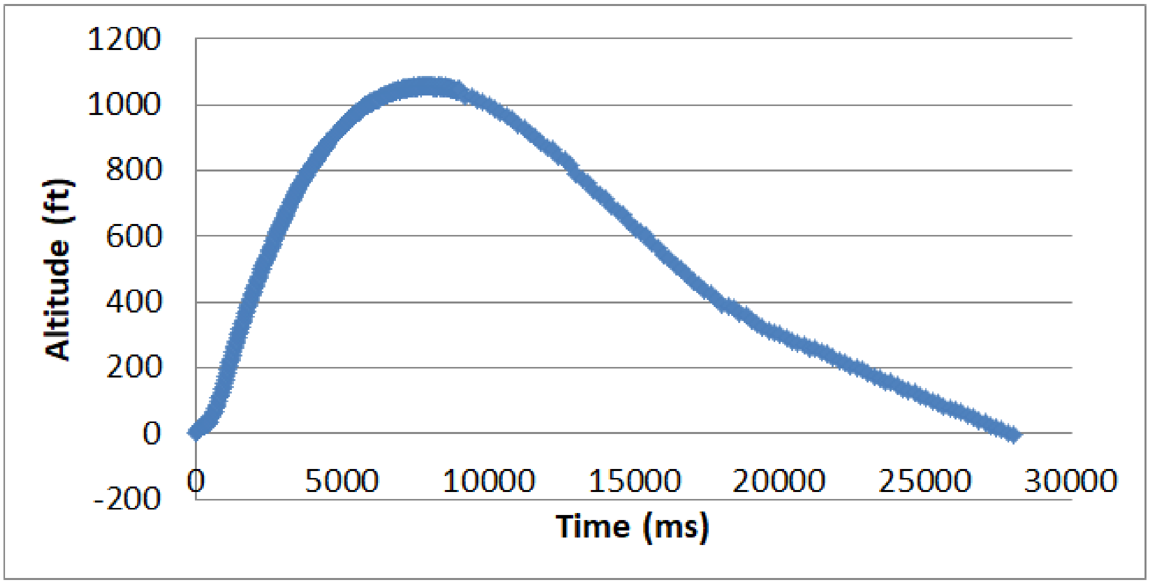


Figure 29: Data collected by the Eggtimer Model Flight Computer for subscale flight

3.5.6 Motor Choice

The motor chosen to slide the plates in the latch mechanism is the Power HD HD-1235MG servo motor. The specifications for the motor can be seen in Table 28.

Table 28: Specifications of PowerHD servo motor

Characteristic	Value
Size:	59.5 × 29.5 × 54.3 mm
Weight:	170 g
Speed at 7.4V:	0.18 sec/60°
Stall torque at 7.4V:	40 kg·cm
Speed at 6V:	0.20 sec/60°
Stall torque at 6V:	35 kg cm

The HD-1235MG was chosen due to its high torque to weight ratio, which is needed to overcome the friction acting on the sliding plates.

3.5.7 Battery Choice

The batteries that will power the servo motors and the altimeters will be AT: Tenergy Li-Ion batteries. The specifications for the batteries are shown in Table 29.

Table 29: Specifications for Tenergy Lithium Ion Battery

Characteristic	Value
Chemistry	Li-ion
Nominal Capacity	2600mAh
Nominal Voltage	7.4V
Charge Cut-off Voltage	8.4V
Maximum Charge Current	1300mA
Maximum Discharge Current	5200mA
Charge Current	0.5C
Minimum Capacity	2500mAh
End Voltage of Discharge	5.5V
Weight	98g
Dimensions	86 x 37 x 19mm

Tenergy batteries were chosen as they have a enough voltage to power both the servo motors and the altimeters. They also boast a battery life which can power all of the avionics for over 10 minutes at maximum power, which is far longer than necessary for a successful recovery.

3.5.8 CRAM Assembly

The CRAM (Compact Removable Avionics Module) is the component of the recovery system that houses the altimeters that control parachute ejection and the batteries that will power the altimeters and the servos. The CRAM consists of two major components, a body piece and a core piece. The multi-part avionics bay was chosen due to the ease in which the altimeters can be accessed after flight. Figure 30 shows the fully assembled CRAM.

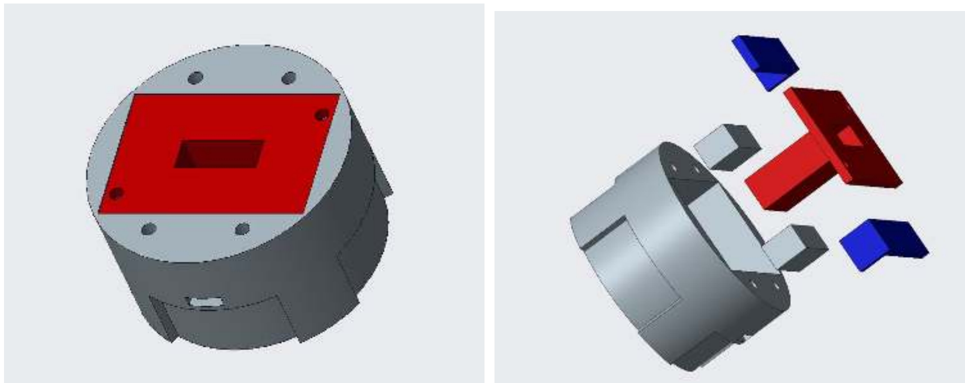


Figure 30: Computer rendered model of the CRAM assembly

3.5.8.1 CRAM Body

The CRAM body is a casing that will provide a mounting point for the servo bay, as well as the connection between the spring deployment system and the launch vehicle body. Figure 31 shows the CRAM body design.

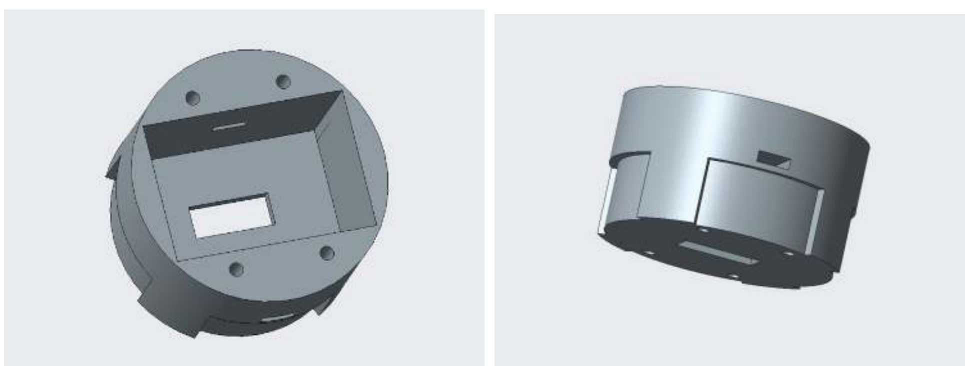


Figure 31: Computer rendered model of the CRAM body

The CRAM body consists of a cylinder with a large, central cutout that allows the CRAM core, with the altimeters and batteries,, to slide easily into and out of the body. The slits cut into the side of the CRAM allow access to the switch that connects the battery to the altimeters, as well as providing access to outside air such that the altimeters can properly function. The small holes in the top of the CRAM, which run all the way through the body, allow for bolts to connect the servo bay and CRAM together. In the bottom of the CRAM is a large hole that will allow the shock cord (which connects the top portion of the launch vehicle to the parachute) to connect to a structural bulkhead set into the launch vehicle. Due to its geometric complexity, the CRAM will be 3-D printed from ABS plastic. 3-D printing allows for the CRAM to be manufactured with high precision and reliability at a relatively low cost.

The body of the CRAM will be mounted in the body tube using external screws and a mounting bulkhead. The mounting bulkhead, pictured in Figure 32 below, has protrusions that will mate with the cutouts of CRAM body.

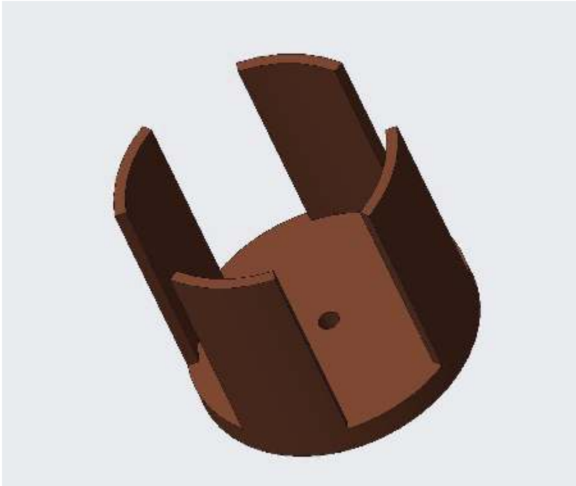


Figure 32: Computer rendered model of the mounting bulkhead for the CRAM

The bulkhead will be epoxied into the body tube to provide a secure mounting point for the rest of the recovery system. To secure the CRAM in place, screws will be driven through the exterior of the launch vehicle, through the protrusions in the mounting bulkhead, and into brass tapping inserts set into the CRAM. The protrusions in the mounting bulkhead will provide a backing to prevent the screws from shearing the body tube should excessive forces be encountered, while the tapping inserts will ensure that the screws will not strip out of the CRAM body. The combination of the mounting bulkhead and external screws guarantees secure mounting while allowing the CRAM to be removed with relative ease. Figure 33 shows how the CRAM body will mate with the mounting bulkhead.

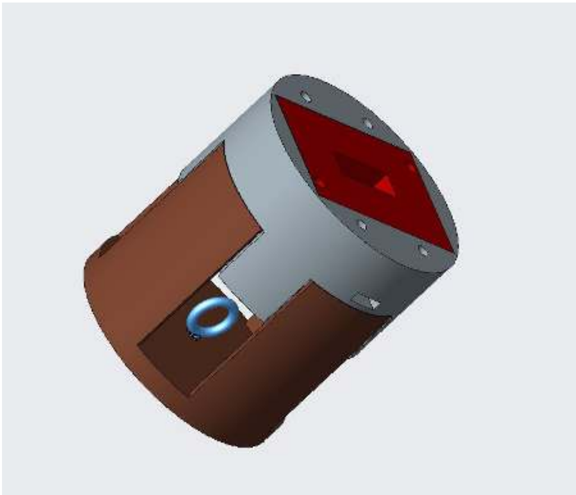


Figure 33: Computer rendered model of the mounting bulkhead and CRAM

3.5.8.2 CRAM Core

The CRAM core is a removable sled that the altimeters and batteries are mounted to. The removeable sled design allows easy access to the altimeters and batteries after the launch vehicle is successfully recovered, while tightly retaining the electronics in flight. Figure 34 shows the current design of the CRAM core.

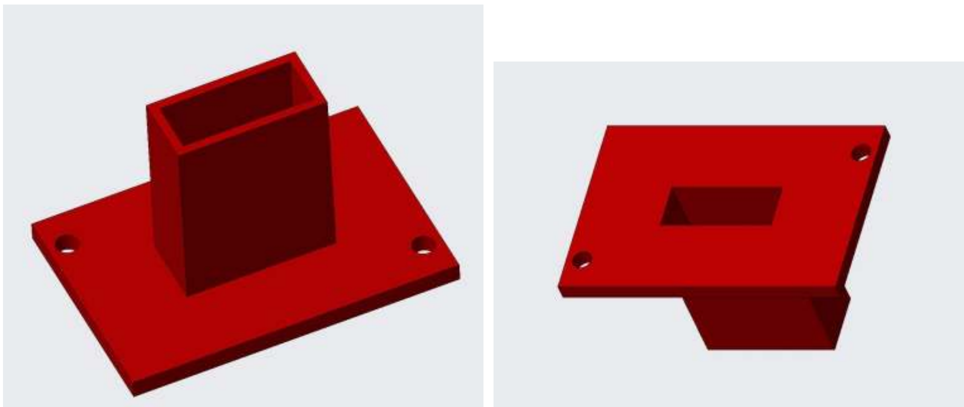


Figure 34: Computer rendered model model of the CRAM body

The hole in the top of the CRAM core travels all the way through the core to allow the shock cord to pass through. The 'skirt' of the core provides a mounting location for the altimeters, while the holes in the 'skirt' will allow electrical connections to pass through to the servo bay. The batteries will be mounted to the surface of the core, above the altimeters. The CRAM core will be 3-D printed from ABS plastic, which allows for high precision at relatively low cost. Figure 35, below, is the CRAM core, complete with altimeters and batteries.

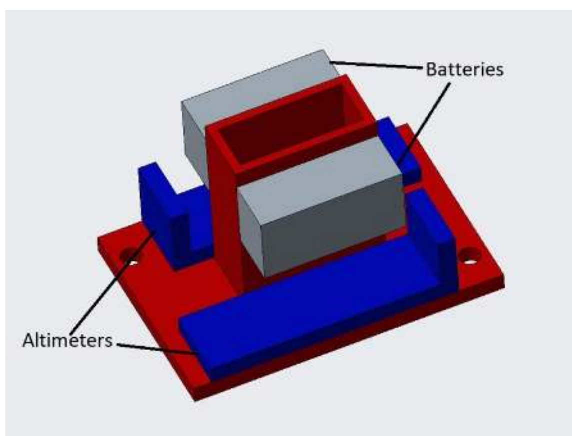


Figure 35: Computer rendered model of CRAM core with battery and altimeter locations

3.5.8.3 Shock Cords and Connecting Links

9/16in flat nylon shock cord with a breaking strength of 3000lb will be used to connect the sections of the launch vehicle after separation. The aft section will be secured at an eye bolt in the ABS, while the fore section will be connected to an eye bolt in a structural bulkhead fore of the CRAM. The shock cord will be routed through the recovery system in order to traverse from the parachute to the structural bulkhead. Nylon shock cords were chosen due to the extra width of the cord which reduces the chance of zippering, and the slightly elastic nature of the cord which reduces the impulse that the rocket receives during parachute deployment. Figure 36. depicts the shock cords that will be used in the rocket.

Figure 36: 9/16 in shock cord to be used in launch vehicle

In order to increase the easy of assembly of the launch vehicle, the shock cord will be connected to the eye bolts with 'quick links', which are carabiners with a threaded gate. Quick links were chosen in order to reduce assembly time during launch preparation, and allow for sections of the shock cord to be easily clipped in place. The quick links are 1/4 in think, made of 316 stainless steel, and can hold up to 1400 lb. 316 stainless steel was chosen due to its high yield strength and corrosion resistance.

The eye bolts that the shock cords will connect to will be 3/8 -16, forged construction, 316 stainless steel eye bolts capable of withstanding loads up to 1400lbs. These eye bolts connect the ABS and the structural bulkhead to the shock cords and the rest of the launch vehicle.

3.5.9 Vehicle Separation Points

The launch vehicle has two hard separation points where it will separate during normal operation. The first is in the middle of the launch vehicle, where the air braking system meets the parachute compartment. This point will split at the launch vehicle's apogee, releasing both the main and drogue parachutes. After separation, the two sections of the launch vehicle will be tethered together. The second point is at the nose cone, which will separate after the launch vehicle has landed in order to deploy the UAV payload. The launch vehicle also has a soft separation point immediately aft of the transition section with aids in the construction and retrieval of the recovery subsystem.

The recovery system also contains several soft separation points that will not split in flight, but are rather present to simplify launch preparation and data retrieval. The CRAM and servo bay can be separated, while the servo bay itself splits into a top and bottom component, where the top component is attached to the springs and the bottom component contains the servos and latch mechanism. This separation of components allows the altimeters in the CRAM to be prepared while the springs on the servo bay are compressed, shortening launch preparation.

3.5.10 Black Powder Backup System

The team recognizes the possibility for failure when designing a complex mechanical system of any kind. In anticipation of this, the team has been developing a black powder mechanism as a contingency plan for failure of the mechanical recovery system. The tests described in Section 6 will be conducted on the mechanical system to ensure that the parachutes will deploy without any issue; if confidence cannot established in the spring-based system before the first full-scale launch, the black powder system, which has been shown to be effective in previous years, will be utilized. A computer rendered model of the black powder system is shown in Figure 37.

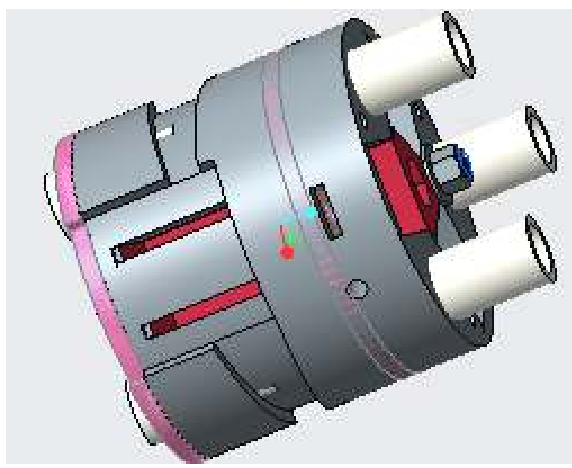


Figure 37: Computer model of the black powder backup system

The team has used black powder in several previous years, and an understanding as to how black powder recovery systems should be implemented has been developed. In replacing the mechanical system the design of the launch vehicle itself would not be altered; only the CRAM would need to be changed. This new CRAM would hold the altimeters and batteries in the same way, but the altimeters would then connect to e-matches in order to light the charges rather than servos. The charges would be held in PVC pipe in order to direct the explosion. This system still utilizes the chute release, so the purpose of the charges will be to create separation in the launch vehicle and push the main and drogue parachutes out of the recovery tube. The team will be able to convert the recovery mechanism of the launch vehicle from a spring based one to a black powder based one with little issue because a majority of the components can be reused. In fact, the only materials that the team would need to acquire in order to make this transition would be PVC pipe to hold the charges, Nomex to shield the parachute from the explosion, e-matches, and the charges themselves. The Eggtimer altimeters that are being utilized in the launch vehicle this year are able to modulate servos as well as detonate powder charges - the altimeter would just need to be reprogrammed. If deemed necessary, the switch between these two systems would be very feasible.

In this black-powder recovery mechanism there would be two redundant subsystems that operated independently, each with its own battery, altimeter, and charge. These two systems would be offset by 2 seconds in order to prevent the explosions from damaging the launch vehicle. Figure 38 shows how each of these subsystems would operate.

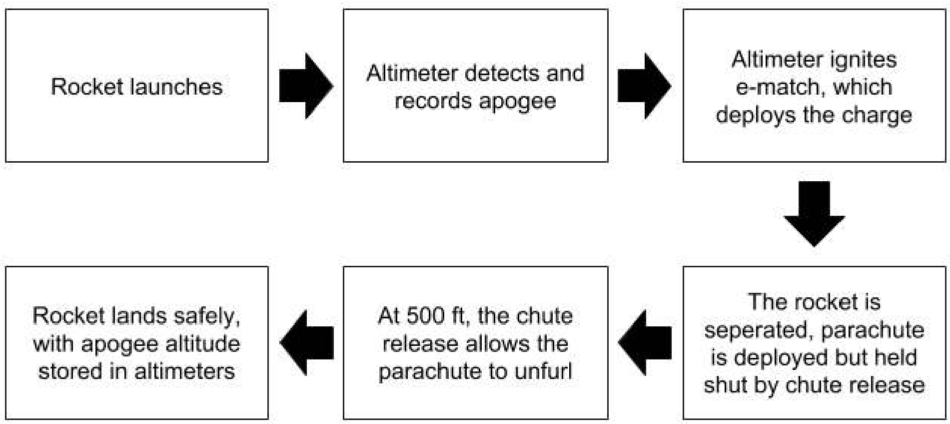


Figure 38: Flow of black powder recovery system

Before launching with the black powder system, testing would need to be done in order to ensure that everything is done properly. The focus of these tests would be ground-testing to ensure that the right amount of powder is inserted into the launch vehicle. If not enough powder is put in, the parachute will not be deployed, but if too much powder is inserted then the launch vehicle could be damaged. The team would try to find an ideal amount of powder that creates separation in the launch vehicle and propels the parachute without damaging any of the other components of the launch vehicle. This ground testing would be done in order to ensure that the results are repeatable and that the amount of powder chosen consistently separates the launch vehicle and sends the parachute out from the tube. No matter what system is chosen, the altimeters, the connections coming from the altimeters, and the chute releases will be tested before every launch to ensure a safe recovery.

The team can say with confidence that this black powder system is a very reliable backup plan to a mechanical system due to the success that the team has had with black powder in previous years. NDRT has many members with experience dealing with a black powder recovery system in previous designs, so switching to this simpler system will always be an option. NDRT will work to ensure that the recovery system of the launch vehicle is safe, regardless of the design implemented.

3.5.11 GPS tracking

The vehicle location will be tracked by an on board GPS transmitter. This transmitter will be located in the fiber glass nose cone in order to avoid interference from the Carbon Fiber body tube if placed in another section. Possible GPS systems considered included the Eggfinder TX kit, Altus Metrum TeleGPS, and a custom designed Xbee based telemetry circuit. The Eggfinder and TeleGPS were considered stronger options due to their professional support and reliability which reduces the amount of testing required.

The Eggfinder is the selected GPS tracking system. Primary factors considered include the significantly lower cost and 900 MHz operating frequency range, which will allow for operation without an amateur radio license. The Eggfinder weighs 0.71oz and meets mission requirements with a transmission power of 100 mW, below the 250 mW limit. GPS data will be transmitted from the on board Eggfinder TX Transmitter to the Eggfinder LCD Handheld Receiver.

The Eggfinder has a run current of 70 mA, with a peak of 200 mA on power up while acquiring satellite signals. A single 7.4 V, 300 mAh LiPo battery pack will be used to power the Eggfinder for flight. At a run current of 70 mA, this should provide approximately 4.2 hours of run time, greater than the 3 hour run time requirement.

3.5.12 Prototype Construction

Construction has begun on a prototype deployment system in order to test the viability of the mechanical deployment system. The prototype was made out of plywood and Masonite, instead of Garolite and ABS plastic, in order to limit cost. A latch mechanism was constructed using steel cable and held down with steel bars. Figure 39 shows the prototype latch mechanism spring setup.

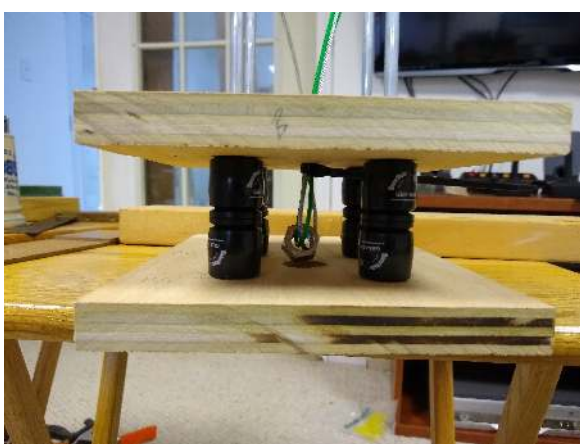


Figure 39: Prototype latch mechanism with springs without compression

The sliding bar setup was also constructed and is shown in Figure 40. The bars were removed manually, instead of with servo motors in order to increase simplicity of design.

Figure 40: Prototype sliding bar mechanism

The prototype latch mechanism had to be compressed using a system of c-clamps, which is indicative of how the system will need to be prepared in the launch vehicle. Preliminary tests have shown successful spring releases, which indicates that a spring deployment system is viable for use in the launch vehicle. Further tests will be performed to ensure that the force exerted by the spring is sufficient for ejection, as outlined in Section 6.1.

4 Safety

4.1 Safety Officer

James Cole is the Safety Officer for the Notre Dame Rocketry Team for the 2018-2019 season. The primary responsibility of the Safety Officer is to ensure the safety of all team members, students, and members of the public involved with any activities conducted by NDRT. To ensure this, the safety officer shall ensure that the team abides by all requirements set for the NASA USLI Competition as defined in Section 5.3 of the NASA SLI Handbook in addition to team-derived safety procedures.

4.2 Safety Analysis

Hazards are evaluated at a level of risk based on their severity and probability of occurrence. This method shall be applied to every step of the project and team operations. Each hazard identified shall be evaluated by the Safety Committee and documented such that the team will be proactively and promptly become aware of all hazards and mitigations. Thus, safety will be an iterative and interactive document that will remain ahead of any and all risks the team may encounter. In order to assist with this, the Safety Committee will be using a scoring system when evaluating risks. Probability of occurrence will be evaluated and designated with a letter between A and E, with E being that the event in question is almost certain to happen under present conditions, and A being that it is improbable the event occur. The criteria for this scoring is outlines in Table 30 below.

Table 30: Probability of hazard occurrence classification

Description	Value	Criteria
Improbable	A	Less than 5% chance that the event will occur
Unlikely	B	Between 5% and 20% chance that the event will occur
Moderate	C	Between 20% and 50% chance that the event will occur
Likely	D	Between 50% and 90% chance that the event will occur
Unavoidable	E	More than 90% chance that the event will occur

As mentioned, this probability is evaluated according to present conditions, meaning two assumptions were made. The first is that if the conditions change, the probability will be re-evaluated and changed accordingly. The second assumption is that all personnel involved in the activity will have undergone proper training and clearly acknowledged understanding of the rules and regulations outlined in safety documentation. This may include, but not limited to, the safety manual, compiled SDS document, FMEA tables, most recent design review, and lab manual if applicable. The evaluation of occurrence probability will also assume that proper PPE was used, all outlined procedures were correctly followed, and all equipment was inspected before use. Severity of the incident is evaluated on a scale of 1 through 4, where 4 is that the incident will prove catastrophic, and 1 is that the incident will prove negligible. Severity is evaluated according to the incident's impact on personal health and well-being, impact on mission success, and the environment. The score shall be based off of whatever the worst case scenario for the types of impacts being considered. These considerations will be re-evaluated anytime new hazards are identified. The criteria used to evaluate severity of each hazard is outlined are Table 31 below.

Table 31: Severity of hazard classification

Description	Value	Criteria
Negligible	1	Could result in insignificant injuries, partial failure of systems not critical to mission completion, project timeline or outcome possibly affected and might require corrective action, or minor environmental effects.
Marginal	2	Could result in minor injuries, complete failure of systems not critical to mission completion, project timeline or outcome affected and requires corrective action, or moderate environmental .
Critical	3	Could result in severe injuries, partial mission failure, severe impact to project requiring significant and immediate corrective action for project continuity, or severe and reversible environmental effects.
Catastrophic	4	Could result in death, total mission failure, complete failure of project rendering project unable to continue, or severe and irreversible environmental effects.

By combining the severity and probability values, a risk score will be assigned to each hazard. Risk scores will have a alphanumeric designation from 1A to 4E, where the number designates the severity and the letter designates the probability of occurrence. Risk levels can be reduced through mitigating actions which will lower either the severity score or the probability score. Actions will be taken starting with the highest risk level hazards, and will continue through the lower levels until all hazards have been reduced as much as possible. All hazards pose a risk and will not be ignored, but the classifications help the Safety officer prioritize resources to those that require the most immediate attention. Mitigations can take the form of design considerations to reduce severity or probability of failure, verification systems created to ensure proper operating conditions, and better handling procedures to follow. Risk scores and the risk levels that correspond with each score are outlined in the risk assessment matrix shown in Table 32, and the description of each risk level is listed in Table 33.

Table 32: Risk assessment matrix

Probability Level	Severity Level			
	Negligible (1)	Marginal (2)	Critical (3)	Catastrophic (4)
Improbable (A)	1A	2A	3A	4A
Unlikely (B)	1B	2B	3B	4B
Moderate (C)	1C	2C	3C	4C
Likely (D)	1D	2D	3D	4D
Unavoidable (E)	1E	2E	3E	4E

Table 33: Description of Risk Levels and Management Approval

Risk Level	Acceptable Level/Approving Authority
High Risk	Highly Undesirable. Must be approved by team captain, safety officer, and supervising squad lead.
Medium Risk	Undesirable. Must be approved by safety officer and supervising squad lead.
Low Risk	Acceptable. Must be approved by supervising squad lead or safety officer.
Minimal Risk	Acceptable and negligible. Risk level is minimal enough that the safety officer has deemed it negligible. No approvals needed.

In order to properly assess the risk facing the mission, key areas for assessment were identified: project risks, personnel hazards, failure modes and effects, and environmental concerns. Each one of these areas was then broken down further into more specific categories of interest and analyzed in the same manner. That is, a potential hazard, its cause, and its effect were identified within each category. The hazard was then given an alphanumeric risk score, as defined above, based off the severity and probability posed by the risk before the implementation of any mitigation (including those that would normally be assumed for assigning the actual risk score of the hazard). Mitigations and a method of verification, including for mitigations not yet implemented, were then identified, and the hazard was assigned a post-mitigation score that according to the criteria defined above. The results of this analysis were then recorded in tables that will be expanded and used by the Safety Committee to identify, track, and improve on its response to safety hazards.

4.2.1 Project Risk Analysis

A table outlining all the risks to the the project timeline and the mitigations being implemented to ensure that these risks are accounted for and reduced can be found in Appendix A.1

4.2.2 Personnel Hazard Analysis

4.2.2.1 Construction

A table identifying all hazards, causes, effects, and mitigations to personnel during construction can be found in Appendix A.2.1

4.2.2.2 Testing

A table identifying all hazards, causes, effects, and mitigations to personnel during testing can be found in Appendix A.2.2

4.2.2.3 Launch

A table identifying all hazards, causes, effects, and mitigations to personnel during launch can be found in Appendix A.2.3

4.2.2.4 Recovery

A table identifying all hazards, causes, effects, and mitigations to personnel from the Recovery system can be found in Appendix A.2.4

4.2.2.5 Unmanned Aerial Vehicle

A table identifying all hazards, causes, effects, and mitigations to personnel from the Unmanned Aerial Vehicle system can be found in Appendix A.2.5

4.2.3 Failure Modes and Effects Analysis

4.2.3.1 Vehicles

A table identifying all hazards, causes, effects, and mitigations to the success of the Vehicles system can be found in Appendix A.3.1

4.2.3.2 Recovery

A table identifying all hazards, causes, effects, and mitigations to the success of the Recovery system can be found in Appendix A.3.2

4.2.3.3 Air Braking System

A table identifying all hazards, causes, effects, and mitigations to the success of the Air Breaking System can be found in Appendix A.3.3

4.2.3.4 Unmanned Aerial Vehicle

A table identifying all hazards, causes, effects, and mitigations to the success of the Unmanned Aerial Vehicle system can be found in Appendix A.3.4

4.2.3.4.1 Launch Operations

A table identifying all hazards, causes, effects, and mitigations to the success of launch operations can be found in Appendix A.3.5

4.2.3.5 Launch Support Equipment

A table identifying all hazards, causes, effects, and mitigations to the success of launch support equipment can be found in Appendix A.3.6

4.2.3.6 Payload Integration

A table identifying all hazards, causes, effects, and mitigations to the success of payload integration can be found in Appendix A.3.7

4.2.4 Environmental Hazards

4.2.4.1 Environmental Hazard to Rocket

A table identifying all hazards, causes, effects, and mitigations to the environment's effect on the rocket can be found in Appendix A.4.1

4.2.4.2 Rocket Hazard to Environment

A table identifying all hazards, causes, effects, and mitigations to the rocket's effect on the environment can be found in Appendix A.4.2

4.3 Launch Safety Checklists

Safety procedures are important to ensure the safe execution of a launch. All safety procedures will be created according to the process described in Section 4.5 and will be used to help ensure smooth operation on launch day. When steps in the launch procedures require the use of certain PPE, the required PPE will shown with team-standard visual indicators, which are outlined in Table 34.

Table 34: List of PPE and corresponding Visual Indicators

Visual Indicator	Required PPE
	Antistatic Gloves
	Cut Resistant Gloves
	Heat Resistant Gloves
	Leather Gloves
	Nitrile Gloves
	Safety Glasses
	Safety Goggles
	Dust Mask
	Lab Coat

Whenever a PPE visual indicator is shown there will be corresponding, bolded directions with the visual indicators to say say either that the PPE will be used only for the following step, or until instructed to take it off. In this case, another bolded step will instruct when to remove the PPE. In some cases, steps in the procedure must be followed in a particular order, or are required to be performed by a particular person (such as the overseeing technical lead or the team mentor). In these cases, a bolded step in the procedure will appear to explain what special instructions must be followed, and a warning indicator, as seen in Figure 41, will appear with the step.

Figure 41: Warning visual indicator to indicate when special instructions or care must be followed with proceeding steps

Be sure to follow these directions closely - potential hazards or failures that may occur as a result of failing to heed these important instructions will also be listed in the procedure with the instructions. As with PPE, when the steps that are pertinent to the special instructions are complete, another bolded instruction step will indicate that the instructions are no longer in effect. The launch procedure checklists can be found in Appendix A.6.

4.4 Safety Manual

The Safety Officer and Safety Committee shall produce, publish, and maintain a Team Safety Manual. The first Safety Manual shall be finalized, released to the team via, and published on the team website prior to the construction of the full-scale rocket. The Safety Manual Shall contain up to date guidelines pertaining to

- Machine and Tool Use
- Personal Protective Equipment Use
- Construction
- Testing
- Launch
- Local, State, and Federal Law Compliance
- NAR/TAR Safety Code Compliance
- MSDS Purpose and Use

And shall be updated as needed, with the team being notified of each update. Members of the team shall be required to understand and agree to the contents of the safety manual, and to maintain a current knowledge of the contents of any updates made to it, which shall be enforced through a signed agreement that all members must sign. A physical copy of the Safety Manual shall be kept in the team's workshop, and will be updated to the most current version within 3 days of the release of any updates.

4.4.1 Material Safety Data Sheets

Material Safety Data Sheets (MSDS) are currently being acquired from suppliers upon purchase of any materials. An up-to-date compilation of all MSDS shall be kept in a dedicated document as well as in the Safety Manual. A physical copy of the MSDS document shall be kept in the team's workshop, and added to as more materials are acquired. The Safety Manual shall also include a section with guidelines on the organization of MSDS sheets and the relevant safety precautions when dealing with each specific material.

4.5 Procedures

Prior to an operation, the Safety Committee and team leadership shall develop procedures for the construction, testing, and launch of all vehicles, subsystems, and payloads. The technical design leads most closely related to the subject matter of each procedure will have primary input to ensure that procedures will yield the intended results. The safety officer will then review all procedures to ensure that they outline an operation that poses an acceptable and approved risk. If this is not the case, and any risks cannot be approved, the safety officer will recommend changes to the procedure, and it will not be released until changes are agreed upon. Once a procedure is released, the Safety Officer shall publish it in the Safety Manual and notify the team. The procedure will then be considered active and the operation will be able to proceed. Members of the team wishing to participate in an operation must thoroughly read and understand the procedure for that operation. If a procedure is violated, it will be documented in order to better understand the causes and effects, and to make whatever changes are necessary for the future in order to ensure that this does not happen in the future.

4.5.1 Competency Quizzes

In order to ensure that for a given operation, participating team members understand the operation's procedure to a point where the operation can be safely and competently carried out, the Safety Officer may require a competency quiz. Competency quizzes will test knowledge and understanding of the contents of the operation procedure, as well as any relevant knowledge pertaining to the tasks that must be performed for the given operation. Each quiz will have a minimum passing grade that team members must achieve in order to assist with the operation in question. Competency Quizzes will be implemented for all launches and prior to any major phase of construction.

4.5.2 Operation Readiness Reviews

For especially important operations, the Safety officer or technical lead in charge may require an Operation Readiness Review (ORR) be conducted prior to the operation. This consists of a presentation to brief participating members about what will occur during the operation, knowledge relevant to the operation, goals and outcomes of the operation, and contingency plans. Following an ORR, a competency quiz will be administered. Operations requiring ORRs include launches and construction phases.

4.6 NAR Safety Code Compliance

The Notre Dame Rocketry Team will be taking several steps to ensure compliance with the National Association of Rocketry High Power Rocket Safety Code that has been effective as of August 2012. Appendix A.5 outlines each of the items in the safety code, and how the team and its mentors will be compliant with it.

5 Unmanned Aerial Vehicle Payload Technical Design

5.1 Payload Overview

The unmanned aerial vehicle (UAV) with simulated navigational beacon delivery is the Notre Dame Rocketry Team's experimental payload for the 2019 NASA Student Launch Competition.

5.1.1 Mission Success Criteria

The following items have been deemed qualifications for a successful mission at the 2019 NASA Student Launch Competition.

1. The payload shall be powered off until the rocket has safely landed and has been approved for remote-activation by the Remote Deployment Officer.
2. The payload shall remain retained inside the vehicle utilizing a fail-safe active retention system.
3. The payload shall deploy from inside the launch vehicle from a position on the ground.
4. The payload shall fly to a NASA specified Future Excursion Area.
5. The payload shall drop a simulated navigational beacon on the Future Excursion Area and then shall move a safe distance away from the Future Excursion Area.

5.1.2 Alternatives and Design Selection

The following items, found in Table 35, are changes made since the submission of the Preliminary Design Review.

Table 35: Alternatives and design selections since PDR.

Feature	***Design Selection***	Rationale
Linear Transport Mechanism	***Leadscrew*** Versus Rack and Pinion	In order to fulfill Mission Criterion #3 (the payload shall deploy from inside the launch vehicle from a position on the ground), the team had to devise a mechanism to transport the UAV out of the rocket body. The two main options were a leadscrew mechanism and a rack and pinion mechanism. The team conducted a trade study to best determine which option was optimal for the team's design. Ultimately, the leadscrew was chosen due to its lighter weight, better efficiency, and easier assembly. The leadscrew is not as complex as a rack and pinion system. Therefore, it will be easier to manufacture. It can also provide sufficient force to remove the nose cone and give clearance for takeoff. The leadscrew system has fewer parts than a rack and pinion system as well, which allows the team to be economical with the payload bay's limited space.
Future Excursion Area Detection Feature	***Hand-Crafted*** Versus Data-Driven	The team decided to pursue a hand-crafted approach instead of a data-driven approach due to simplicity. The hand-crafted approach is easier to refine and is more straightforward. Additionally, a data-driven solution would only distinguish the color of the tarp, most likely. Thus, the hand-crafted feature has greater versatility in its ability to distinguish other features such as texture and shape.
Frame Design	***Iteration II*** Versus Iteration I	The UAV body will be constructed using the second body design iteration due to its reduction of weight and increase in strength. The top and bottom plates are now connected using aluminum rods that will also serve as landing struts. The separation of the top and bottom plates allows for a feasible manufacturing process of the body in carbon fiber as the pieces are easier to model and mold. Lastly, the second iteration has been designed to implement the torsion spring deployment and locking system to increase reliability with a mechanical system.

Feature	***Design Selection***	Rationale
Arm Extension Mechanism	***Belt and Pulley*** Versus Sprocket and Chain	The belt-and-pulley and sprocket-and-chain systems function identically, transferring power along the belt/chain to the pulley/sprocket and any attached axles. The belt and pulley mechanism is significantly lighter than a sprocket and metal chain, while a plastic chain is significantly weaker than a similarly-sized belt. Thus, a belt and pulley is the optimal mechanism for synchronizing the motion of the drone's arms.
Orientation Correction Motor	***Servo Motor*** Versus Stepper Motor	The team initially considered both stepper motors and servo motors for rotating the UAV platform. But a servo motor has a higher torque generation and more precise movement. Additionally, the servo motor runs in a closed loop, which provides feedback regarding its position, increasing the precision of the rotation. This is desired by the team because the UAV needs to be rotated until it is parallel to the ground in order to take off, which requires an accurate control.

5.2 System Level Design and Integration

The design of the entire UAV payload is such that it will not affect the flight and stability of the rocket. This design is created using CATIA and Creo Parametric computer-aided design software and is supplemented with Abaqus finite element analysis software. The total UAV system breakdown may be found in Figure 42.

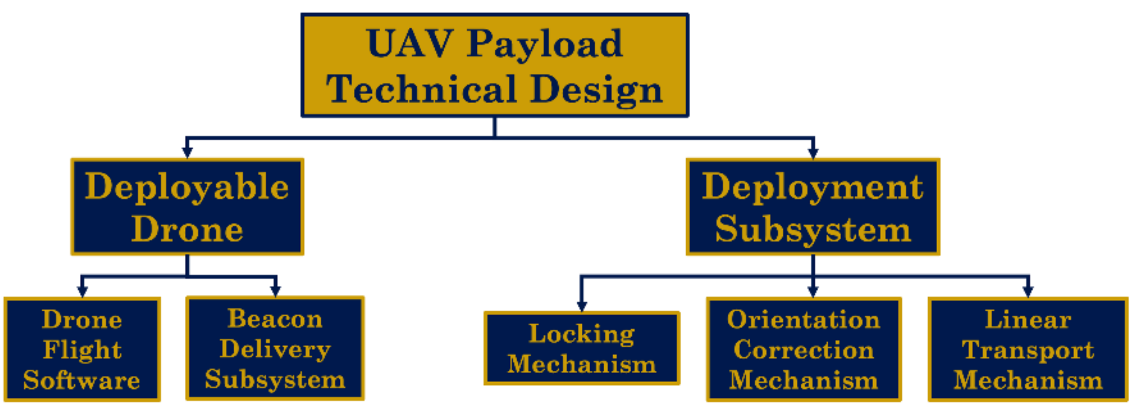


Figure 42: System level design for the 2019 Notre Dame Rocketry Team scoring payload.

5.2.1 Deployable Drone

The folding configuration of the UAV, seen in Figure 43, has physical dimensions that will align with the constraints of the inner diameter of the launch vehicle.

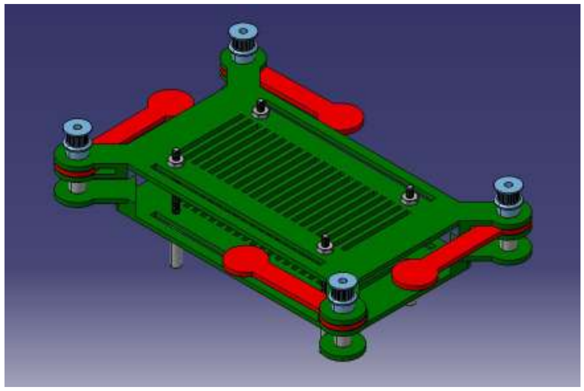


Figure 43: Folded configuration of the UAV.

The UAV arms and their folding orientation have been designed to maximize robustness and integrity while minimizing weight and volume. The arms will be rotated 135 degrees counterclockwise from the flying position so that the UAV is in a rectangular shape and its dimensions are minimized. When the UAV is oriented in its folded position, the torsion springs will be rotated and generate the torque required to deploy the UAV to its flying position upon deployment from the rocket. The arms will be locked in place in the folded position by placing the UAV against the aft bulkhead. The arms will attempt to unfold but will be prevented by the aft bulkhead. Since the arms are all connected via the belt and pulley system, the obstruction of motion of the arm against the aft bulkhead also impedes the motion of the other three arms. As the UAV is deployed from the rocket, the arms will rotate synchronously into the flying position, seen in Figure 44.

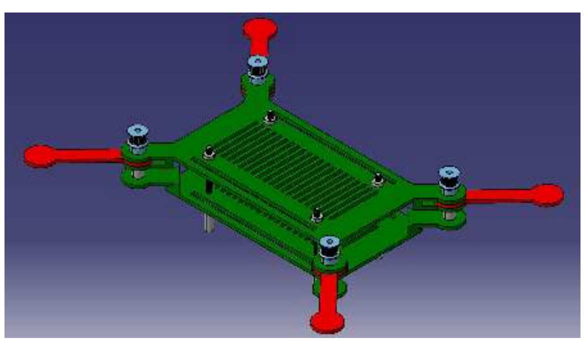


Figure 44: Flying configuration of the UAV.

Once the UAV and platform have moved away from the aft bulkhead, the arms will unfold just enough to fit inside the launch vehicle. Now, the inner wall of the UAV payload bay will prevent the arms of the UAV from moving into the flight-ready position. The torque from the Nema 14 stepper motor will overcome the friction between the arms of the UAV and the inner wall of the UAV payload bay. The team will complete ground tests before any full-scale flights to ensure that the Nema 14 does indeed produce enough torque to overcome this friction.

During the flight of the rocket, the UAV will be secured in place by inserting cotter pins through the aluminum landing struts of the UAV into the bed of the deployment system. This will ensure there is no motion in the x, y, or z directions. These pins will be attached to the aft bulkhead using string and will be gradually pulled out as the UAV is deployed from the rocket. As the deployment platform reaches the end of the lead screw, the cotter pins holding the UAV's landing struts in place are pulled free by strings attached to eyebolts on the rear bulkhead, and the arms will reach their fully-deployed position. The measurements of the Deployable Drone may be found in Table 36.

Table 36: Measurement assessment of the Deployable Drone.

Dimension	Value
Length (Folded)	8 in
Length (Deployed)	11.95 in
Width (Folded)	5.14 in
Width (Deployed)	9.15 in
Height	3.32 in
Weight (With All Electronics)	35.8 oz

Figure 45 shows a CAD drawing of the UAV frame in its flight orientation. The drawing shows all important dimensions of the UAV in inches.

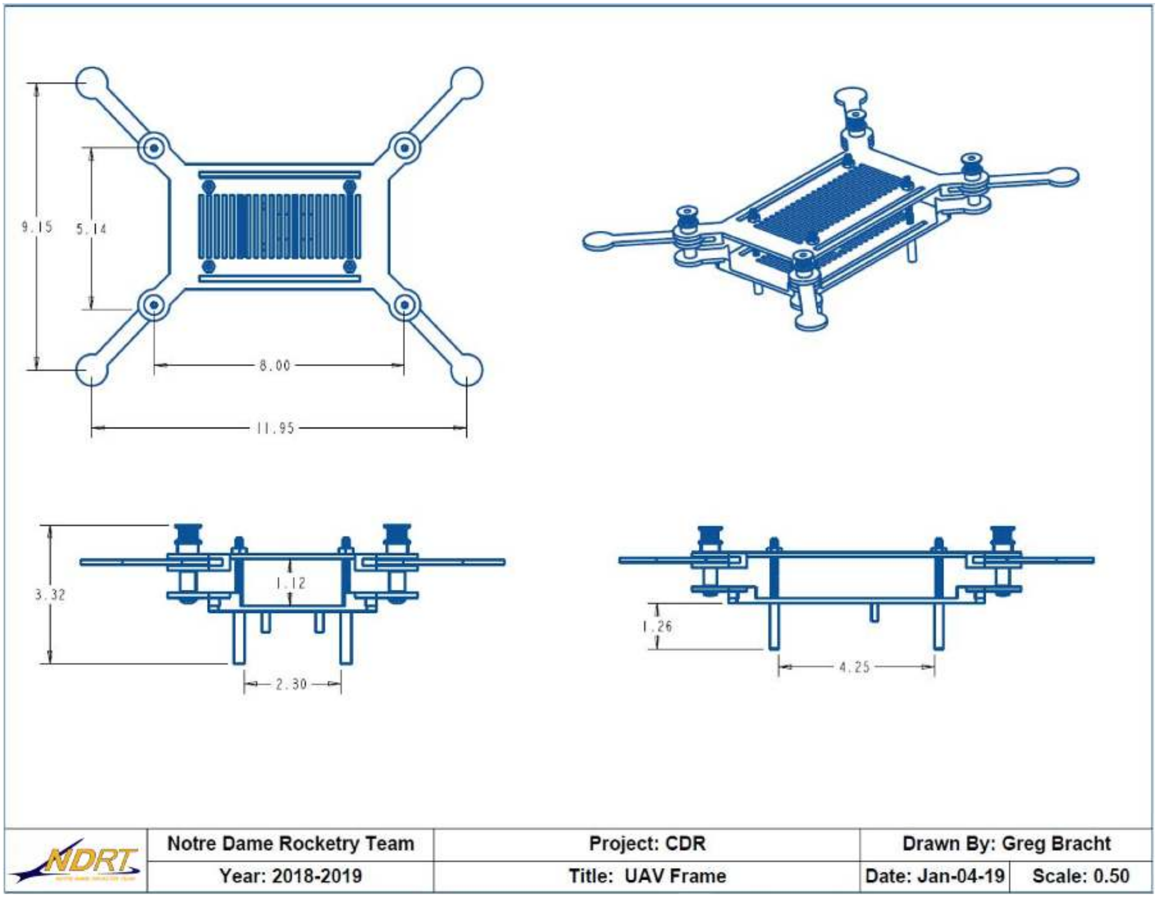


Figure 45: Drawing of the UAV with dimensions.

In the folded position, the UAV will be 5.14 inches wide and 3.32 inches tall which is within the 7.5 inch diameter of the rocket. Additionally, the center section of the UAV is 1.12 inches tall and 2.30 inches wide which will enable the battery to fit securely during flight. The length of the landing struts is 1.26 inches which is longer than the minimum of 1 inch to fit the beacon deployment system.

The following, Table 37, gives an overview of the different parts of the drone with mention of the materials used for each corresponding part.

Table 37: Drone part overview.

Item(s)	Material	Justification of Material
Arms and Frame	Carbon Fiber	Carbon fiber is a composite material with a high yield strength of 145000 psi and a density of 0.05 lb/in^3 making it a lightweight yet strong material. The UAV will need to be as light as possible for rocket flight and for the maximization of UAV flight time. Due to the turbulent nature of rocket flight and recovery and the possibility of windy flying conditions, the UAV will need to be able to withstand any impulses during both launch vehicle flight and UAV flight. Because low-density carbon fiber is able to withstand both the loads experienced during rocket flight and those during UAV flight, it is the optimal material for the UAV.
Supports and Struts	Aluminum	Aluminum is a metal used in many aerospace applications due to its low density. It is strong and lightweight like carbon fiber; however, while carbon fiber is a brittle composite prone to fracturing, aluminum is able to yield. This quality is desired for the supports and struts of the UAV as they will be subjected to strong impulses upon landing. Additionally, the UAV will undergo many test flights which will result in many landings and repetitive impulses. Therefore, the reduction of strut failure is achieved by using aluminum that may yield slightly rather than generate cracks that will propagate over time.
Pulleys	Polycarbonate	Polycarbonate is a lightweight and durable plastic that performs well in pulleys subjected to light loads, as is the case with the UAV's pulley system. Additionally, polycarbonate pulleys are readily available and a low-cost, which makes them easily replaceable if a pulley is damaged.
Pulley Belt	Neoprene	Neoprene is durable, lightweight, and strong. It is not easily abraded, which means that a belt made of neoprene will not degrade quickly and will not need to be replaced. Fiberglass-reinforced neoprene timing belts are readily available and will satisfy the requirements of the UAV's use of a belt and pulley system.

Item(s)	Material	Justification of Material
Torsion Springs	Steel Wire	The torsion springs used for the deployment of the arms are required to be resistant to deformation and to lock the arms in the flying position. Therefore, a steel wire torsion spring with a rotation potential of 225 degrees and a spring constant of 0.011 inch-pounds per degree was selected. The spring will be rotated 90 degrees in the flying position and will apply a torque of 1 inch-pound to the arms holding them in the flight position. The steel wire will ensure that the springs will not deform due to repetitive use during test flights and are also inexpensive to repurchase if deformation does occur.

5.2.2 Deployment Subsystem

The Deployment Subsystem is the largest component of the UAV payload. This subsystem is broken down into three different stages, identified by their mechanisms:

- Locking Mechanism
  - Properly constrains the UAV during the flight and recovery of the launch vehicle
- Orientation Correction Mechanism
  - Ensures that the UAV will be facing upright after the recovery of the launch vehicle for successful takeoff
- Linear Transport Mechanism
  - Moves the UAV out of the launch vehicle and gives it the clearance needed to takeoff

Additional details about three different mechanisms may be found in the Payload Mechanical Design and Payload Electrical Design sections of the report. The following, Figure 46, shows the CAD of the subsystem.

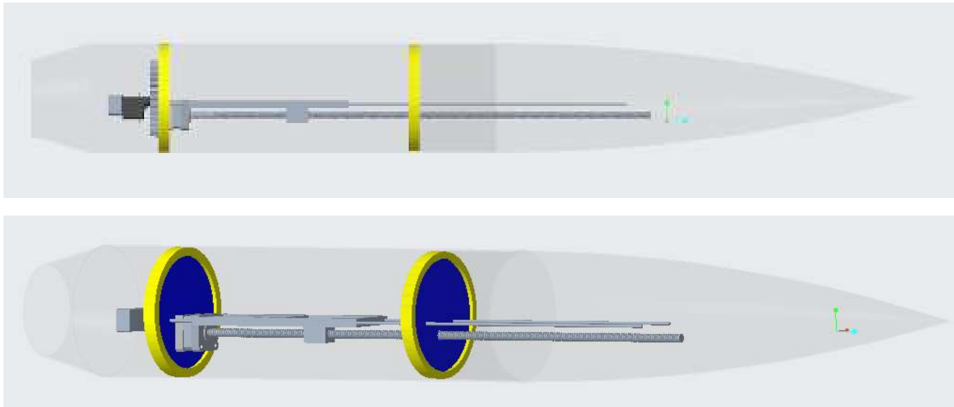


Figure 46: CAD of the entire UAV Deployment Subsystem.

The following, Table 38, gives an overview of the different parts of the Deployment Subsystem.

Table 38: Deployment Subsystem part overview.

Item	Material	Justification of Material
Leadscrew	0.625 Inch Diameter Nylon 6/6	Nylon is strong, stiff, smooth, and has exceptional bearing and wear properties, which is why it can often be used in place of metal. Other benefits to using nylon in place of metal include a reduction in part weight and decreased wear on mating parts like the hex screw epoxied in the fore bulkhead. Using nylon will also help fulfill NASA Vehicle Requirement 2.24.10. (Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses).

Item	Material	Justification of Material
Rotating Bulkhead and Track System (The fore set is connected to the nose cone and also translates linearly along the leadscrew. The aft set is connected to the inside of the UAV payload bay but does not translate linearly.)	MDS-Filled Cast Nylon	The MDS-filled cast nylon offers the impact resistance and toughness of unfilled nylon, but the addition of molybdenum disulphide acts as a lubricant. This addition allows for the material's repeated use with negligible wear. This material is low-friction, self-lubricating, and offers sufficient impact resistance.
Dowel Rods (2)	1/8 Inch Diameter Carbon Fiber	Carbon fiber is one of the strongest plastic composites available. It is incredibly strong, comparable to aluminum 6061, but also lightweight. Another material considered was aluminum alloy 7075. However, this material, though strong, is far too heavy for the system. The properties of carbon fiber will be very important in the prevention of twisting. In other words, the Orientation Correction System requires the simultaneous rotation of both bulkheads. The two high-strength carbon fiber rods will ensure that the fore and aft bulkheads rotate together, as opposed to asynchronous rotation.

5.3 Payload Mechanical Design

5.3.1 Deployable Drone

The UAV was designed to ensure a lightweight, strong, economical, and effective means to fulfill Mission Success Criterion 4 (The payload shall fly to a NASA specified Future Excursion Area). The UAV frame has been designed to maximize the structural strength of the UAV while minimizing weight. The frame is composed of two identical plates made of carbon fiber that act as the top and bottom of the UAV. The electronics will be attached to the top plate of the UAV, as seen in Figure 47.

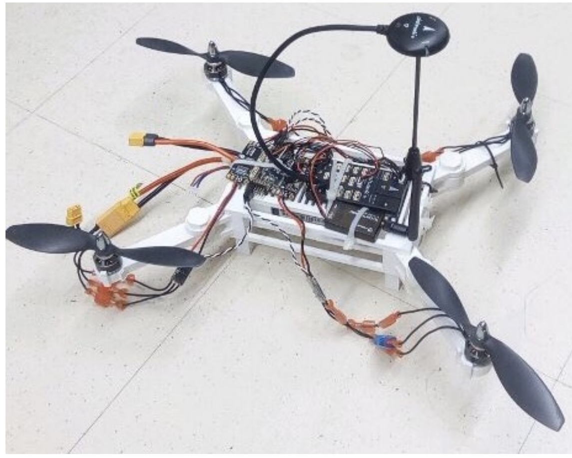
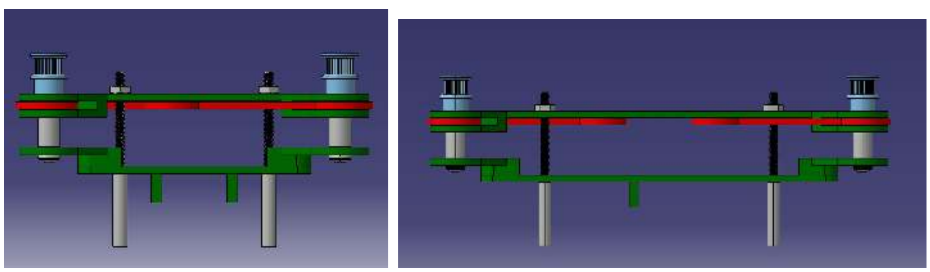


Figure 47: UAV with mounted electronics.

The battery will be secured between the two plates. This space is shown in Figure 48.



(a) Front view. (b) Side view.

Figure 48: Battery space on the UAV.

The Beacon Delivery Subsystem will attach to the bottom plate under the UAV. The plates are secured using aluminum rods that extend from the bottom of the top plate to 1.2 inches past the bottom plate to provide adequate space for the Beacon Delivery Subsystem. The struts are attached to the plates using aluminum screws. The arms are also made of carbon fiber and are locked into place using an aluminum rod. The rod extends from the top plate to the bottom plate so that the torsion springs used to unfold the arms into the flying position are adequately supported. These rods are also secured using aluminum screws.

The team has completed two 3D prints of the UAV frame design. Iteration I, seen below in Figure 49, was printed in PLA and consisted of the body, the arms, and pins to hold the arms. While this design was viable, it was bulky and many areas of the design could be improved to reduce weight and size.

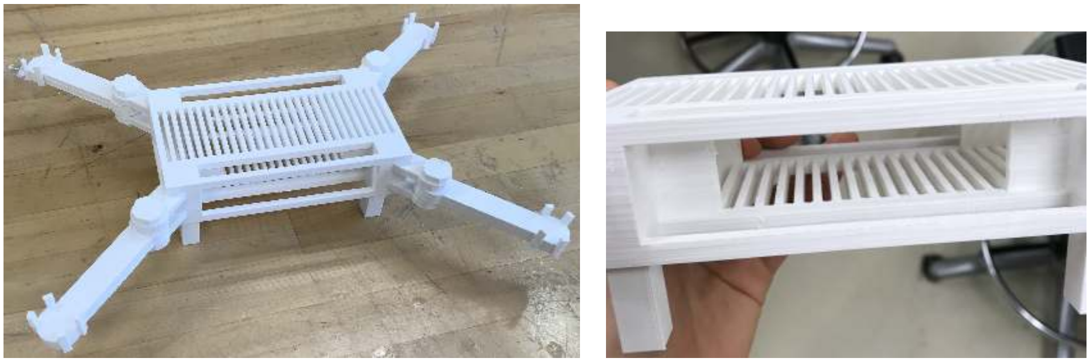
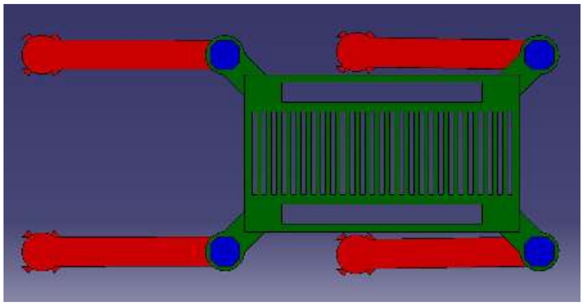


Figure 49: 3D print of Iteration I.

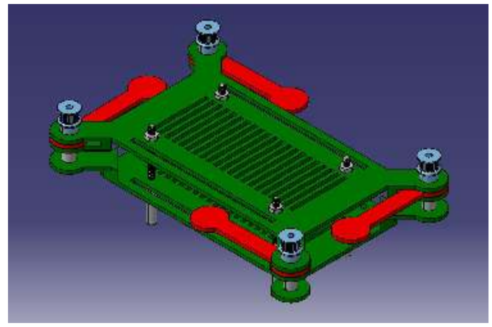
Iteration II, seen in Figure 50, of the UAV body was printed in ASA because it is a stronger and more flexible material.

Figure 50: 3D print of Iteration II.

Here it can be seen that the body is now composed of multiple parts. The body consists of a top and bottom plate, the arms, rods and struts to connect the UAV, and pins to hold the arms. This design iteration reduced weight by decreasing the thickness of the arms and body plates from a fourth of an inch to an eighth of an inch. Additionally, the creation of two plates removed the filler material between the top and bottom of the UAV and was replaced by four thin, aluminum rods. This increases the strength of the UAV frame. Figure 51 shows the UAV designs in their folded configurations. It can be seen that the Iteration II folding design minimizes the dimensions of the UAV by rotating all four arms counterclockwise instead of folding back all four arms as the Iteration I folding design did.



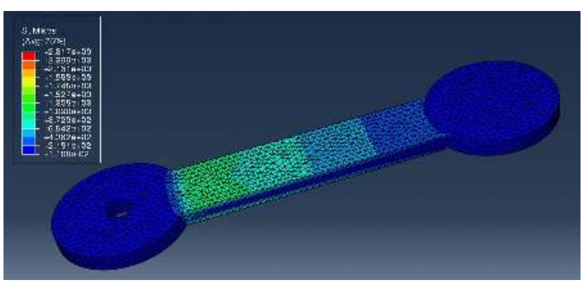
(a) Iteration I folding design.



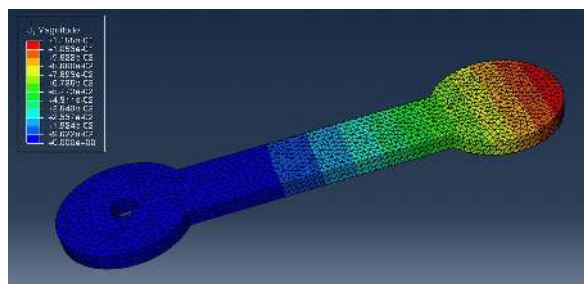
(b) Iteration II folding design.

Figure 51: UAV folding configurations.

A finite element analysis using the Complete Abaqus Environment was conducted on the arms and the top and bottom plates of the UAV, seen in Figure 52. These parts will bear the major loads during flight and therefore an analysis was necessary in order to verify that the parts could withstand these loads. Each prop will generate 0.75 pounds force of thrust at full power: this was the load applied to each part during the analysis. The material used in the analysis was ASA with a Young's modulus of 380000 psi and a Poisson's ratio of 0.35. This material was analyzed instead of carbon fiber because ASA will be used to create the UAV prototype frame, and carbon fiber is stronger than ASA. Thus, a frame made from carbon fiber will be successful in bearing the same loads.



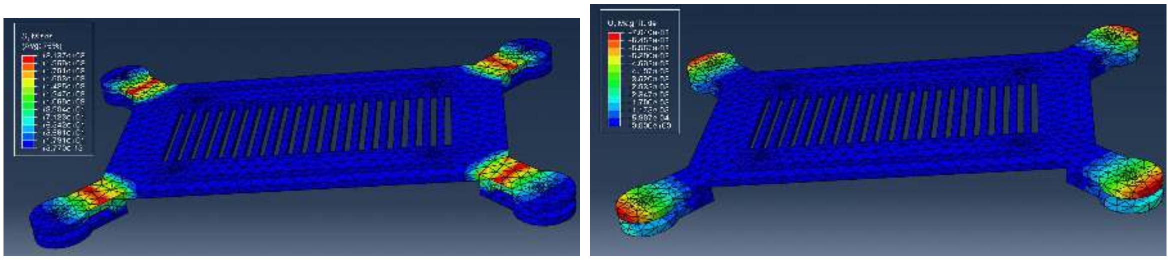
(a) Von Mises stress on the arm.



(b) Displacement on the arm.

Figure 52: FEA on the UAV arm.

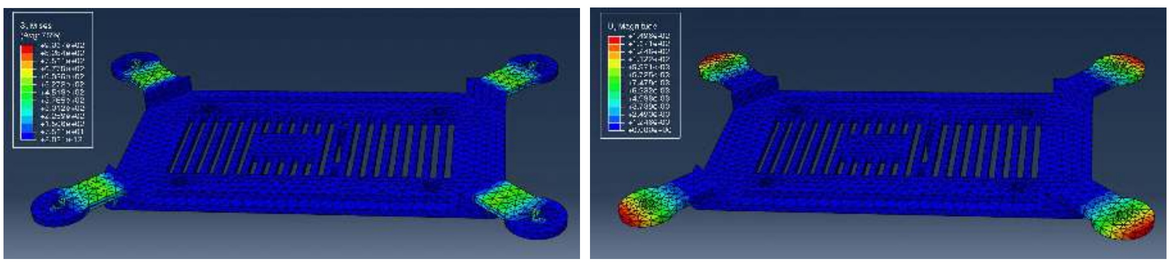
From Figure 52, it can be seen that the arm of the UAV will experience a maximum stress of around 1750 psi. The yield strength for ASA is 4000 psi. This results in a safety factor of 2.29 for the UAV. The maximum displacement the arm will experience is 0.1 inches. A similar analysis was completed for the top and bottom plates of the UAV. The analysis for the top plate may be found in Figure 53.



(a) Von Mises stress on the top plate. (b) Displacement on the top plate.

Figure 53: FEA on the top plate of the UAV.

The maximum stress the top plate will experience is 214 psi, which is well under the yield criterion. The maximum displacement the top plate will experience is 0.007 inches, which is negligible. The analysis for the bottom plate may be found in Figure 54.



(a) Von Mises stress on the bottom plate. (b) Displacement on the bottom plate.

Figure 54: FEA on the bottom plate of the UAV.

The maximum stress the bottom plate will experience is around 500 psi, which is well under the yield criterion. The maximum displacement the bottom plate will experience is 0.015 inches, which is negligible.

The arm deployment configuration can be seen in an exploded view in Figure 55 (torsion spring not pictured).

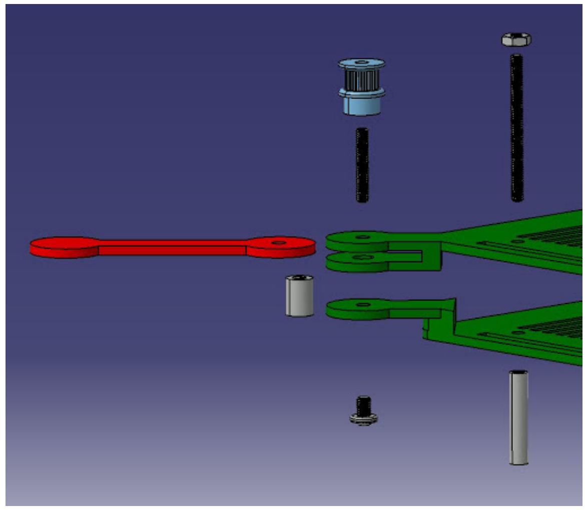


Figure 55: UAV arm deployment configuration.

The system is composed of the arm, the top UAV plate, an aluminum rod, an aluminum support, an aluminum screw, a sprocket, and a pulley (also not pictured). The mechanism works by linking one end of the torsion spring to the UAV bottom plate and the other end to the arm. In the flight position, the spring will be rotated 30 degrees counterclockwise to apply a constant force to the arm and lock it in place. To close the arms in the folded position, one arm will be rotated counterclockwise which will also rotate the other arms via the belt and pulley system. Once in the folded position, the UAV will fit inside the rocket. The aft bulkhead will prevent motion of the arms by obstructing the motion of the arm in contact with the bulkhead. The belt and pulley system will prevent the motion of the other arms. Because all four arms are constrained together by the belt and pulley system, all four arms will be held in the folded position.

In summary, the arms of the UAV fold 135 degrees counterclockwise from their deployed position to rest against the body of the UAV. Torsion springs attached to each arm rotate the arms into their flight orientation and apply a constant torque to maintain that orientation. To ensure that all four arms deploy together, they are linked by a belt and pulley system.

Figure 56: 225° torsion spring with a max torque of 2.5 in-lb.

A torsion spring was chosen such that there would be enough rotational freedom so that the spring would be slightly twisted in the flight position. This is needed to ensure the arms stay locked in place during flight and is achieved by having the torsion springs apply a constant torque to the arms. Therefore, a 225 degree steel torsion spring was chosen. This specific spring has a maximum torque of 2.5 inch-pounds. The ability to hold the arms in the flight position will be verified by testing the locking mechanism with the spring held at various degrees. Once the arm is secured, the system will be further tested through multiple practice deployments to ensure reliability.

The arms will be attached to four identical polycarbonate pulleys connected by a neoprene belt. The pulleys are 0.63" in diameter and 0.688" wide, with 0.08" pitch trapezoidal teeth, seen in Figure 57.

Figure 57: UAV pulley.

The belt is 0.25" wide and has the same 0.08" teeth to mesh with the pulleys' teeth, seen in Figure 58.

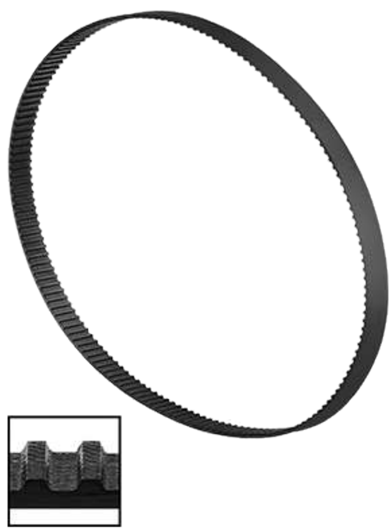


Figure 58: UAV belt.

During flight, the arms are locked in place at the end of their rotation by the constant torque supplied by the torsion springs.

The prop chosen was selected through the consideration of the two main characteristics of propellers: the diameter and the pitch, seen in Figure 59.

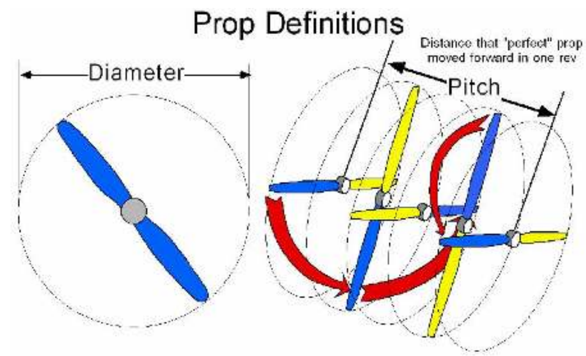


Figure 59: Two main characteristics of props.

The diameter is the length from one end of a propeller blade to the other. The pitch is the forward distance a propeller will travel through a medium in one revolution. The aircraft's motor and battery specifications influenced the diameter and pitch of the propellers. For the UAV, four identical propellers are used, seen in Figure 60.

Figure 60: Multirotor Carbon Fiber T-Style Propellers.

The propellers used are seven inches in diameter with a pitch of 2.4 inches, and are made out of carbon fiber. They are attached to a brushless electric motor, seen in Figure 61.

Figure 61: T-MOTOR MN1806 KV1400 Brushless Electric Motor.

Using a 3s battery with 4500 mAh at full charge, the drone will have a flight time of 9 minutes at full throttle, but 13.8 minutes of hover time. The choice of propellers that have a diameter of 7 inches and a pitch of 2.4 inches was based on the recommendation of the battery manufacturer and was made to ensure that the UAV would fit into the body of the rocket during the rocket's flight. The quadcopter UAV will be flown in an "X configuration," seen in Figure 62, to maximize its control, especially along the roll axis when pitching forward.

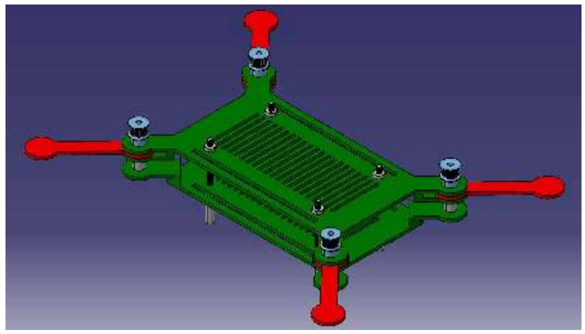


Figure 62: X configuration flight.

Flying in this configuration also means that there are two propellers contributing to the pitch and roll movements with perpendicular moment arms of about 0.71 times the length of the arm, maximizing the rotational acceleration.

For steady flight, the four propellers will be spinning at the same rate, with slight differences accounting for balance and environmental perturbations. Given that the x axis points from the center of the UAV to the front, the y axis points to the right, and the z axis points down, the movements around these axes are roll, pitch, and yaw, respectively. This is demonstrated in Figure 63.

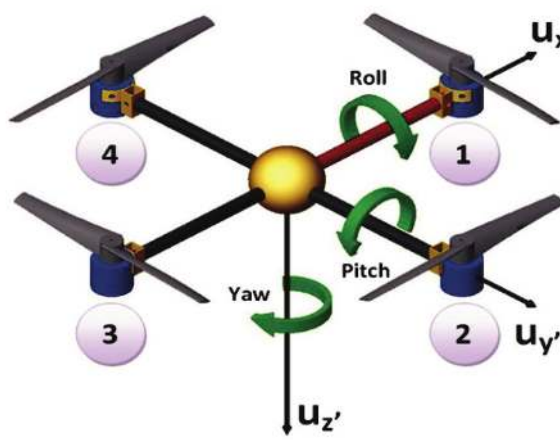


Figure 63: Roll, pitch, and yaw of a quadcopter.

To rotate along the rolling axis, the thrust of either the right or left side increases while the thrust of the other side decreases. This will result in a roll in the direction of the decreased thrust. To rotate about the pitching axis, the thrust of either the front or the back increases while the thrust of the other side decreases, resulting in a pitching moment in the direction of the decreased thrust. To rotate clockwise about the yaw axis, the thrust of the clockwise rotating propellers increases, with the same holding true for counterclockwise propellers and rotation. Since the UAV will be able to support its own weight in trimmed flight at around 75% power, increasing the power for specific propellers to control the direction of flight should not be an issue.

For manual flight, a pilot will fly the drone via handheld transmitter. A schematic of the FrSky Taranis X9D Plus 2.4 GHz ACCST Radio used in this mission is shown in Figure 64.

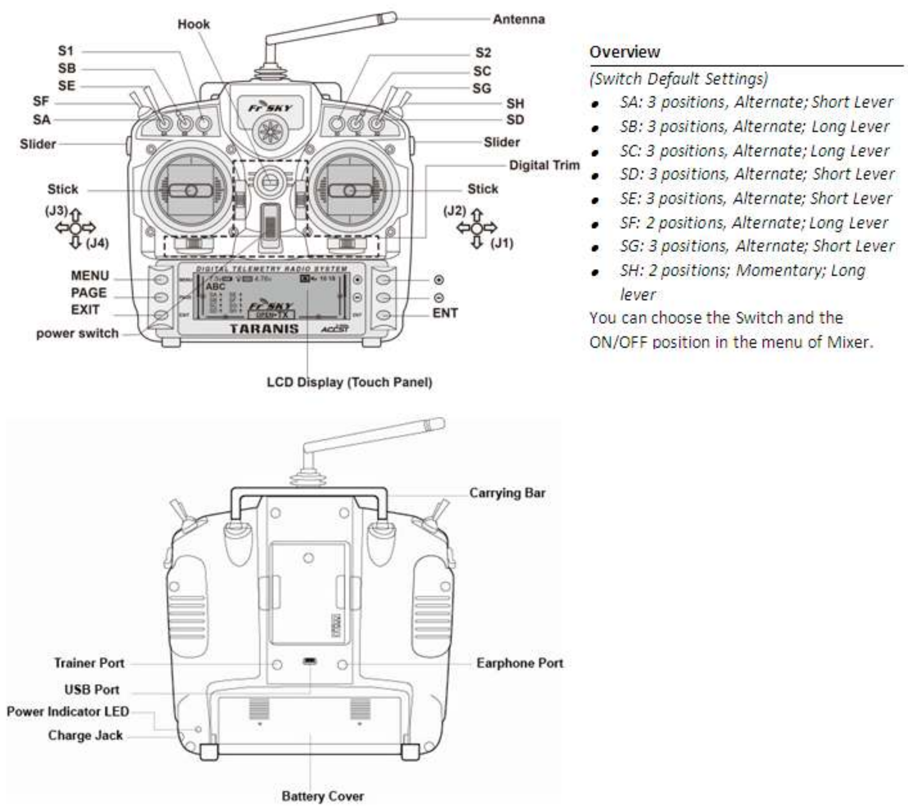


Figure 64: Taranis radio schematic.

It has two joysticks, one to control thrust and yaw, and another to control pitch and roll. Thrust is controlled by moving the left stick up and down, corresponding to increasing and decreasing thrust. Moving the left stick right and left corresponds to controlling the yaw, in other words the clockwise and counterclockwise rotation about the z axis. Up and down movement of the right stick controls the pitch of the drone, allowing it to move forward and backward, while left and right movement of the right stick controls the roll of the drone, corresponding to left and right movement. Along with the joysticks on the handheld, there are a few other toggles that control other operations of the drone. There is a switch located on the upper right hand corner of the controller that is used to switch between autonomous flight control and manual flight control. A simple flip of the switch will allow for the pilot to take over control of the flight of the drone. This can be important if there is a need for more precise flying when the drone approaches the Future Excursion Area and prepares to drop the beacon in the case that autonomous flight fails.

5.3.2 Deployment Subsystem

5.3.2.1 Locking Mechanism

The Locking Mechanism is essential to ensure that the UAV is properly constrained inside the launch vehicle. The struts of the UAV will be secured in custom-made pipe flanges that will be 3-D printed directly onto the platform that supports the UAV. This will restrict any movement on the plane of the UAV platform. There will be holes extruded through the pipe flanges and the aluminum struts on the UAV for the cotter pins, shown in Figure 65.

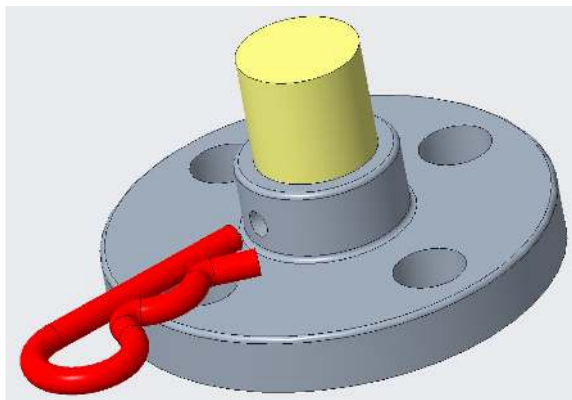


Figure 65: Cotter pin integration with an aluminum strut and a flange.

The cotter pins will prevent the UAV from moving in the vertical direction during flight. Strings will be tied to the cotter pins and secured to the aft rotating bulkhead. As the UAV translates along the leadscrew, the strings will be pulled taut, thus removing the cotter pins. The UAV will be free to move in the vertical direction, allowing for its unobstructed takeoff and the successful completion of Mission Criteria #4 (the payload shall fly to a NASA specified Future Excursion Area). Ground tests will be performed during the weeks of January 28 and February 4 in order to assess this system before the team's first full-scale flight on February 9. More details may be found in the Project Plan section of the report. The following, Table 39, gives an overview of the different parts of the Locking Mechanism with mention of the materials used for each corresponding part.

Table 39: Locking Mechanism part overview.

Item	Material	Justification of Material
Eyebolt	1/8 inch ID stainless steel	Ensures strong connection points for attached string
Wire	Polyethylene fiber wire (fishing line)	Minimizes friction, thin to reduce entanglement
Cotter pin	Stainless steel	Ensures firm connection, allows movement when strong force is applied

5.3.2.2 Orientation Correction Mechanism

The Orientation Correction Mechanism is a critical aspect of the deployment of the UAV, as the UAV is required to take off in the vertical direction. As the launch vehicle is recovered, an Orientation Correction Mechanism is needed to determine the position in which the rocket lands and correctly position the UAV for successful takeoff.

Based on a trade study, outlined in the Preliminary Design Review, a system using an Adafruit 9-Degrees-of-Freedom Absolute Orientation IMU Fusion Breakout BNO055 (with built-in accelerometer and gyroscope) and a servo motor, the FS5106R Continuous Rotation Servo, was selected. After remote activation via a 433 MHz RF transmitter and receiver kit, the sequence will begin. An Arduino UNO will receive a signal from the sensor (including both accelerometer and gyroscope data) that will induce the rotation of the payload for proper orientation. The servo motor will interface with a bulkhead via a gear-like connection, shown in Figure 66.

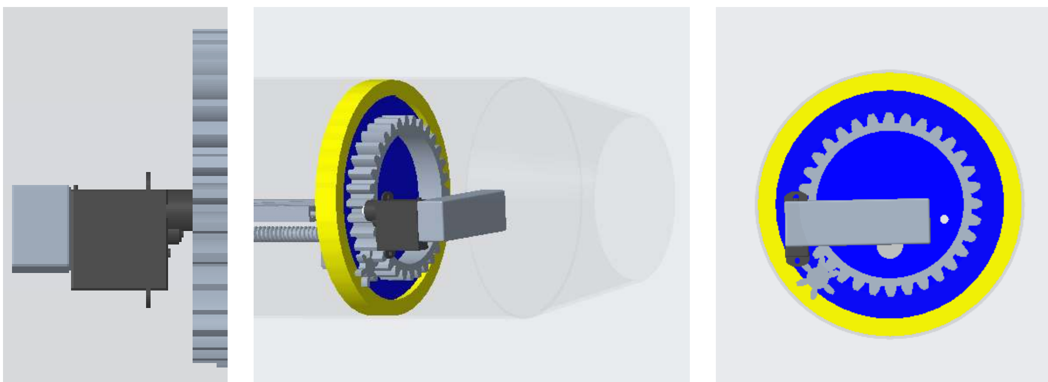


Figure 66: Integration between FS5106R Servo and Orientation Correction Mechanism gear.

The gear-like connection will be constrained by two concentric tracks. The tracks will serve to prevent the bulkhead from translating but will allow it to rotate. This aspect of the design is shown in Figure 67.

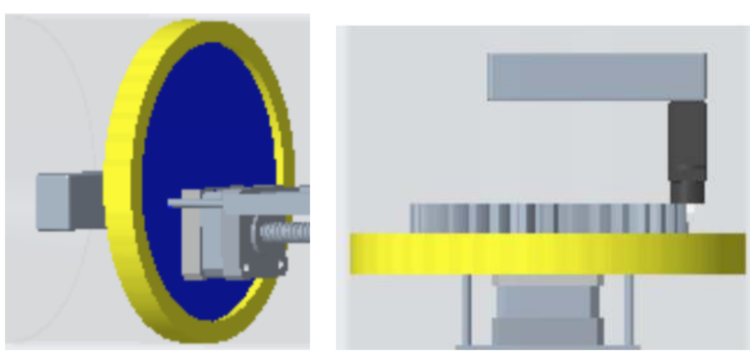


Figure 67: Aft bulkhead with concentric tracks.

In this figure, the concentric tracks are shown in yellow, and the aft rotating bulkhead is shown in blue. Note that the rightmost image is a top view of the bulkhead. This aft bulkhead does not translate linearly forward during deployment. The back of this bulkhead contains the gear connection for the orientation stage of deployment. The stepper motor and leadscrew for the linear transport stage are also visible in Figure 67. The fore bulkhead is shown in Figure 68.

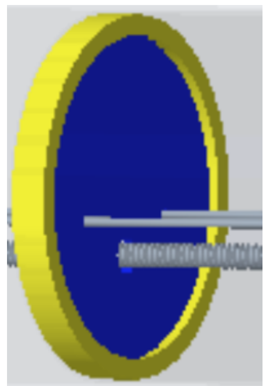
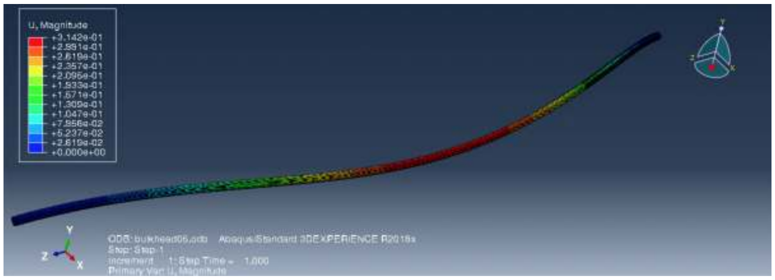


Figure 68: Fore bulkhead with concentric tracks.

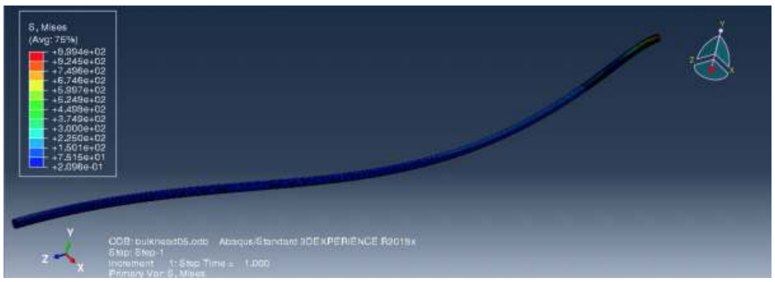
Shown in this figure, the leadscrew and carbon fiber rods run through the fore bulkhead, as it will translate linearly forward after the orientation stage of deployment. The bulkheads and tracks will be manufactured out of 3/8 inch MDS-filled cast nylon to minimize friction during rotation but maintain strength and durability. The servo motor, when locked, will prevent the UAV and its housing from moving. This is essential for in-flight motion, as rotation of the UAV can negatively affect flight performance and stability. Conversely, the motor will spin the UAV and its housing once the rocket has landed. The servo motor will be fixed to the inside of the body tube using RocketPoxy glue.

5.3.2.3 Linear Transport Mechanism

The team decided on a nylon 6/6 leadscrew, available from McMaster Carr, and Nema 14 stepper motor system to serve as the Linear Transport Mechanism for the UAV payload in order to fulfill NASA Vehicle Requirement 2.24.10. (Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses). In order to fulfill Mission Criterion #3 (the payload shall deploy from inside the launch vehicle from a position on the ground) and Mission Criterion #4 (the payload shall fly to a NASA specified Future Excursion Area), the Linear Transport Mechanism must separate the nose cone from the rest of the UAV payload bay. This separation must give enough clearance to allow for the unobstructed takeoff of the UAV. Nylon was chosen because it will run smoothly, it will be lightweight, and it will not deflect or fracture under the point loading of the UAV and platform. FEA using the Complete Abaqus Environment was performed on the nylon leadscrew at different diameters. For the purposes of simplification, the leadscrew was modeled as a cylindrical rod. The following, Figure 69, are the results of analyzing a 52-inch cylindrical rod of diameter 0.5 inches.



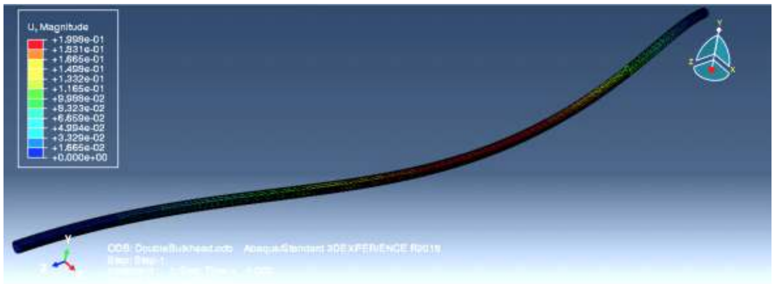
(a) Displacement



(b) Von Mises Stress

Figure 69: Nylon rod of diameter 0.5 inches.

From this figure, the maximum displacement was 0.3 inches, which is quite large when compared to the diameter of 0.5 inches. Additionally, the maximum von Mises stress was 899 psi, which is well under the yield strength of nylon 6/6 (between 6500 and 8500 psi). The following, Figure 70, are the results of analyzing a 52-inch cylindrical rod of diameter 0.625 inches.

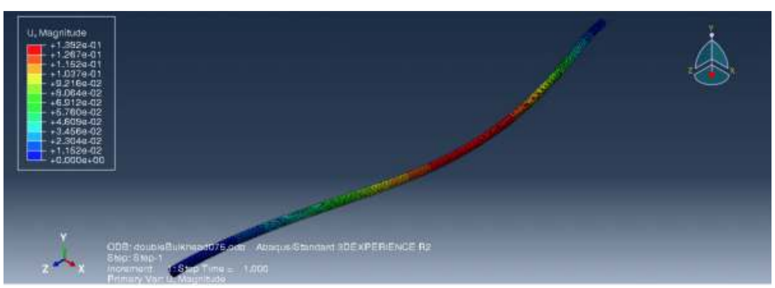


(a) Displacement

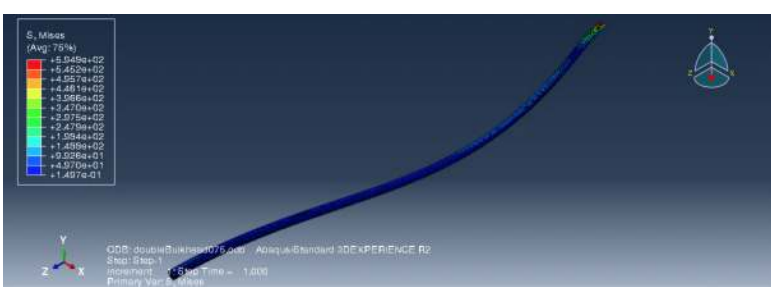
(b) Von Mises Stress

Figure 70: Nylon rod of diameter 0.625 inches.

From this figure, the maximum displacement was around 0.2 inches. Additionally, the maximum von Mises stress was 712 psi, which is well under the yield strength of nylon 6/6. Finally, the following, Figure 71, are the results of analyzing a 52-inch cylindrical rod of diameter 0.75 inches.



(a) Displacement



(b) Von Mises Stress

Figure 71: Nylon rod of diameter 0.75 inches.

From this figure, the maximum displacement was around 0.1 inches. Additionally, the maximum von Mises stress was 595 psi, which is well under the yield strength of nylon 6/6. The UAV and its platform will not be bearing weight on the leadscrew at full extension for a long period of time. Thus, it is acceptable to use a nylon 6/6 threaded rod at a diameter of 0.625 inches as the leadscrew for the Linear Transport Mechanism. Its maximum von Mises stress, at 712 psi has a factor of safety of around 9.1 when compared to the lower threshold of nylon 6/6 yield strength, 6500 psi. Additionally, its diameter of 0.625 inches is about three times larger than the maximum displacement it will endure. The weight used for the UAV and its platform, 60 oz, was also an overestimate by around 15 oz.

The leadscrew and stepper motor will be fixed onto the aft bulkhead, shown previously in Figure 67, to allow rotation with the Orientation Correction Mechanism. The leadscrew will be threaded through the fore bulkhead, shown previously in Figure 68, by a small hex nut epoxied to this bulkhead. The remaining length of the leadscrew will be housed inside the nose cone, shown in Figure 72.

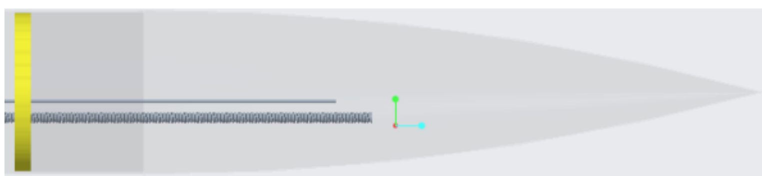


Figure 72: Leadscrew section in the nose cone.

As the stepper motor runs, the fore bulkhead, with the UAV platform attached to the nose cone, will translate down the leadscrew.

5.3.3 Beacon Delivery Subsystem

The Beacon Delivery Subsystem was designed to ensure an accurate, economical, and effective way to deliver the NDRT beacon onto the Future Excursion Area. Additionally, the Beacon Delivery Subsystem was designed with the UAV as a whole in mind. The system itself consists of four parts: the beacons, the holding plate, the rods, and the servo motor which controls the deployment system. Two beacons are fitted onto two rods, which rest upon the holding plate. The plate is controlled by the servo motor, which turns the plate to allow a primary and then secondary deployment of a beacon.

The following, Figure 73, details the dimensions of the holding plate, which is used to hold the beacons in place until their deployment. The plate is to be 3D printed out of ASA, which will retain enough strength to hold the beacons but will also be lightweight so as to not hinder the flight of the UAV. Additionally, ASA was chosen over PLA due to its lighter weight.

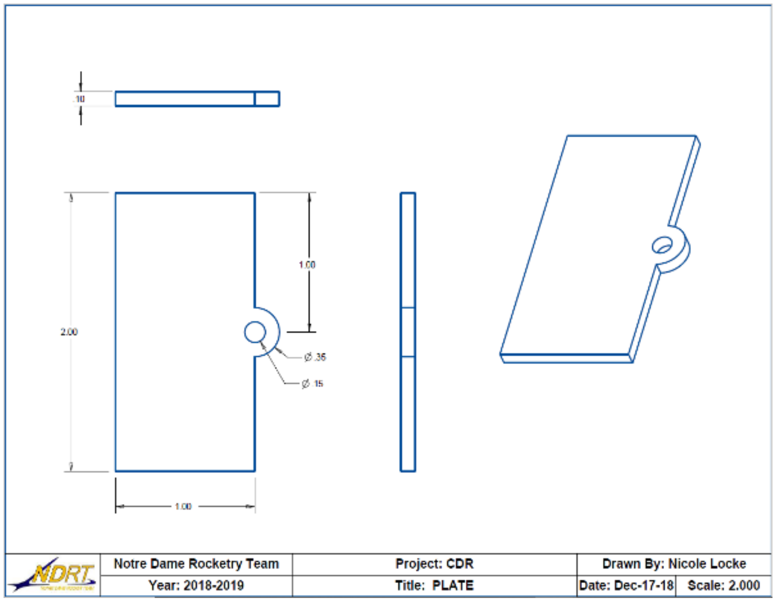


Figure 73: Holding plate for the two beacons.

Figure 74, seen below, depicts the rods upon which the beacons will be held while waiting to be deployed. The rods, in the same fashion as the holding plate, will be 3D printed out of ASA. The rods were created in a rectangular fashion to ensure that the beacons would not twist at all during the flight of the UAV. The center of the rods have been hollowed to lighten the overall weight of the beacon deployment assembly.

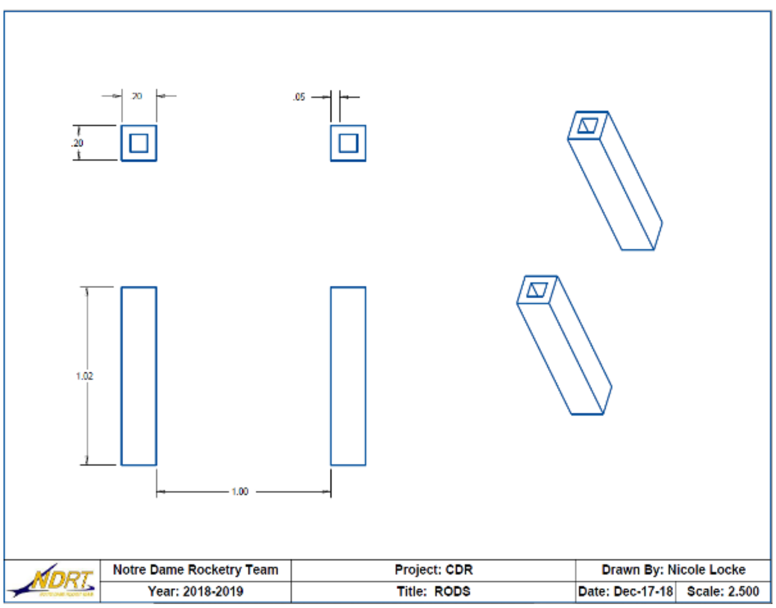


Figure 74: Rods for the two beacons.

The motor chosen for this assembly is the FEETECH FS90R which is a continuous rotation robotic servo. A servo motor was chosen over a step motor because it provides more stability during disturbances such as liftoff, and provide a continuous torque for a wide range of speed. This specific servo motor was chosen because it gave the necessary torque required to move the plate, but was not overpowered such that it drained energy from the UAV's battery unnecessarily. Additionally, the dimensions of the servo allow it to fit well on the undercarriage of the UAV.

The assembly of the mechanical beacon deployment can be seen in the following Figure 75, which detail the different phases of the system.

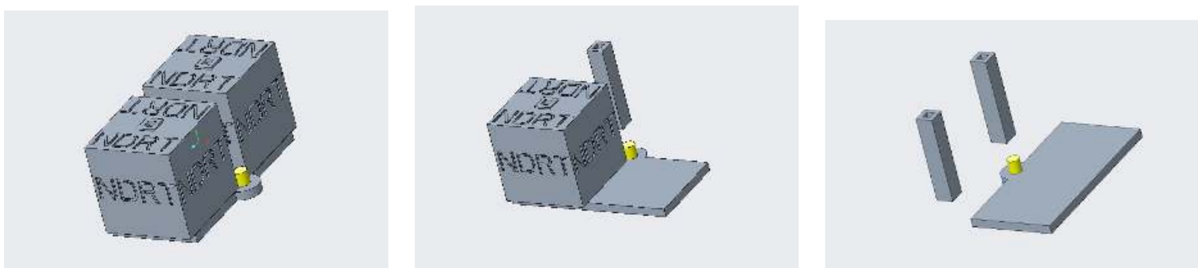


Figure 75: Figure showing the three main beacon deployment phases.

Two beacons are attached, one to each square rod, as depicted in Figure 75, which lays on the top of the lower platform. The reasoning behind a square rod is to minimize the ability of the beacon to rotate about the rod during deployment. During the flight of the UAV, the leftmost state, known as Phase I, would be in effect. Upon deployment of the first beacon, a servo motor, yellow in the model, will activate and rotate the platform ninety degrees, thus giving the primary beacon zero support. This state is known as Phase II and can be seen in Figure 75 as the middle image. The beacon will then slide down the rod and onto the target due to gravity. Because the beacon is very lightweight and the torque produced by the servo is strong, the friction between the beacon and the platform is negligible. For secondary deployment, in the case of initial failure, the motor can be activated to turn an additional ninety degrees. This state is known as Phase III and would allow the secondary beacon to deploy. This final phase can be seen in Figure 75 as the rightmost image. This deployment system was chosen due to the need for only one servo motor and the ability of the system to simply hold the beacon in place before deployment. Additionally, it allows for a double deployment at separate times. This double deployment would add the benefit of redundancy to the system, in case of failure on the initial attempt. Figure 76 shows two views of how the Beacon Delivery Subsystem, identified by the rods for the two beacons, will integrate with the UAV frame.

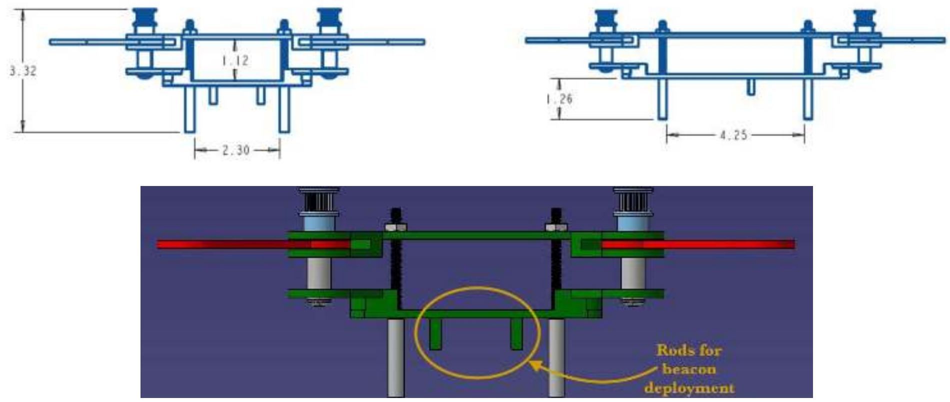


Figure 76: Figure showing rods for the Beacon Delivery Subsystem.

The Beacon Delivery Subsystem attaches to the undercarriage of the UAV. The system is shorter than the legs of the UAV so that it does not interfere with landing. The battery used to power beacon deployment is the battery used for the entire UAV system. Therefore, the servo motor chosen will not largely affect the battery life of the UAV. The following, Figure 77, shows the beacon used for the Notre Dame Rocketry Team.

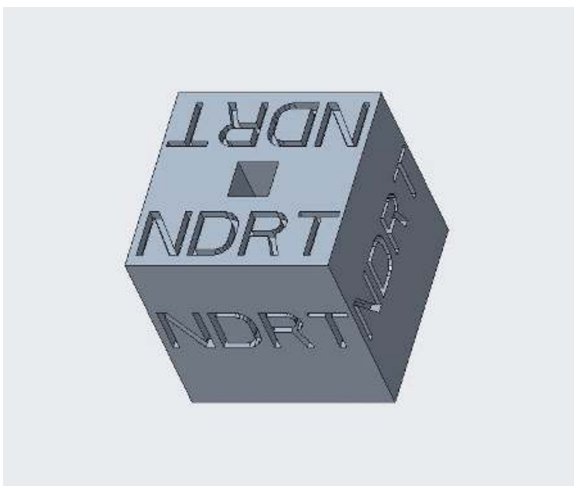


Figure 77: Cube with the Notre Dame Rocketry Team (NDRT) acronym on each side.

This design will be 3D printed out of ASA and will therefore be lightweight and simple to fabricate. Additionally, the beacon is hollow to make the design even more lightweight, therefore decreasing the overall weight of the entire beacon deployment system and lessening its effect on the battery life of the drone. A detailed drawing of the beacon, with dimensions, can be seen in Figure 78. The beacon was designed with the volumetric constraints given by NASA in mind, and fulfills those constraints by being one cubic inch in volume.

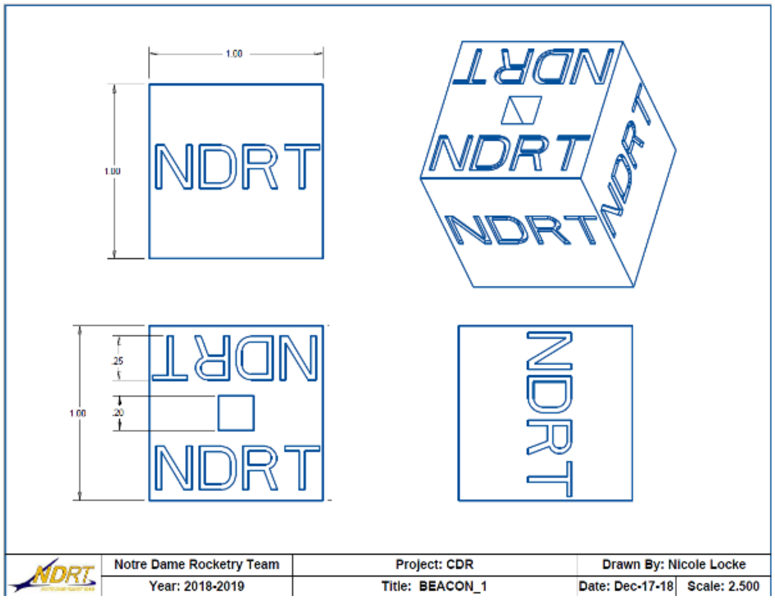


Figure 78: Drawing of the 3D printed beacon with dimensions.

FEA using the Complete Abaqus Environment was performed on the bottom holding plate for the two beacons, since it will only have a pin connection. This analysis may be seen in Figure 79.

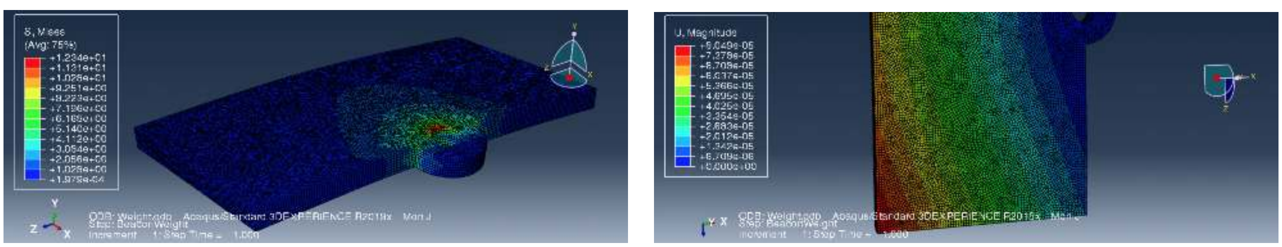


Figure 79: FEA on the Beacon Delivery Subsystem holding plate.

Note that the leftmost figure shows the von Mises stress in psi, and the rightmost figure shows the magnitude of displacement in inches. The FEA shows that the maximum displacement, shown in red on the rightmost figure, is 0.00008 inches at each corner. Thus, the middle pin connection will be more than adequate to support the weights of the two beacons.

The bill of materials for the Beacon Delivery Subsystem as well as an exploded view of the assembly may be found in Figure 80.

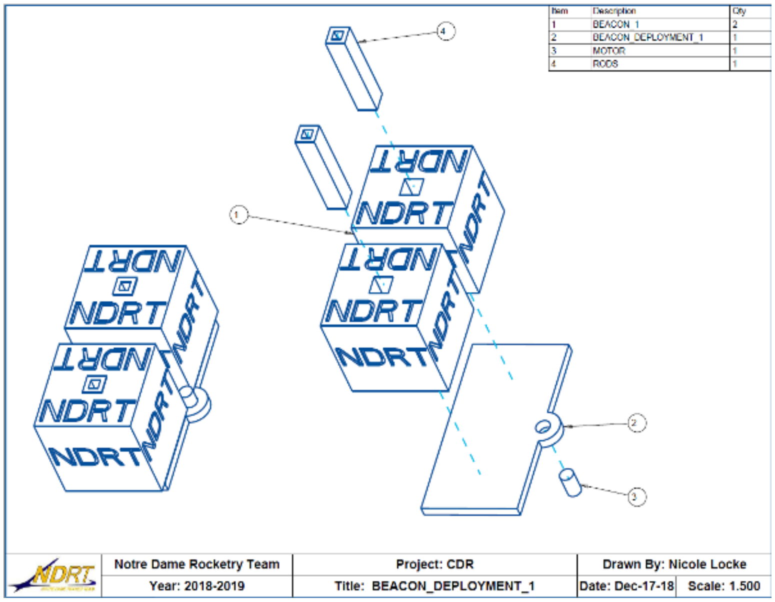


Figure 80: Bill of materials for the Beacon Delivery Subsystem.

The weights and cost of this system can be found in the following Table 40. The Innovation Park, located at the University of Notre Dame, will work with the Notre Dame Rocketry Team in 3D printing the various parts.

Table 40: Weights and costs of the Beacon Delivery Subsystem.

Item	Weight (grams)	Cost (USD)
FEETECH FS90R	10	11.94 for two
ASA 3D Printed Members	8.81	30.00

5.4 Payload Electrical Design

5.4.1 Deployable Drone

The electronics for the UAV were chosen to ensure the most effective means of fulfilling the Mission Success Criteria. Power for the UAV is supplied by one 3S, 4500 mAh Turnigy Lithium-Polymer battery. The battery is connected to the Power Distribution Board where it is routed to each component, as shown in Figure 81.

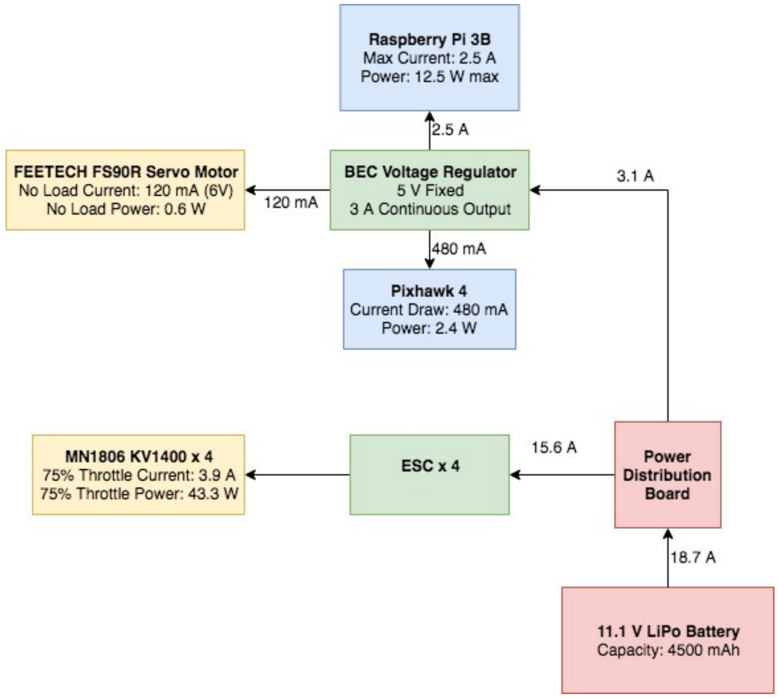


Figure 81: Power flowchart.

Each motor is connected to power via an Electronic Speed Controller which provides 3-phase power from DC. Each motor is rated to draw 3.9 amperes at 75% throttle, which is what was targeted for hover. At hover, the motors are pulling a total of 43.3 W. The flight controls are handled by a Raspberry Pi 3B and Pixhawk 4, and the beacon deployment system is run by a servo motor. Each of these components requires 5 V, so a BEC voltage regulator is used to step down the 11.1 V battery voltage to 5 V. The regulator has a continuous current rating of 3 A, but can handle more for short periods of time. Since the servo motor will be operating only to deploy the beacon, the regulator will suffice. The servo draws 120 mA at 6 V with no load for a nominal power draw of 600 mW. The Pi is maximally rated to draw 2.5 A at 5 V for a power draw of 12.5 W, depending on peripherals used. The Pixhawk 4 pulls 480 mA at 5 V for 2.4 W. In total the battery will supply a maximum of 58.8 W.

An overview of the Communication System architecture is visible in Figure 82.

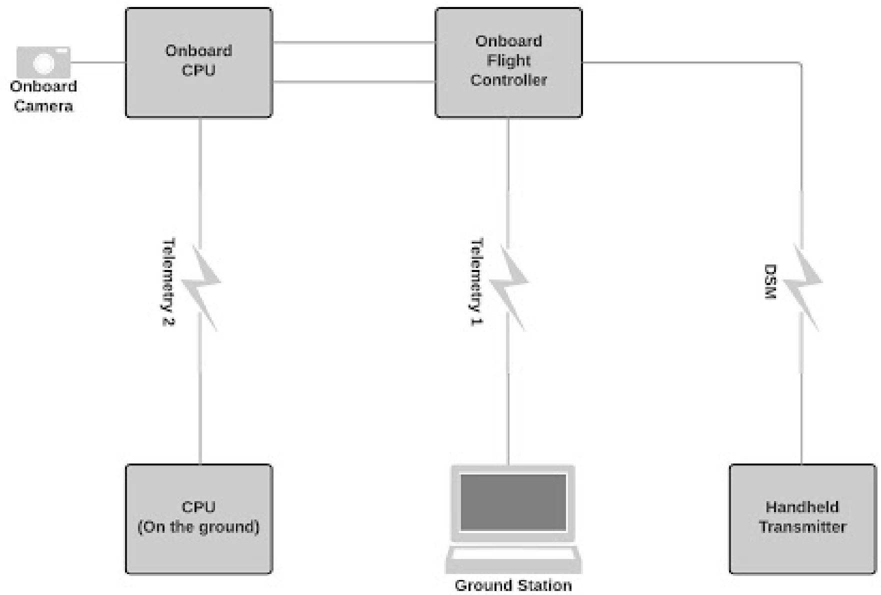


Figure 82: Communication system architecture.

The UAV system is designed such that it will be able to fulfill its mission with complete autonomy. However, the system will also have a redundancy such that a switchover to manual flight control is possible. The UAV will fly a preprogrammed flight plan upon deployment from the drone. During flight, the onboard CPU, a Raspberry Pi 3 Model B, will process data from the onboard camera using a search algorithm to detect the target. Once the target has been detected, the onboard CPU will upload a new flight plan to the flight controller, a Pixhawk 4.

In the interests of redundancy, the onboard CPU will stream the visual data via telemetry from the onboard camera to a CPU on the ground (also a Raspberry Pi 3 Model B) which will display the data for first person view. There will also be a telemetry link between the flight controller and the ground station, a laptop. This will provide real time spatial coordinates of the UAV visible on Google Maps. Lastly, there will be a handheld controller for use in the case where manual takeover is deemed necessary.

Since the total payload weight allocation is 80 oz, the team designed the deployable drone to be between 30 and 40 oz; thus leaving sufficient weight for the deployment mechanism. The selected motor, the T-Motor MN1806 KV1400 in Figure 83, provides the required thrust at 75% throttle, making it suitable for sustained flight.

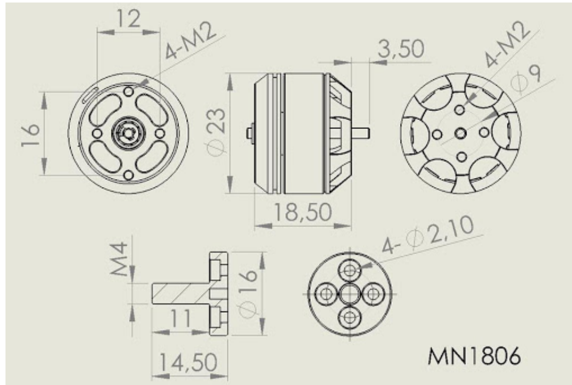


Figure 83: Motor dimensions in mm.

Each of these motors will be directly wired to an electronic speed controller (ESC) that dictates motor rotation speed, seen in Figure 84.

Figure 84: Lumenier 18A 32bit Silk ESC OPTO.

The ESC will generate the corresponding control signal based off a reference signal it receives from the flight controller, the Pixhawk 4. The nominal motor specifications are provided in Table 41.

Table 41: Nominal motor specifications.

Characteristic	Value
Nominal Voltage	11.1 V
Throttle	75%
Nominal Speed	10100 RPM
Nominal Current	3.9 A
Nominal Power Consumption	43 W
Nominal Thrust	252 g
Nominal Efficiency	5.82 g/W
Operating Temperature	50°
Weight	18 g
Internal Resistance	325 mΩ
Stator Diameter	18 mm
Stator Length	6 mm
Shaft Diamter	2 mm

The team selected the Raspberry Pi 3B as the deployable drone onboard CPU, shown in Figure 85.

Figure 85: Raspberry Pi 3 Model B.

This device will directly process video feed gathered by the drone camera to autonomously detect the FEA. Once the target is located, the Raspberry Pi will upload the coordinates to the flight controller. Such functionality allows the drone to perform target zone detection and navigation independently; thus preventing failure modes that may arise due communication loss with the ground station.

As a redundancy, the Raspberry Pi will also stream video to the ground station. The team will utilize this feed both to monitor drone operation and to navigate if autonomous navigation fails and manual takeover is necessary.

The team selected the Pixhawk 4, shown in Figure 86, as the onboard flight controller for the UAV.

Figure 86: Pixhawk 4 flight controller.

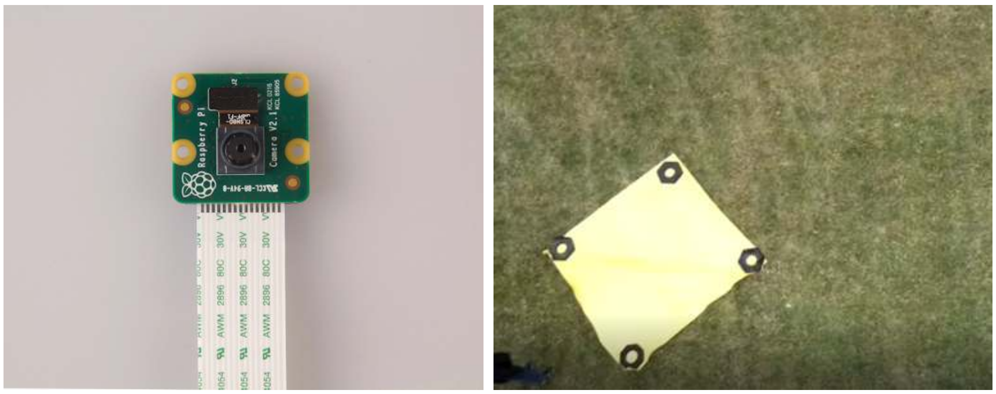
The Pixhawk brand was chosen based on previous experience of team members. This model was chosen based on its heating capabilities, which will be useful for cold-weather testing in South Bend, Indiana. In addition, its connection ports and servo rail will be useful for power splitting. The Pixhawk will control the power flow to the motors, stabilize the UAV's flight using its sensors, and track and update the GPS coordinates of the UAV. It will also be used to communicate the UAV's flight path with the ground station.

The FrSky Taranis X9D, shown in Figure 87, will be used to control the flight of the UAV in the case of manual flight takeover.

Figure 87: FrSky Taranis X9D Plus 2.4 GHz ACCST Radio.

The Taranis will communicate with the flight controller through a 2.4 GHz receiver. This handheld transmitter features a long range system, real-time data logging, and receiver lock.

The UAV will be equipped with a Raspberry Pi Camera Module V2. This is a standard camera module that integrates with Raspberry Pi CPUs. It provides 8 megapixels of resolution and can take high resolution videos as well as still photographs, seen in Figure 88.



(a) Raspberry Pi Camera Module V2. (b) Test image from the RPi camera.

Figure 88: Deployable drone camera.

This device will be used to stream constant video to the Raspberry Pi 3B, which can then be used either for target detection or manual flight.

The UAV will use a Button-on-Arm power-on system, which includes two mechanical buttons and two contacts, one per arm. The first button will be inserted between the power distribution board and the flight controller, and it will be placed on the side of the UAV body. The second button will be placed between the power distribution board and the onboard CPU, and it, too, will be placed on the side of the UAV body. The contact will be a small plastic rod placed on the inside of one of the UAV arms. While the UAV is folded and inside the rocket, the contact will push the button and prevent the power distribution board from powering the flight controller and CPU. During the deployment sequence, a torsion spring will unfold each of the four arms. Once the arm with the button-contact interface unfolds, the contact will no longer press the button and the power distribution board will power on the electrical system. This design consumes no electrical power and removes the potential for the system to turn on due to battery depletion, as might be the case for an electromagnetic relay. An overview of the systems architecture is visible in Figure 89.

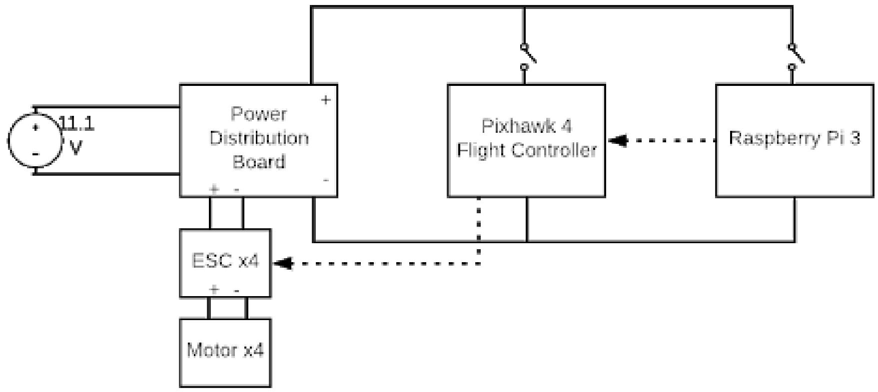


Figure 89: Deployable drone power-on sequence.

5.4.2 Deployment Subsystem

The deployment subsystem is particularly complex in terms of electronic components, and it performs a crucial function for the payload. Thus, it must be powered as properly and efficiently as possible. The accelerometer and the receiver require a regulated 5 V rail, which is provided by the Arduino's voltage control capabilities. The servo motor operates at this voltage but requires a greater current, and the stepper motor operates at 10 V. The two motors used for the deployment of the UAV are pictured in Figure 90.

(a) Nema 14 Stepper Motor.

(b) Model #FS5106R Continuous Rotation Servo.

Figure 90: Motors for UAV deployment.

To alleviate this problem, the team will employ BJT transistors to amplify the current coming from the Arduino into each sensor. The team selected the Turnigy 2200 mAh 3S 25C Lipo Pack to meet the power needs of the system. Figure 91 illustrates how power is managed within the deployment subsystem. Since this subsystem will be operating for a short amount of time (a maximum of 2 minutes), it can be powered by the chosen 2200 mAh battery.

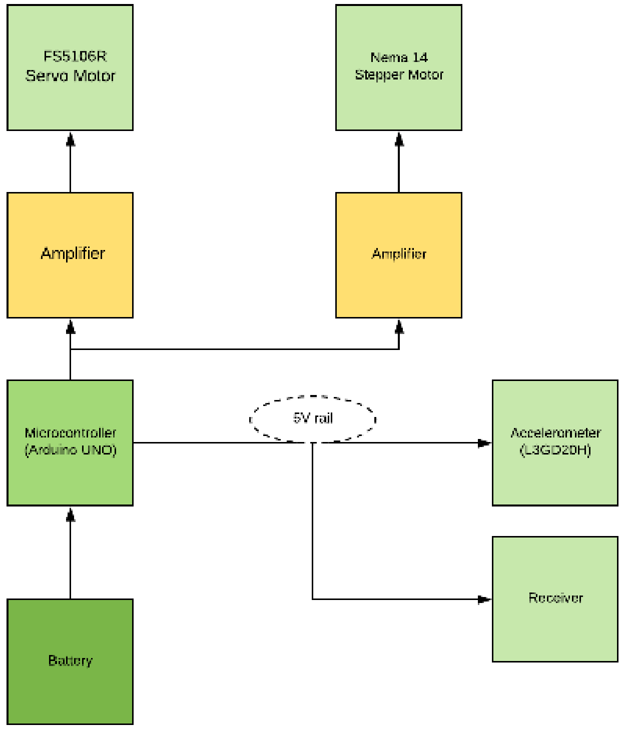
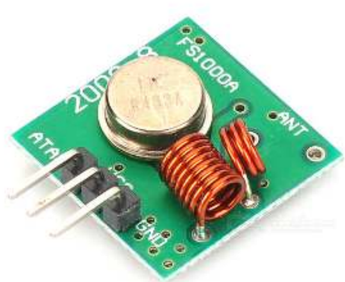


Figure 91: Power management of the subsystem.

The team chose the 433 MHz RF transmitter and receiver kit to remotely activate the deployment sequence. This radio frequency is chosen because it supports wireless control at a relatively low cost. The receiving range for this frequency is up to 100 meters outdoors, which meets the requirements at the launch site. The receiver circuit will be connected to the Arduino microcontroller inside the rocket body. When the receiver circuit receives a signal from the team, it will start the deployment sequence. Figure 92 shows the transmitter and receiver.



(a) Transmitter.

(b) Receiver.

Figure 92: 433 MHz transmitter and receiver.

The team was able to test the chosen Orientation Correction Mechanism sensor at the Notre Dame Rocketry Team's first sub-scale launch on December 2 in Three Oaks, Michigan. The L3GD20H Triple-Axis Gyro Breakout Board may be seen in Figure 93.

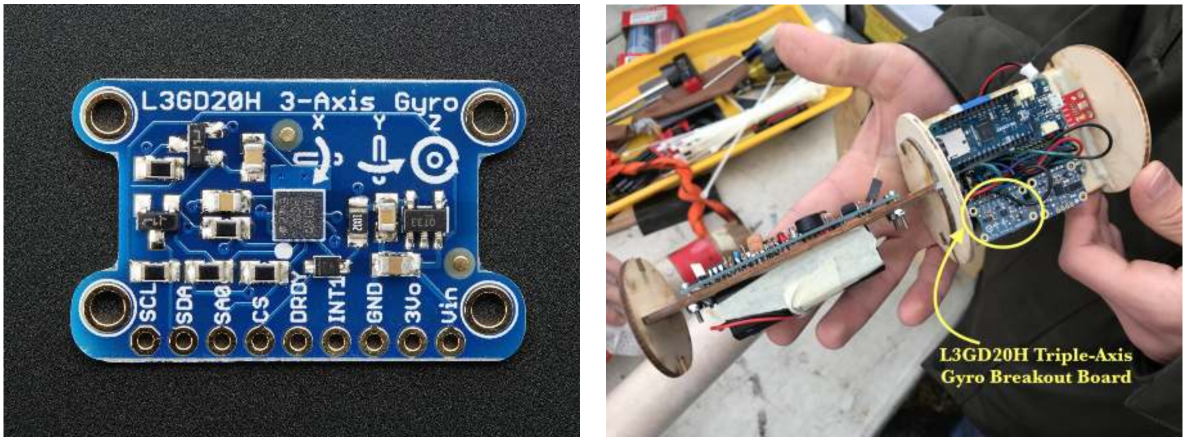


Figure 93: L3GD20H Triple-Axis Gyro Breakout Board.

After the sub-scale launch, it was determined that it will be best to have both an accelerometer and a gyroscope, since a gyroscope gives an orientation, and an accelerometer uses the gravitational field of the Earth to detect the ground. Thus, the team will use the Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout BNO055 for the Orientation Correction Mechanism. It can detect which way is down toward the ground and give orientation data as the mechanism turns. The 9-Degrees-of-Freedom sensor is a MEMS accelerometer, magnetometer, and gyroscope, shown in Figure 94.

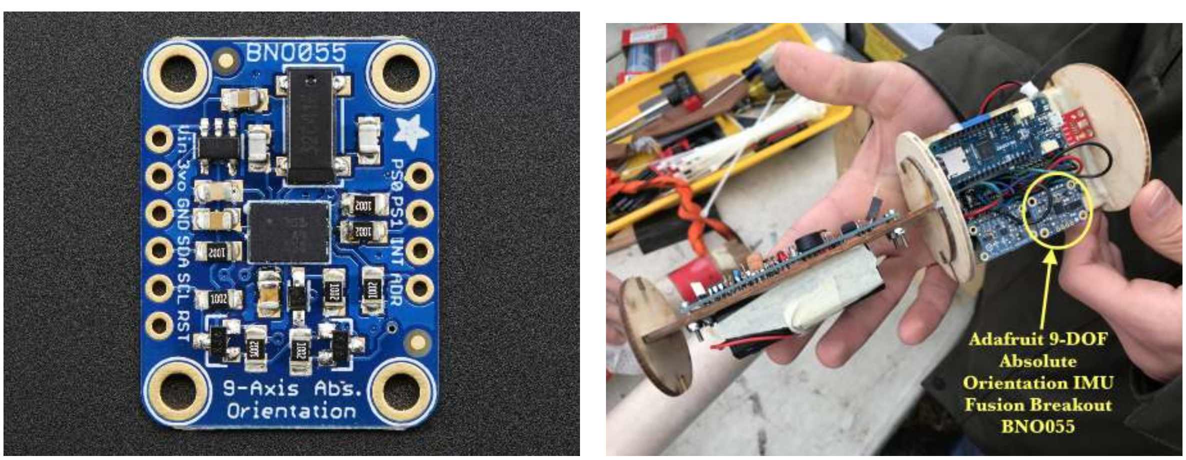


Figure 94: Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout BNO055.

The team decided to use the Arduino UNO (board model: UNO R3) as the Deployment Subsystem microcontroller, shown in Figure 95.

Figure 95: Arduino UNO R3.

It controls the voltage to 5 V. When it receives the signal from the transmitter, the rotation will begin. The Arduino UNO will receive signal from the accelerometer and gyroscope. When the data shows the UAV body is upright, it will start the linear deployment stage, until the UAV body is outside the rocket. Figure 96 shows the flowchart of the Arduino UNO control system.

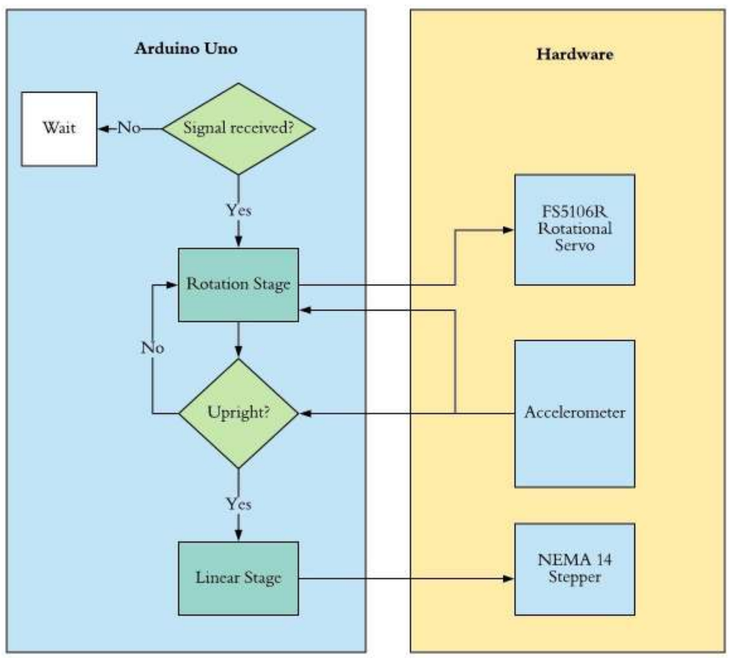


Figure 96: Arduino UNO control system.

The torque required to rotate the UAV platform is calculated via Equation 5,

$$\tau = \frac{mr^2}{2}\alpha \tag{5}$$

where τ is the torque, m is the mass of the rotating components of the Orientation Correction Mechanism including the mounted UAV, r is the radius of the inner housing, and α is the desired angular acceleration of 2 rad/s^2. The team initially considered both stepper motors and servo motors for rotating the UAV platform. A servo motor, the FS5106R, was chosen in the end because of its high torque generation and precision of movement. Compared to stepper motors that use an open loop, the servo motor runs in a closed loop, which provides feedback regarding its position, increasing the precision of the rotation. This is desired by the team because the UAV needs to be rotated until it is parallel to the ground in order to take off, which requires an accurate control.

The torque required to rotate the leadscrew was found via Equation 6,

$$\tau = \frac{1}{2}\pi P(F + \mu W g) \tag{6}$$

where τ is the torque, F is the external force, W is the mass of the load, μ is the friction coefficient on the sliding surface, g is the acceleration due to gravity, and P is the ball screw lead. The team considered both stepper motors and gear motors but ultimately chose the former. Gear motors produce more torque, but stepper motors produce a sufficient amount for the task at hand and present a simpler control system. Thus, the team selected the Nema 14 Step Motor. This motor must be able to rotate the leadscrew such that it pushes the entire UAV assembly out of the launch vehicle during the orientation correction stage.

5.5 Payload Software Design

5.5.1 Autonomous Flight Subsystem

The drone will be controlled by Python code which will direct the drone to take off, fly to the Future Excursion Area, drop off the beacon, and then fly to a safe area. The team will record the GPS coordinates of each FEA the morning before the launch and upload them to the drone. The drone will choose the target FEA by first calculating the distance to each point and then selecting the closest FEA as shown in Figure 97.

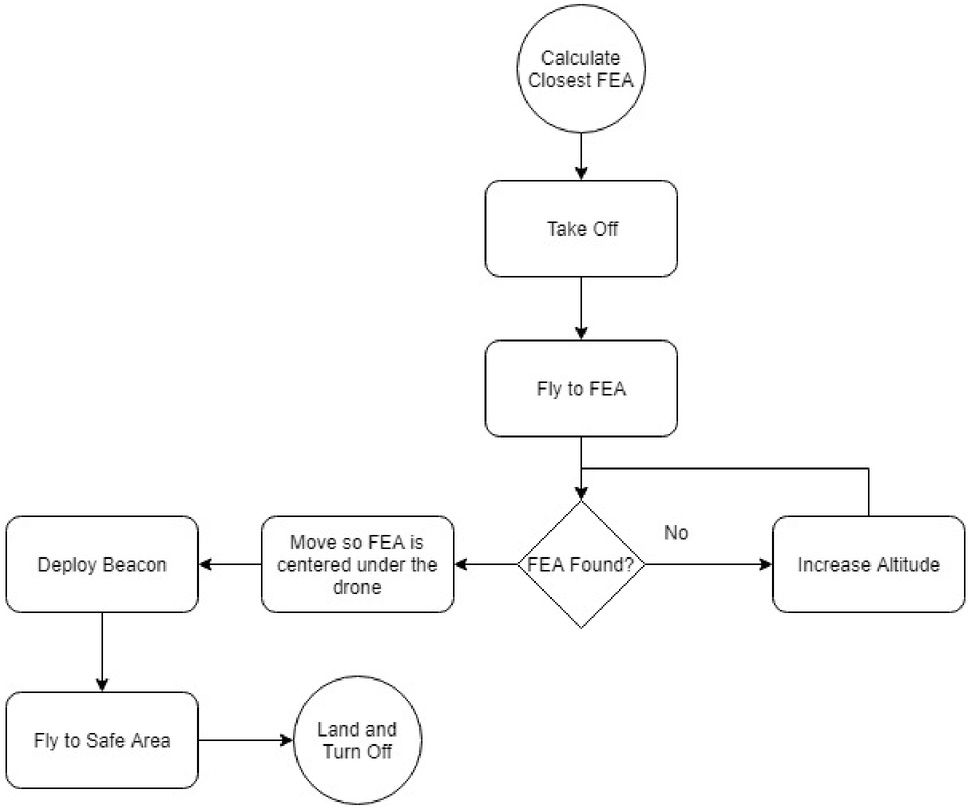


Figure 97: Autonomous flight process for finding the FEA.

The code governing this FEA detection feature is the following:

```
#Points is a list of the FEA's GPS coordinates
for point in points:
  if(close > get_distance(drone_position,point)):
close =  get_distance(drone_position,point)
closePoint = point
```

The drone can be switched from autonomous to manual control at any time with a switch on the controller. This acts as a fail-safe switch to ensure safety. The autonomous flight subsystem has been tested virtually and on a physical drone, namely, the 3DR IRIS+ Quadcopter, seen in Figure 98.

Figure 98: 3DR IRIS+ Quadcopter.

The current version of the code has been tested virtually and works as expected. The virtual drone chooses the closest FEA, drops off the beacon and then returns to a designated location. However, it is not possible to integrate the target detection subsystem in the virtual testing platform. Thus, during these iterations, the drone found the FEA by GPS alone. Time constraints, in conjunction with inclement weather, have prevented the team from testing the current version of the code on a physical drone before the Critical Design Review deadline. However, an older version of the code has been tested on the 3DR IRIS+ Quadcopter. The first test was not successful as the drone would not take off. This was due to an error in the altitude level given to the drone. The drone was using global altitude instead of relative altitude. This led to the drone not rising above a certain altitude and being unable to complete its route. After fixing this error, the drone was able to fly to the inputted GPS coordinates, land, and then return successfully. A picture of the testing from November 18, 2018, may be seen in Figure 99.

Figure 99: November 18, 2018 testing with the 3DR IRIS+ Quadcopter.

The target detection code, which is still being developed, was not tested at this time. The team is still analyzing video data to train the drone to differentiate between the FEA and the ground via Hue, Saturation, Value (HSV) data.

5.5.2 Future Excursion Area Detection Subsystem

Once the unmanned aerial vehicle (UAV) navigates to the specified GPS coordinates, the Future Excursion Area Detection Subsystem will activate and allow the UAV to accurately maneuver into position above the target. This process is seen in Figure 100

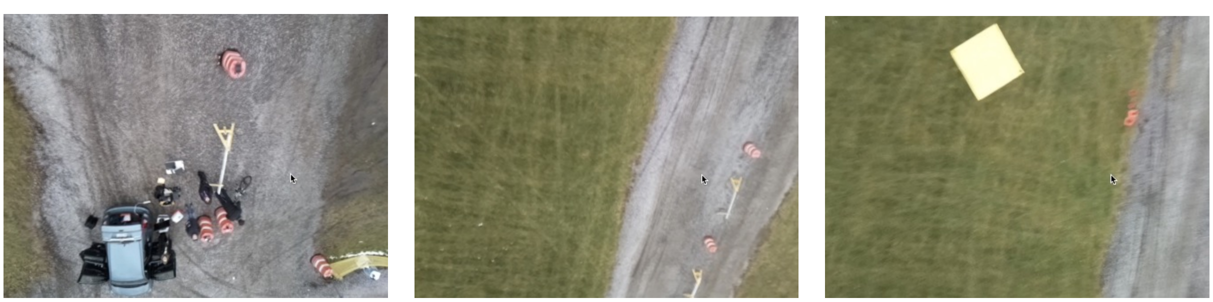


Figure 100: This figure shows the chronological scenes (from takeoff to final positioning) in the field of view of the UAV as it gradually moves into position above the yellow FEA.

In order to accurately navigate to the target, the UAV will analyze footage from a camera attached to the Raspberry Pi. This analysis will be done using the OpenCV library in Python. In designing this system, the team has collected footage of a practice 10 foot by 10 foot FEA by attaching the Raspberry Pi and its camera to a drone, as seen in Figure 101 and flying it over the FEA in various conditions.

Figure 101: Team attaching the Raspberry Pi and its camera to the 3DR IRIS+ Quadcopter.

This footage has been collected at various altitudes, from multiple angles, against multiple different backdrops, and in a variety of weather conditions. Moving forward, this footage will be manually annotated. To do this, the team has written a program, found in Appendix B.1, which displays every tenth frame in the video and asks a user to click the corners of the target in sequence. With these annotations, the team will be able to construct an error metric to determine a detection algorithm's performance. The metric which will be used is intersection over union. The formula for this error metric is shown in Equation 7 below.

$$E = \frac{\mid A \cap I \mid}{\mid A \cup I \mid} \tag{7}$$

In this equation, E is error, A is the set of pixels in the manually delineated FEA, and I is the set of pixels delineated by the algorithm as part of the FEA. This metric awards algorithms which identify most of the target without identifying areas outside of the target. With this metric, different algorithms and combinations can be directly compared to one another in an empirical way.

In constructing the most accurate target detection system, the team will consider several different features. These features include color, texture, and shape. With color, the team will analyze several different color spaces. As a basis, the team will analyze the red, green, and blue (RGB) spectrum. However, alternate spaces will also be considered. Hue Saturation Value (HSV) provides some advantages over RGB in that it is more consistent at identifying similar colors across different brightness levels. Some other spaces which will be considered are the L*a*b* color space (which is based on one channel for luminance and two color channels), seen in Figure 102, and the hue, saturation, lightness (HSL) space.

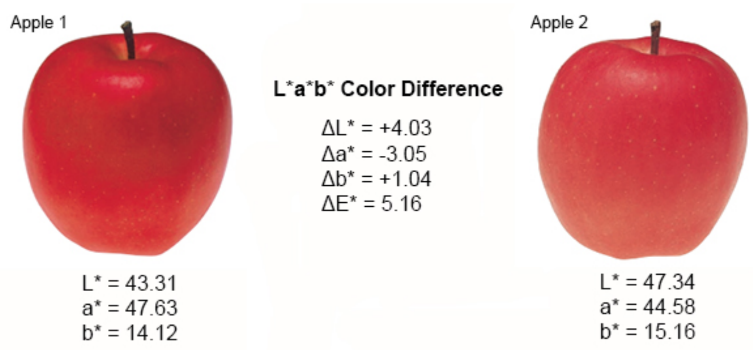


Figure 102: The L*a*b* values show that Apple 2 is lighter and less red than Apple 1.

In addition to whole color spaces, individual channels will also be analyzed. Another thing to consider is the range of values which will be identified as part of the target. To do this, the team will examine the distribution of pixel values for every annotated target and set the delineation to be within a certain number of standard deviations of the mean pixel values. Two standard deviations is a sane default, but other cutoffs, such as 1.5 or 2.5 standard deviations, may be used as alternate cutoffs.

The team is also considering implementing a geometric analysis in the computer vision algorithm. In running tests on color detection software, the team noticed that a nearby fence, which had a similar color to that of the FEA, was registering several false positives for the algorithm. It would detect fence and FEA and have no way of differentiating the two. This issue could potentially result in the UAV behaving in unexpected and unwanted ways while trying to deliver the beacon. In order to combat this problem, the team has begun implementing geometric approaches to distinguish the FEA. Currently, the algorithm accomplishes this by calculating the aspect ratio of the binary image. If this is sufficiently close to 1, the algorithm registers the pixels as the FEA. This approach is based on the distinguishing feature of the UAV as a square. Unfortunately, it currently does have some limitations. While selecting square-like objects helps to filter out non-FEA yellow objects, it can also filter out the FEA itself when only partially in view of the camera. Corners currently register as false negatives, and this is a problem for trying to consistently identify the FEA. In the future, a more sophisticated analysis will be necessary for trying to minimize both false positives and false negatives. Other geometrical factors could be taken into consideration, or even a backup set of features for when the FEA is only partially in view.

Another feature the team is considering adding to the target detection algorithm as an added layer of redundancy is texture-based FEA differentiation. The FEA is a smooth, fabricated surface. This is noticeably different from the surrounding environment, so a quantified measure of texture could help the algorithm make a more accurate decision on the location of the FEA. Texture can be identified by convolving an input image with a Gabor kernel, a type of Gaussian kernel commonly used in textural analysis. The resulting image has high pixel values in more textured areas, and low pixel values in smooth areas. For example, running the transform on an image of the FEA leads to the result seen in Figure 103.

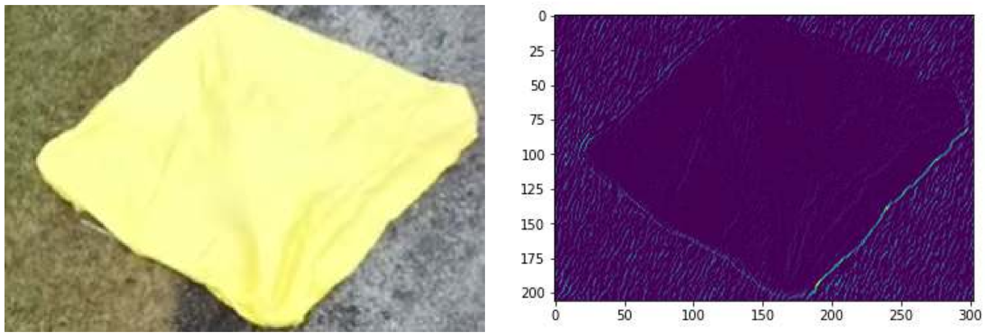


Figure 103: An Image of the FEA and its Gabor Transform.

As can be seen in Figure 103, the FEA is fairly clearly delineated from the surrounding environment when texture is analyzed. While this on its own may not be as reliable as relying on color, it adds a fair amount of confirmation of the FEA's location without much extra compute time, and may be implemented into the algorithm to provide an extra level of information and accuracy.

Figure 104 shows the decision process of the algorithm when attempting to differentiate between the FEA and the surrounding ground.

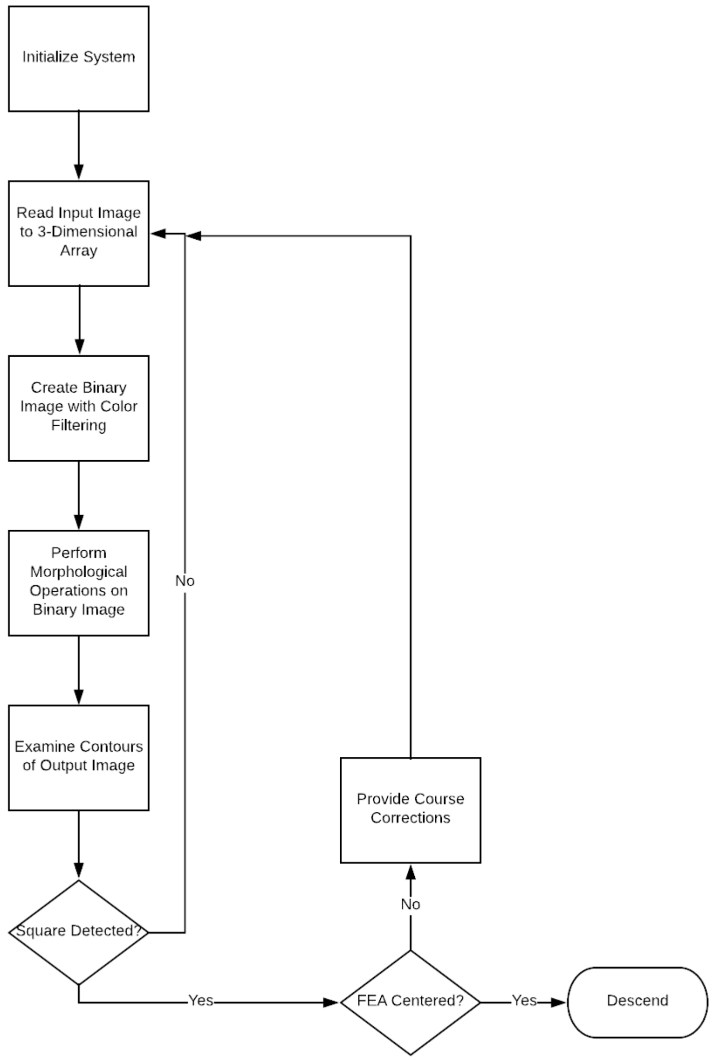


Figure 104: Flowchart of target detection process.

This figure shows the decision process of the current iteration of the FEA detection algorithm. While the specific details of each step are still being refined, the general work-flow is in its final stages and the code can be found in Appendix B.1. Once the UAV reaches the GPS waypoint, the algorithm will initialize as shown. At each stage during its operation, the algorithm reads an input image and stores it as an array. It then performs several operations, including a binary filtering where pixels within an acceptable range of color values are set as ones, and everything else is set as zeroes. Morphological operations are then done, which currently include closing followed by dilation, which help to fill in any gaps in the binary image and create a more solid object. After this, the contours of the object are evaluated, and if they are sufficiently similar to that of a square, the algorithm recognizes the object as the FEA. From here, the center of mass of the FEA can be determined by averaging the positions of every identified pixel. If that center of mass is close to the center of the image, then the UAV can safely descend and deploy the beacon. If not, corrections can be sent to the autonomous flight system. After those corrections are made, the algorithm iterates again, until the UAV is centered on the FEA.

This system adds an extra layer of redundancy to the autonomous flight system. GPS signal is usually only accurate to around 5-7 meters, while the FEA is 10 feet by 10 feet. Because of this, GPS alone cannot guarantee that the FEA will be safely reached. However, with the computer vision system in place, the UAV will be able to switch from navigating by GPS waypoint to position corrections made using information from the camera. At any given point, the UAV can calculate the center of the identified FEA and correct its position to align that center with itself, before descending to a safe height and deploying the beacon.

So far, the team has used a UAV to collect aerial footage on two different dates, November 18 and December 2. The weather was cloudy on both of these dates, so the footage taken is fairly similar. Footage was collected against several backdrops, including a gravel road, grass, and a hybrid of the two. A variety of heights were tested, and the FEA was approached at many different angles and speeds. The team did not steer the UAV based on input from the FEA detection subsystem, but the footage captured has been analyzed and is acting as the basis for future algorithmic development. Figure 105 below shows an example of footage taken from the UAV, as well as the output generated by the target detection algorithm.

Figure 105: Footage taken from UAV with algorithm applied.

In Figure 105, the leftmost image shows footage taken from the UAV with a bounding box drawn showing where the algorithm detects the FEA to be. The center and rightmost images show the results of color filtering and morphological operations, which play an integral part in determining the position of the FEA in an image.

In the future, the team plans to collect footage and test algorithms in a wider variety of conditions. For example, the team has so far only collected footage on cloudy days. Going forward, the team will have to seize any opportunities to fly on sunny days and days with clearer skies. Additionally, the team will seek to vary the backdrop placed against the FEA, such as placing it on the turf inside Loftus Sports Center. Doing so will help the system's performance and pave the way for the development of a more robust system.

6 Project Plan

6.1 Testing Plan

6.1.1 Vehicle Component Testing

6.1.1.1 Physical Testing

Shake / Stress Test
To verify the integration of each section, the component will be placed and secured in its correct position in the rocket. Then, the rocket will be shaken vigorously in the horizontal and vertical directions. This is to simulate any turbulence that the rocket might experience during flight, as well as the violent vibrations felt during descent and separation. The components being tested will be visually examined and deconstructed (if possible) after the test to ensure that they were not damage and did not shift a significant amount during testing. These tests will be carried out once materials have been acquired, and once each section has been built. This will most likely begin in late January 2019.

Subscale Launch
To verify both construction techniques and the overall soundness of the design, two Subscale launches took place in December 2018.The first flight was a control flight and flew with no ABS simulator tabs. The second flight included these tabs to verify that the addition of an airframe discontinuity would not compromise the integrity of the launch. This is discussed in greater detail below.

Wind Tunnel Testing
Wind Tunnel testing will be preformed in January 2019 to verify:

- The transition does not cause flow separation over the main body of the vehicle.
- The flow disturbance due to the transition does not interfere with altimeter readings.
- The C_D calculations are accurate for the flow over the ABS tabs.

6.1.1.2 Computational Testing

Vehicle Simulations
Both OpenRocket and RockSim are being used to calculate C_P as well as the stability and projected apogee of the launch vehicle. This is important to monitor as the vehicle is being constructed. The use of two packages gives redundancy in the case of computational or modelling errors. So far, the programs have calculated masses based on approximate densities of the materials. However, when the materials for the full scale are obtained, they will be weighed individually and input into the programs.

Computational Fluid Dynamics Analysis
A computational mesh has been developed to study the effect of the transition component

on the flow over the aft portion of the vehicle. Boundary layer anaylsis is important to understand how the vehicle interacts with the air around it and how this effects the rest of the systems. This analysis will be completed in late January 2019.

6.1.2 Recovery Subsystem Test Plan

The Mechanical Parachute Deployment System being implemented this year is completely new, and therefore needs to undergo extensive testing to ensure flight readiness. The recovery system will be tested in multiple phases, and compared to previous year's black powder system to safeguard against any potential failures during flight. The team's procedures will test the functionality of the latch mechanism in releasing the compressed spring in flight conditions, the ability of the compressed spring to properly deploy the parachute, and the ability of the mechanical system to work with the Eggtimer altimeters. Table 42 outlines the general test plan for the recovery system.

Table 42: Test Procedure Overview

Test	Test Description	Requirements Verified	Status
Latch Mechanism Test	A basic test of the retraction of the angled plates using the servo motors with the rack and pinion.	RC 3.2-1	Incomplete, scheduled for January 27th
Drop/Shake Test	The system will be tested to ensure that any potential flight conditions will not compromise the operation of the system.	2.7	Incomplete, scheduled for January 28th
Ground Tests	The mechanical system will be tested within the body tube to ensure that the compressed springs can properly deploy the parachute.	3.2	Incomplete, scheduled for January 30, 31
Simulated Flight Tests	A vacuum chamber will be used to test the performance of the Eggtimer with the mechanical system in flight conditions.	3.2	Incomplete, scheduled for February 4th
Full-Scale Flight Tests	The entire recovery system will be present in both full-scale flight tests to certify the system's full functionality.	3.2	Incomplete, scheduled for February 9th

6.1.2.1 Latch mechanism test

The latch mechanism will be tested as a component. The test will measure the ability of the servo motor gear system to retract the angled metal plates that retain the stopper in the spring system. Criteria for a successful test are shown in Table 43.

Items to be tested

- Functionality of rack and pinion system within 3D printed core
- Servo motors properly retract angled plates to release stopper

Table 43: Pass Fail Criteria- Latch Mechanism Test

Test Name	Requirements to be Verified	Pass/Fail Criteria
Latch Mechanism Test	RC 3.2-1	This test will be considered passed if each individual plate retracts effectively in more than 95% of test cases

Set-up

- Assemble bottom half of 3D printed ABS servo bay, with pinion components
- Assemble angled plates with rack, and top of 3D printed servo bay
- Set up stopper with shock cords in tension
- Actuate servo motor to retract plates

Equipment

- Two angled plates
- Rack and pinion
- Three parts 3D printed ABS servo bay
- Stopper with shock cords

6.1.2.2 Drop/Shake Test

TA drop test will be performed and used to discern if the system can withstand flight conditions without sustaining any critical damage or deploying prematurely. The criteria for a successful test are outlined in Table 44.

Items to be tested

- The angled plates retention and retraction of stopper
- The overall damage sustained by the system in test

Table 44: Pass Fail Criteria- Drop/Shake Test

Test Name	Requirements to be Verified	Pass/Fail Criteria
Drop/Shake Test	2.7	This test will be considered passed if the angled plates do not retract when the system is dropped/shaken, and can still retract after the system is dropped. The system must also sustain negligible damage.

Set-up

- Take the Mechanical Parachute Deployment System and drop it from varying distances

- Actuate Servo motors to discern if plates can still retract

Equipment

- Mechanical Parachute Deployment System
- Meter Stick

6.1.2.3 Ground Test

A ground test will be performed in order to demonstrate that the parachute can be properly deployed by the system. The criteria of a successful ground test are shown in Table 45.

Items to be tested

- The system fits and secures within the body tube
- The springs' ability to properly separate the body tube, and deploy the parachute
- The Garolite bulkhead and phenolic coupler do not cause any binding when the springs

Table 45: Pass Fail Criteria- Ground Test

Test Name	Requirements to be Verified	Pass/Fail Criteria
Ground Test	3.2	The release of the stopper delivers enough force to release a parachute substitute without any damage to the body tube.

Set-up

- Epoxy Garolite bulkhead in body tube
- Secure rubber springs to servo bay
- Compress springs
- Secure Deployment System in body tube
- Place metal plate
- Actuate servo motors

Equipment

- Mechanical Parachute Deployment System
- 8 rubber springs
- Carbon fiber body tube
- Two Garolite bulkheads (one structural)
- Metal plate (equivalent to weight of parachute)

6.1.2.4 Simulated Flight Test

A simulated flight test will be performed in order to ensure that the Eggtimers can properly activate the servo motors while the launch vehicle is in flight. The criteria for a successful simulated flight test are shown in Table 46.

Items to be tested

- The Eggtimer altimeter's engagement with the servo motors

Table 46: Pass Fail Criteria- Simulated Flight Test

Test Name	Requirements to be Verified	Pass/Fail Criteria
Simulated Flight Test	3.2	The Eggtimers properly engage the servo motors at the simulated apogee.

Set-up

- Place recovery system in vacuum chamber

Equipment

- Recovery System
- Vacuum Chamber

6.1.3 Full Scale Vehicle Flight Test

The entirety of the Mechanical Parachute Deployment System will be used in all full scale flight tests to certify that the system works properly in series with the rest of the launch vehicle. A successful test is indicated by achieving the target apogee, proper parachute deployment at apogee and 500ft, and negligible damage to the launch vehicle throughout the flight.

Items to be tested

- Parachute is properly deployed in actual launch vehicle conditions
- Apogee is within range of predicted altitude
- Flight remains within descent time and drift radius requirements

Set-up

- Compress springs using stopper and shock cords
- Place Deployment system into the body tube
- Pack parachute
- Liftoff

Equipment

- Entirety of the parachute deployment system
- Launch vehicle

Mission Success Criteria

- Rocket is able to be reused after landing
- Apogee is within 150ft of predicted altitude
- descent time is less than 90s
- . Drift radius is less that 2500ft

6.1.4 ABS Testing

Table 47: Air Braking System Test Plan

Test Name	Test ID	Description	Requirements Tested	Status
Subscale Testing	AT1	Verify stable flight with a 3D printed subscale drag tab coupler attached to subscale vehicle; Verify successful avionics datalogging.	AB-2, AB-7, AB-9, AB-13	Complete.
Electronics Ground Testing	AT2	Verify electronic component functionality and secure integration into printed circuit board.	AB-5, AB-6, AB-12	Incomplete.
Mechanical Hardware Ground Testing	AT3	Verify successful operation and robustness of ABS mechanical components and system.	AB2.24.1-1, AB-3, AB-10, AB-15, AB-17	Incomplete.
Software Ground Testing	AT4	Test to verify ABS control code properly responds to previous flight data and controls the assembled mechanism.	AB-3, AB-7, AB-11, AB-13	Incomplete.
Flight Testing	AT5	Verify braking power of ABS and test success of control algorithm in flight.	AB2.20.2-1, AB-1, AB-2, AB-4, AB-8, AB-9, AB-14, AB-15	Incomplete.

6.1.4.1 AT1: Subscale Testing

Objective:

The Air Braking System will conduct a test with two objectives during the Notre Dame Rocket Team sub-scale launch in preparation for Critical Design Review. The first objective is to verify that the flight trajectory is stable and apogee is reduced compared to a control flight when a coupler with drag tabs extended is attached to the rocket. For the full scale rocket, ABS must reduce the apogee by approximately 200 ft., so for the 40% sub-scale the tabs must reduce the apogee by approximately 80 ft. The second objective will be to verify successful data collection on a prototype of the avionics for the full scale Air Braking System. Additionally, data collected by an on board Inertial Measurement Unit (IMU) and gyroscope sensors will be used to assist the UAV payload team in selecting an orientation correction sensor.

Tested Items:

- Stable flight with sub-scale drag tab coupler attached.
- Impact of sub-scale drag tabs on flight apogee.
- Prototype avionics data acquisition.

Motivations:

- Validate feasibility of stable flight and apogee attenuation with drag tabs.
- Validate preliminary avionics prototype and gather data for algorithm and Kalman filter development.

Table 48: AT1 Success Criteria

Description	Criteria	Result
Rocket apogee shall be reduced by 80 ft. from the control apogee with the drag tab coupler as measured by on-board altimeters	Pass/Fail	Pass
Sensors shall successfully log data to SD card in computer-readable format	Pass/Fail	Pass
Recorded data shall be statistically similar to Recovery Subsystem measurements	Pass/Fail	Fail. Measured altitude follows similar trajectory but with a significant gap in measured apogees. Calibration needed to ensure equal altimeter readings for ABS and Recovery altimeters.
Adequate raw data shall be gathered to assist in constructing Kalman data filter parameters	Pass/Fail	Pass

Equipment:

- Subscale Rocket

- Removable 3D printed drag tab coupler
- Avionics System
    - Arduino MKR Zero
    - Bosch BNO055 Accelerometer
    - Freescale MPL3115A2
    - 3.3 V Li-Po Battery
    - Status LEDs
- Laptop for data verification

Setup:

Refer to the vehicle test plan for full subscale vehicle setup. The ABS subscale electronics bay is constructed from laser cut plywood. The avionics prototype board is constructed with soldered female header pins which allow for easy assembly and disassembly of the Arduino and sensors from the board. This board is attached then screwed to the vertical plywood deck of the electronics bay. On the opposite side of the deck, a 3.3V LiPo Battery is taped and zip tied to the deck and then connected to the Arduino. The aft bulkhead of the ABS subscale payload bay is then epoxied to the forward bulkhead of the recovery data acquisition payload bay for ease of assembly into the body tube. A picture of the assembly pre-flight is shown in Figure 106 below.

Figure 106: ABS Subscale Avionics

Safety Notes:

Flight safety procedures shall be followed at launch. Team members shall only interact with the payload bay with permission of the team safety officer and RSO. Li-Po batteries shall be transported in a fire-proof battery case and batteries shall be inspected for swelling, punctures, or leakage before handling.

Procedure:

Follow procedure outlined in the vehicle test plan for launch vehicle procedure. The 3.3 V battery will be plugged into the Arduino and the team shall confirm that the blue and green status LEDs light up to indicate successful data recording and save to the SD card. The ABS electronics bay shall then be loaded for the duration of the flight and then removed after each flight for data transfer from the SD card to a laptop. Prior to the second launch, a 3D printed coupler with a subscale drag tab assembly will be attached to the vehicle body.

Results:

Measured (unfiltered) flight apogees as recorded by the ABS avionics prototype and the recovery system avionics are shown in table 49 below. Pictures of the 3D printed tab coupler and avionics system post-launch are shown in Figures 107 and 108 and below. Note that due to issues with the parachute during the landing of the second flight, one of the drag tabs broke off of the coupler upon landing, as shown in figure 107 below.

Table 49: AT1 Subscale Apogee Results

Flight Number	ABS Recorded Apogee (ft.)	Recovery Recorded Apogee (ft.)
1	1065	1022
2	978	905

Figure 107: Subscale Drag Tab Coupler Upon Landing

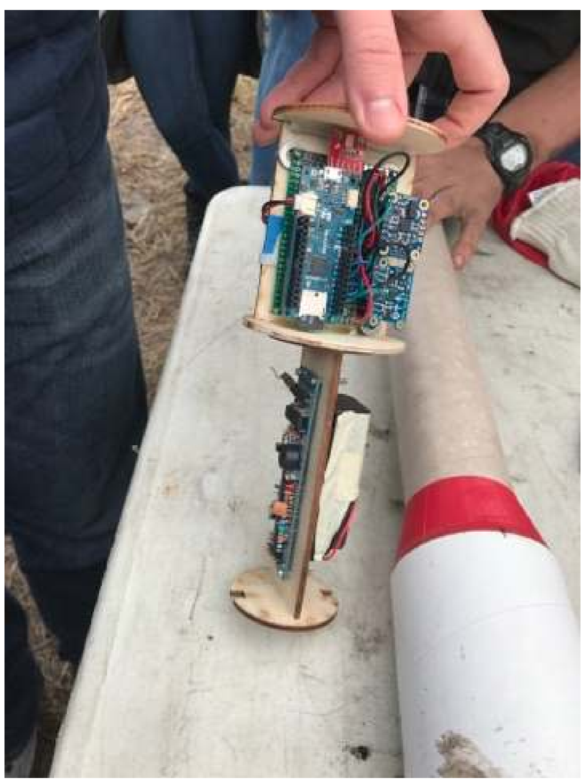


Figure 108: Subscale Avionics Payload Upon Landing

The drag tab coupler for the second subscale flight met the success criteria by experiencing a stable flight and reducing the apogee by 87 ft. according to the ABS avionics data, or by 117 ft. according to the recovery avionics data. The flight demonstrated an apogee reduction greater than the 80 ft. requirement suggesting the tabs still operated successfully. The success criteria was met to collect data for use in Kalman filter configuration.

The ABS flight data did not meet the success criteria of showing the data to be statistically close to the recovery data. The data for ABS and Recovery show a similar flight trajectory, but the first flight had a 43 ft. difference in the recorded apogees of the ABS and recovery altimeters, while the second flight had a difference of 73 ft. Based on the data and inspection of the vehicle, it was determined that the difference in the altimeter data resulted from not properly calibrating the altimeters to ensure matching readings. Additionally, the difference occurred partially due to an issue with the pressure-sealing bulkhead which may have led to an unpredicted pressure event during flight. To counter this problem in the full scale flight, calibration procedures will be prepared for the ABS sensors and the pressure sealing of the bulkheads will be inspected during construction.

There are two main takeaways from the subscale launch flight data for control code development. First, the subscale data is being used to devise more accurate flags to represent transitions into different flight stages. Our launch code correctly transitioned through all stages between ARMED and LANDED during flight, however the data we recovered suggests that we can make some adjustments to ensure further accuracy of the transitions, such as relying more heavily on Kalman-filtered altitude data to set transition flags.

Comparing altitude graphs in Figures 109 and 111 to acceleration graphs in Figures 110 and 112 makes it apparent that, even with the application of our Kalman filter, the former is subjected to far fewer data spikes and sensor noise. Further, adjustments will be made to ensure more accurate Kalman data filtering, as the graphs indicate a tendency to overshoot the actual measurement as indicated by the figures below and comparisons with the data gathered by the recovery avionics.

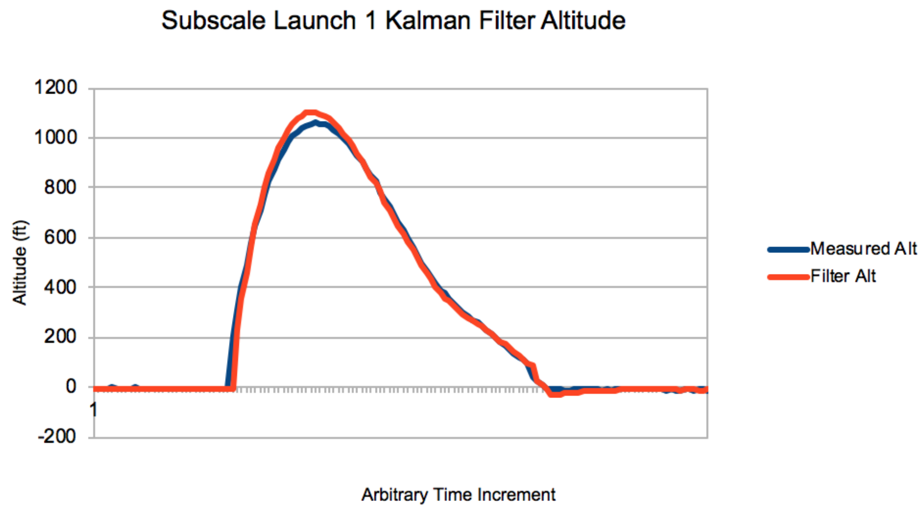


Figure 109: ABS Subscale 1 Altitude Data

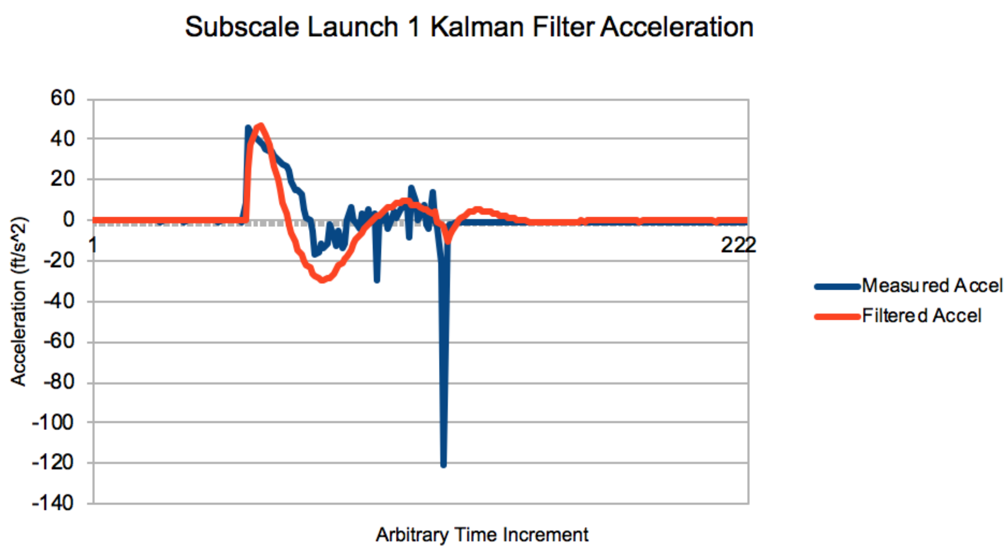


Figure 110: ABS Subscale 1 Acceleration Data

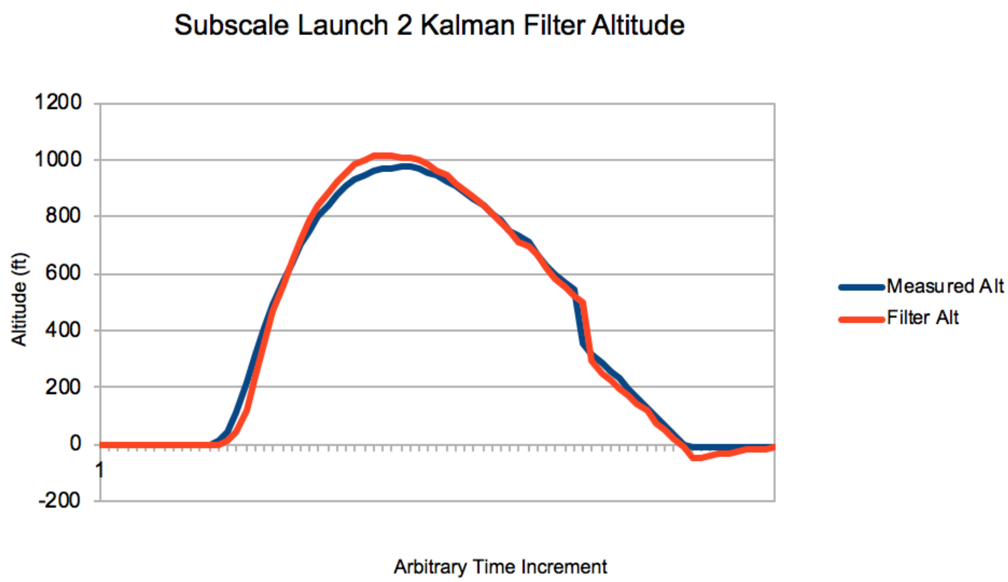


Figure 111: ABS Subscale 2 Altitude Data

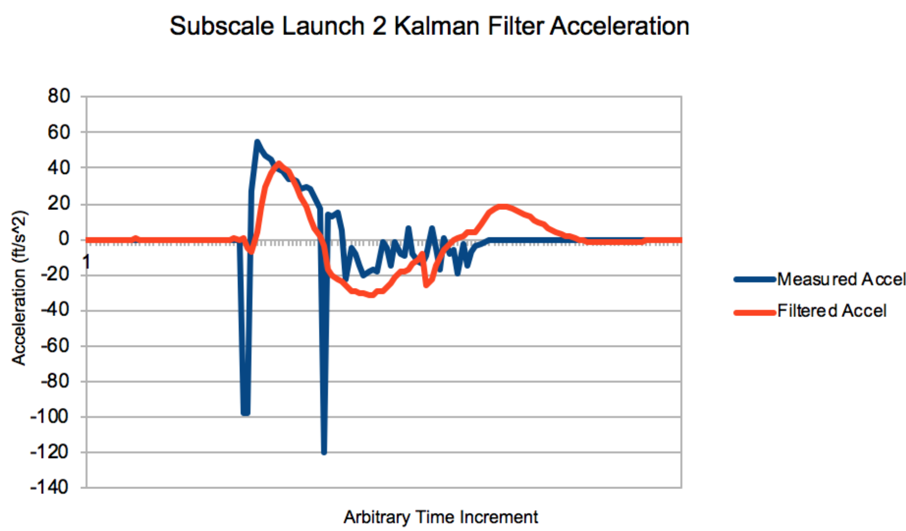


Figure 112: ABS Subscale 2 Acceleration Data

6.1.4.2 AT2: Electronics Ground Test

Objective:

Low-level performance tests shall be performed with the printed circuit board (PCB) and ancillary equipment before it is fully integrated into the rocket body. This test shall determine the proper connectivity of the board with attached components and base electronics performance characterization.

Tested Items:

- Verify electronic components function properly
- Test PCB connection security and continuity
- Verify battery runtime on idle

Motivations:

- Ensure avionics hardware performance
- Ensure avionics assembly integrity

Table 50: AT2 Success Criteria

Description	Criteria	Result
Printed circuit board shall provide solid electrical connection to all components	Pass/Fail	Incomplete
LED user interface shall illuminate under proper input when wired through printed circuit board	Pass/Fail	Incomplete
Motor shall operate as expected when wired through printed circuit board	Pass/Fail	Incomplete
Sensors shall log data as expected when wired through printed circuit board	Pass/Fail	Incomplete
Assembled ABS shall successfully remain powered in an idle state for a minimum of 3 hours	Pass/Fail	Incomplete

Equipment:

- Multimeter
- Soldering iron and solder
- Soldering smoke absorber
- Hitec D980TW Servo Motor
- Assembled Avionics PCB with associated components

Setup:

Solder all required components to PCB as illustrated in the board diagram. Attach motor and battery to appropriate Molex connectors on PCB. Fully assemble all avionics components. Ensure valid test code is loaded on microcontroller.

Safety Notes:

Safety precautions should be followed when handling the battery. The battery should be inspected for defects and placed in a fire proof case when not in use. Team personnel should exercise caution when operating the soldering iron and use the smoke absorbing fan to reduce the hazard of inhalation. Caution should be exerting when handling the servo motor when power is connected to avoid risk of pinching from unexpected rotation.

Procedure: Verify electrical continuity between PCB contacts with multimeter for all connections defined in board diagram file. Power on and arm system by toggling mechanical switches. Verify all status LEDs illuminated as expected under test code logic. Verify motor turns when induced by test code. Assemble the system with the motor connected and power turned on and leave the system running on idle. Verify that the system does not power off for a minimum of 3 hours.

Results:

This test has not yet been completed. This test will be completed prior to test flights and results will be included in FRR documentation.

6.1.4.3 AT3: Mechanical Ground Test

Objective:

The objective of this test is to assess the successful operation and robustness of the Air Braking System mechanical system.

Tested Items:

- Successful control of servo motor actuation with fully assembled mechanical system using avionics control connections
- Verify ABS mechanical system actuation and associated metrics

Motivations:

- To ensure a safe and stable flight by ensuring symmetrical tab extension and proper actuation
- To Verify ABS mechanism capabilities and address possible improvements

Table 51: AT3 Success Criteria

Description	Criteria	Result
ABS drag tabs must deploy symmetrically from the enclosure	Pass/Fail	Incomplete
Mechanism shall be capable of continuous full extension and retraction without jamming or damage to the mechanism	Pass/Fail	Incomplete
Drag tabs shall be capable of full extension in under 0.5 seconds	Pass/Fail	Incomplete
Shaft Potentiometer successfully transmits positional data	Pass/Fail	Incomplete

Equipment:

- Assembled ABS Mechanical System and Mounting
- Hitec D980TW Servo Motor
- Arduino MKR Zero
- Assembled Avionics for full test
- 7.4 V Battery
- Laptop

Setup:

Fully assemble the ABS mechanical system and connect the servo motor to the associated pins of the Arduino. Connect the 7.4 V battery to the servo motor and connect power to the Arduino through a 5V regulator from the 7.4 V battery.

Safety Notes:

Team members shall inspect batteries for defects before handling and store batteries in a fireproof bag when not in use. Team members shall take care to not put fingers near the mechanism when power is connected to avoid potential injury of pinching if the mechanism were to actuate.

Procedure:

Verify the servo motor is properly calibrated and drag tabs successfully deploy symmetrically upon command from the Arduino programmed via the laptop. Test that the tabs successfully deploy in under 0.5 seconds. Upload a program to the Arduino to run the servo motor through ten consecutive cycles to check for jamming. Verify that shaft potentiometer properly transmits positional data.

Results:

This test has not yet been completed. This test will be completed prior to test flights and results will be included in FRR documentation.

6.1.4.4 AT4: Software Ground Test

Objective:

These tests shall be used to validate that the ABS control code responds correctly to simulated flight data in terms of filtering the data and setting control outputs appropriately. A test will be done to run a simulated flight with the mechanical system connected to verify proper tab actuation and certify sufficient functionality to be considered mission ready.

Tested Items:

- Code robustness and functionality
- Kalman filter performance and trust matrix
- Drag tab extension values (PID Controller)

Motivations:

- Validate successful ABS control code design and operation for mission success
- Evaluate possible improvements, specifically in the Kalman filter trust matrix

Table 52: AT4 Success Criteria

Description	Criteria	Result
Kalman filter must be effective in smoothing out data spikes from previous flight data.	Altitude vs time and acceleration vs time graphs will be plotted with raw data and Kalman filter data to visually confirm that the filter is effective.	Incomplete
Kalman trust matrix must be optimized to best filter data.	The final values for the trust matrix must most accurately represent the perceived real-world state values given sensor data.	Incomplete
PID controller must output correct values for drag tab extension when testing with data from a previous flight and recording extensions to the SD card for later analysis.	Tab extensions produced by the simulation must match values for tab extensions produced by human computation at a sufficient number of test points in the range of data.	Incomplete
With an assembled mechanical system, actuation under a simulated flight must match expected performance. A simulated detected jam must result in tab retraction.	Pass/Fail	Incomplete

Equipment:

- Arduino MKR Zero
- USB 2.0 cable
- SD card
- Laptop
- Assembled mechanical system
- 7.4 V Battery

Setup:

Ensure a proper connection between the Arduino and the test computer through the USB cable, as well as a proper connection between the Arduino and the SD card. Assemble ABS mechanical system when running the physical simulation flight.

Safety Notes:

Follow safety procedures for handling batteries and avoiding contact with the mechanical system while power is connected to avoid pinching.

Procedure:

Utilize the Kalman Filter simulation (in Excel) to produce relevant acceleration and altitude graphs from last year's full scale launch data. Repeat process with the data from both subscale test launches. Next utilize a modified version of the control code that takes previous flight data from the SD card as sensor data input. Upload this code to the Arduino and run it with each of the three previously mentioned data sets. Independently calculate the drag tab extensions at random test points during the flight interval and compare these to the control code (and PID controller) determined extension values which were outputted to the SD card.

Connect the ABS mechanical system. Run a simulated flight test with previous flight data and observe mechanical system actuation. Note any issues and verify operation under specific scenarios such as a detected jam.

Results:

This test has not yet been completed. This test will be completed prior to test flights and results will be included in FRR documentation.

6.1.4.5 AT5: Flight Tests

Objective:

This test shall be used to validate successful ABS integration and payload design performance to verify mission readiness.

Tested Items:

- Data acquisition
- Flight state and control algorithm operation success
- Mechanical system actuation and impact on mission performance (full braking power and apogee control precision)

Motivations:

- Validate successful ABS design and operation for mission success
- To assess practical system limitations and evaluate possible improvements

Table 53: AT5 Success Criteria

Description	Criteria	Result
The ABS electronics deck must be sealed from the lower sections of the design to prevent unpredictable pressure changes for the altimeter data.	Pass/Fail	Incomplete
ABS electronics must remain powered on, collecting data, and properly armed or disarmed depending on the flight number when installed in the vehicle.	Pre-flight checklists will be prepared and followed at the launch. Status LEDs will indicate proper data collection and arming of the software. Pass/Fail	Incomplete
The ABS drag tabs do not extend until motor burnout.	Ground Inspection shows no extension on launch pad. Data confirms no tab extension until motor burnout. Pass/Fail	Incomplete
All ABS components are shown to be capable of withstanding flight and landing forces in order to be used in future flights.	Pass/Fail	Incomplete
The ABS is able to log raw sensor data and flight state algorithm data for post-mission analysis.	Pass/Fail	Incomplete
The ABS must reduce the apogee of the rocket by at least 200 ft. during the second flight which shall test the full braking power of the ABS.	Pass/Fail	Incomplete
The ABS must slow the vehicle to a final apogee within 25 ft. of the 4,700 ft. target during the third test flight.	Pass/Fail	Incomplete.

Equipment:

Assembled Vehicle and associated payloads including ABS.

Setup: Refer to vehicle test plans for vehicle assembly.

- Observe all components are connected to PCB and battery is charged
- Inspect all sections of the Air Braking System for damage and defects that would impact mission performance
- Ensure the proper control code is uploaded to the Arduino MKR Zero. **Ensure that**

SD card is inserted in Arduino prior to powering on

- Flip control switches to power the system. Flip the arming switch for the appropriate flight number (off for control flight 1, on for actuation flights 2 and 3).
- Verify status LEDs report system is ready for launch
- Follow vehicle safety procedures to load Air Braking System into vehicle fin can. Sign off procedure checklists with ABS, Vehicles, and Safety leads.
- Verify drag tabs do not extend prematurely on launch pad

Safety Notes:

All flight test safety procedures shall be followed at the direction of the Safety officer and RSO. Care shall be taken when handling batteries and powered electronics. Team personnel shall only handle the vehicle with authorization from the Safety officer and RSO.

Procedure:

Vehicle test flight procedures shall be followed for launch. The first flight shall serve as a control flight, with an inactive ABS mechanical system that is collecting data. The second flight shall serve as a test of the full braking power of the ABS by fully extending the tabs at motor burnout and retracting at apogee. The third flight shall serve as a test of the precision of the control algorithm in achieving the target apogee of 4,700 ft. The ABS data will be analyzed post launch to assess mission performance and necessary changes or further flight testing. Data will be used to verify flight models and coefficient of drag with the tabs actuating.

- Follow post-launch procedures to safely recover rocket after landing with safety officer approval
- Extract system from rocket body
- Inspect the mechanical system and full payload bay for damage
- Verify electrical system connections are not damaged and could be reused in another flight
- Remove the SD card and insert SD card into computer to read flight data
- Verify valid flight data from all sensors is stored on SD card
- Record maximum altitude recorded by altimeter sensor
- Verify altimeter data confirms the rocket reached apogee near target

Results:

This test has not yet been completed. This test is scheduled to be completed in February and results will be included in FRR documentation.

6.1.5 UAV Payload Testing

The Unmanned Aerial Vehicle Experiment is a challenge unique to the 2019 NASA Student Launch Competition. Thus, the payload will need to undergo extensive testing to help ensure flight readiness and success in April. The UAV payload will be tested in multiple phases, as outlined in Table 54.

Table 54: UAV Payload Test Plan

Test Name	Test ID	Description	Requirements Tested	Status
Subscale Testing	UAV1	Test gyroscopic data of the L3G and compare to that of the BNO	PL4.4.1.-1	Complete
Deployable Drone Electronics Testing	UAV2	Mount electronics, including the Beacon Delivery Subsystem, on Iteration II drone frame for indoor test flight.	PL4.4.2.-1, PL4.4.9.-1, PL4.4.10-1	Incomplete
Software Ground Testing	UAV3	Run FEA detection code on purchased 10 foot by 10 foot yellow tarp under a wide variety of weather conditions for robust target detection. Run autonomous flight code using multiple GPS coordinates. See if the drone finds and flies to the closest set of coordinates.	PL4.4.5-1, PL4.4.6.-1, PL4.4.7.-1	Incomplete.
Deployment Subsystem Ground Testing	UAV4	Test both the electrical and mechanical capabilities of the Deployment Subsystem (Locking Mechanism, Orientation Correction Mechanism, and Linear Transport Mechanism) before the subsystem flies at the first full-scale test launch. Ensure that the drone will be able to successfully exit the rocket in the correct orientation.	PL4.4.3.-1	Incomplete

6.1.5.1 UAV1: Subscale Testing

Objective: This test was used to help the team determine a sensor for the orientation correction stage of deployment.

Tested Item:

- L3GD20H Triple-Axis Gyro Breakout Board versus the Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout BNO055 for the Orientation Correction Mechanism sensor.

Motivation:

- Choose the sensor that will present the most accurate orientation data to help ensure the successful takeoff of the UAV post-recovery at competition.

Table 55: UAV1 Success Criteria

Description	Criteria	Result
Gyroscopic data from both sensors shall successfully log data for comparison.	Pass/Fail	Pass

Equipment:

- Sub-scale launch vehicle
- Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout BNO055
- Arduino MKR Zero
- Freescale MPL3115A2
- 3.3 V LiPo Battery
- Status LEDs
- L3GD20H Triple-Axis Gyro Breakout Board
- Laptop

Setup: Refer to the ABS test plan for the full electronic setup for the sub-scale launch.

Safety Notes: Flight safety procedures shall be followed at launch. Team members shall only interact with the payload bay with permission of the team safety officer and RSO. LiPo batteries shall be transported in a fire-proof battery case and batteries shall be inspected for swelling, punctures, or leakage before handling.

Procedure: Refer to the ABS procedure for the electronic procedure for the sub-scale launch.

Result: Based on the results of the sub-scale launch and the collaboration with members of the ABS team, the UAV team decided to use the Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout BNO055 as the Orientation Correction Mechanism sensor. The sensor has both an accelerometer and a gyroscope, which would give both the direction of the ground and the orientation as the system is spinning, respectively.

6.1.5.2 UAV2: Deployable Drone Electronics Testing

Objective: Identify how the drone flies with the weight of the mounted electronics and the Beacon Delivery Subsystem. The second 3D ASA print, Iteration II, will be used for the frame for this indoor test flight. The belt and pulley system arm unfolding mechanism with torsion spring compression will also be tested at this time.

Tested Items:

- Verify that the four drone motors and props can produce the thrust needed for liftoff.

- Ensure that the LiPo battery fits well between the plates of the drone so that it will not be crushed or punctured during flight.
- Test the ability of the belt and pulley system and the torsion spring compression to unfold the arms together.

Motivation:

- Make sure that all components that affect the flight of the UAV itself are in working order before adding the variable of deployment from the launch vehicle.

Table 56: UAV2 Success Criteria

Description	Criteria	Result
Drone motors and props produce the thrust needed for liftoff.	Pass/Fail	Incomplete
Belt and pulley system synchronizes arm movement.	Pass/Fail	Incomplete

Equipment:

- Pixhawk 4
- Raspberry Pi 3 Model B
- 4 props
- 4 ESCs
- Adapter rings
- 4 T-Motors
- Turnigy 4500mAh LiPo
- Zip ties
- Velcro straps
- 433 MHz Telemetry
- 915 MHz Telemetry
- Raspberry Pi Camera V2
- FEETECH FS90R Servo
- ASA Beacon Delivery Subsystem
- MT60 Connectors
- XT60 Bullet Connectors
- XT90 Connectors
- 4 torsion springs
- 1 belt
- 4 pulleys
- Drone frame with struts, arms, and supports
- FrSky Taranis X9D Plus 2.4 GHz ACCST Radio

Setup: Place all UAV electronics on the top plate except for the LiPo battery, which is placed between the top and bottom plates of the UAV. The Beacon Delivery Subsystem is placed underneath the UAV frame.

Safety Notes: Team members shall only interact with the payload bay with permission of the team safety officer and RSO. LiPo batteries shall be transported in a fire-proof battery case and batteries shall be inspected for swelling, punctures, or leakage before handling. Ensure that everyone in the room is aware of the flight test to avoid any accidents, and make sure that the UAV team mentor is present.

Procedure: Once the electronics and the Beacon Delivery Subsystem are mounted on the UAV frame, use the Taranis Radio for manual flight control. Test flight in a cleared, large room.

Result: This test has not yet been completed. This test will be completed prior to test flights and results will be included in FRR documentation.

6.1.5.3 UAV3: Software Ground Testing

Objective: The team has been testing the UAV software for autonomous flight and for FEA detection since November with a 3DR IRIS+ Quadcopter. The next step is to test the autonomous flight and FEA detection software with the team's custom-made drone.

Tested Items:

- Run a test of the autonomous flight and FEA detection software using the Iteration II drone frame with mounted electronics.

Motivation:

- Verify that the drone design produces flight stable enough to obtain accurate data about the FEA.
- Ensure that the software used while flying 3DR IRIS+ Quadcopter works just as well on the custom-made drone.

Table 57: UAV3 Success Criteria

Description	Criteria	Result
The flight of the Iteration II drone was stable, and it found the closest FEA via inputted GPS coordinates. The flight obtained additional imagery of the team's practice FEA.	Pass/Fail	Incomplete

Equipment:

- Pixhawk 4

- 2 Raspberry Pi 3 Model Bs
- 4 props
- 4 ESCs
- Adapter rings
- 4 T-Motors
- Turnigy 4500mAh LiPo
- Zip ties
- Velcro straps
- 433 MHz Telemetry
- 915 MHz Telemetry
- Raspberry Pi Camera V2
- FEETECH FS90R Servo
- ASA Beacon Delivery Subsystem
- MT60 Connectors
- XT60 Bullet Connectors
- XT90 Connectors
- 4 torsion springs
- 1 belt
- 4 pulleys
- Drone frame with struts, arms, and supports
- FrSky Taranis X9D Plus 2.4 GHz ACCST Radio
- Laptop
- 2 practice FEAs

Setup: Place all UAV electronics on the top plate except for the LiPo battery, which is placed between the top and bottom plates of the UAV. The Beacon Delivery Subsystem is placed underneath the UAV frame. Obtain the GPS coordinates of two practice FEAs. Start recording and saving video data before liftoff.

Safety Notes: Team members shall only interact with the payload bay with permission of the team safety officer and RSO. LiPo batteries shall be transported in a fire-proof battery case and batteries shall be inspected for swelling, punctures, or leakage before handling. Ensure that everyone in the room is aware of the flight test to avoid any accidents, and make sure that the UAV team mentor is present.

Procedure: After liftoff, watch that the drone finds the closest FEA and flies to it. Monitor the live video feed on the laptop while the drone hovers over the FEA.

Result: This test has not yet been completed. This test will be completed prior to test flights and results will be included in FRR documentation.

6.1.5.4 UAV4: Deployment Subsystem Ground Testing

Objective: Identify how the Deployment Subsystem performs mechanically and electronically on its own before the first full-scale test flight.

Tested Items:

- (1) Verify that the Locking Mechanism keeps the UAV secured despite the orientation of the payload bay or the forces it experiences (ie: Perform a shake test).
- (2) Verify that the Orientation Correction Mechanism can properly orient the UAV into a flight ready, upright position (ie: Rotate the payload bay in various orientations and see how the mechanism corrects itself).
- (3) Verify that the Linear Transport Mechanism can push the UAV completely out of the launch vehicle (ie: Ensure that the UAV has clearance for flight after the deployment sequence ends).

Motivation:

- The Deployment Subsystem needs to work in order to fulfill the requirements presented for the Unmanned Aerial Vehicle experiment. All three components, the Locking Mechanism, the Orientation Correction Mechanism, and the Linear Transport Mechanism, need to be successful in order to complete the UAV mission specified in the NASA Student Launch Handbook.

Table 58: UAV4 Success Criteria

Description	Criteria	Result
Fulfill Tested Item (1).	Pass/Fail	Incomplete
Fulfill Tested Item (2).	Pass/Fail	Incomplete
Fulfill Tested Item (3).	Pass/Fail	Incomplete

Equipment:

- Pixhawk 4
- 2 Raspberry Pi 3 Model Bs
- 4 props
- 4 ESCs
- Adapter rings
- 4 T-Motors
- Turnigy 4500mAh LiPo
- Zip ties
- Velcro straps
- 433 MHz Telemetry
- 915 MHz Telemetry
- Raspberry Pi Camera V2
- 2 carbon fiber dowel rods
- Nylon leadscrew
- FEETECH FS90R Servo
- 2 MDS-filled cast nylon bulkheads
- Hex nut for fore bulkhead
- 2 sets of MDS-filled cast nylon tracks

- Nema 14 stepper motor
- FS5106R servo motor
- Turnigy 2200mAh LiPo
- BNO055 sensor
- Arduino UNO (board model: UNO R3)
- BJT transistors
- ASA Beacon Delivery Subsystem
- MT60 Connectors
- XT60 Bullet Connectors
- XT90 Connectors
- 4 torsion springs
- 1 belt
- 4 pulleys
- Drone frame with struts, arms, and supports
- FrSky Taranis X9D Plus 2.4 GHz ACCST Radio
- 433 MHz RF transmitter and receiver kit
- Laptop

Setup: Place all UAV electronics on the top plate except for the LiPo battery, which is placed between the top and bottom plates of the UAV. The Beacon Delivery Subsystem is placed underneath the UAV frame. Fold UAV and place so that it may be placed inside the payload bay.

Safety Notes: Team members shall only interact with the payload bay with permission of the team safety officer and RSO. LiPo batteries shall be transported in a fire-proof battery case and batteries shall be inspected for swelling, punctures, or leakage before handling. Ensure that everyone in the room is aware of the flight test to avoid any accidents, and make sure that the UAV team mentor is present.

Procedure:

- Ensure that the aft rotating bulkhead and track mechanism is locked in place via the FS5106R servo.
- Ensure that the belt and pulley system is in working order via a short test to check that the movement of one arm is synchronized with the movement of the remaining three arms of the UAV.
- Fold the arms of the UAV into the proper position, ensuring that the torsion springs are in place and in compression.
- Check that all electronics are mounted properly and safely to the top plate of the UAV.
- Check that the 4500mAh LiPo is properly and safely secured between the two plates of the UAV.
- Tie the polyethylene fiber wire to the four eyebolts mounted on the aft rotating bulkhead, and tie the other end of the wire to four stainless steel cotter pins.
- Secure each of the four aluminum struts of the UAV into each of four 3D-printed custom pipe flanges mounted on the UAV platform for deployment.
- Insert the four stainless steel cotter pins through the flanges and the struts to ensure

that the UAV will be properly restrained during flight.

- Complete a brief shake test to ensure that the pins were inserted correctly so that the UAV will not move during flight.
- Trigger the main deployment sequence with the 433 MHz RF transmitter and receiver kit.
- Ensure that the system orients and then linearly deploys.
- Ensure that the UAV is oriented in the upright position and that the UAV, when unfolded, has enough clearance for flight.

Result: This test has not yet been completed. This test will be completed prior to test flights and results will be included in FRR documentation.

6.2 Requirements and Verifications

The requirements for the project are broken into NASA provided requirements for the system and the team derived requirements that further guide the design process. The NASA requirements are listed in the order that they appear in the SL Handbook and include the Verification Method and Plan the team has deemed sufficient for meeting the requirement.

6.2.1 NASA Requirements

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.1	Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor).		X			The team shall conduct periodic internal assessments to ensure all work is being done solely by team members and that faculty advisors and mentors are involved in an advising capacity, with the exception of energetics handling.		X	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.2	The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations.		X			The NDRT shall hold weekly meetings to address project milestones and assign tasks. The team shall include all project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigaitons in the milestone review reports.	X		
1.3	Foreign National (FN) team members must be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's may be separated from their team during certain activities.		X			The Notre Dame Rocketry Team shall survey team members regarding foreign citizenship and pass along contact information to the SL Management Team.	X		
1.4	The team must identify all team members attending launch week activities by the Critical Design Review (CDR). Team members will include: 1.4.1. Students actively engaged in the project throughout the entire year. 1.4.2. One mentor (see requirement 1.13).		X			The team shall submit all members attending launch week to the NASA SL Management Team no later than January 2nd, 2019.		X	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
	1.4.3. No more than two adult educators.								
1.5	The team will engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event. A sample of the STEM Engagement Activity Report can be found on page 33 of the handbook.		X			The team shall conduct STEM engagement activities between Oct. 5th, 2018 through Mar. 3rd, 2019 and submit the STEM Engagement Activity Report to the NASA SL Management Team within 10 days of the event. The team shall track the number of students engaged in activities and team members in participation.		X	
1.6	The team will establish a social media presence to inform the public about team activities.		X			The team shall create a Facebook page, Instagram, and Twitter account to promote team activities at the University and in the South Bend community.	X		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.7	Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient.		X			All upcoming deliverable deadlines shall be addressed at weekly meetings. Team officers shall review the document size of each deliverable and verify they are less than 10 mb.		X	
1.8	All deliverables must be in PDF format.		X			Team shall export all documents to a PDF format before officer submits them to the SL Management Team.		X	
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.		X			The team shall create an outline of the sections of each report prior to writing the main text. This outline shall be built into a table of contents.		X	
1.1	In every report, the team will include the page number at the bottom of the page.		X			The team shall write reports in a LaTeX format that auomatically updates the page number.	X		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.		X			The team shall rent a webcam and teleconference phone from the College of Engineering Dean's office 1 week prior to all teleconferences with NASA. This equipment shall be tested with an officer's laptop to be in working order prior to the day of the call.	X		
1.12	All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. Eight foot 1010 rails and 12 foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on launch day. The exact cant will depend on launch day wind conditions.		X			The team shall use either eight foot 1010 rails and 12 foot 1515 rails during all full scale test launches.		x	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.13	Each team must identify a "mentor." A mentor is defined as an adult who will be supporting the team throughout the project year. The mentor must maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to launch week.		X			The team shall identify the "mentor" in Section 1.1 (Team Summary) of the PDR report. This section shall include the NAR/TAR section the mentor belongs to as well as the mentor's contact information.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.1	The vehicle will deliver the payload to an apogee altitude between 4,000 and 5,500 feet above ground level (AGL). Teams flying below 3,500 feet or above 6,000 feet on Launch Day will be disqualified and receive zero altitude points towards their overall project score.				X	The launch vehicle apogee shall be recorded by the recovery system altimeters and used to verify the altitude achieved by the rocket.			x

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.2	Teams shall identify their target altitude goal at the PDR milestone. The declared target altitude will be used to determine the team's altitude score during Launch Week.		X			The vehicle shall be designed to reach a target altitude of 4,700 ft. This altitude shall be identified in the PDR report.	x		
2.3	The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner. The Altitude Award will be given to the team with the smallest difference between their measured apogee and their official target altitude on launch day		X			The altimeter used in the recovery subsystem for recording official apogee will be purchased from an outside vendor.	X		
2.4	Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.		X			The altimeters shall be integrated into the vehicle and a hole shall be made in the vehicle body such that the altimeter switches are accessible.			X
2.5	Each altimeter will have a dedicated power supply.		X			Each altimeter shall be wired to a single battery and each battery shall be wired to a single altimeter.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.6	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).			X		The team shall incorporate simulating maximum flight forces on the full scale avionics assembly into the recovery test plan. The test shall demonstrate that the switches remain locked.		X	
2.7	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.			X		The reusability of the vehicle shall be demonstrated during test flights.		X	
2.8	The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.		X			The vehicle shall have two (2) independant sections.	X		
2.8.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.		X			The vehicle shall have a single separation point running through a coupler extending into a body tube. The length of the coupler shall extend no less than 1 body diameter.		X	
2.8.2	Nosecone shoulders which are located at in-flight separation points will be at least $\frac{1}{2}$ body diameter in length.		X			The launch vehicle shall have no in-flight separation points at the nosecone.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.9	The launch vehicle will be limited to a single stage		X			The vehicle shall be designed to use a single solid rocket motor	X		
2.1	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.			X		Vehicle preparation shall be rehersed and timed at test launches.			X
2.11	The launch vehicle will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components.	X				All electrical power components shall be analyzed and sized to operate under this condition. The anaysis shall consist of determining the voltage and current requirements each component to size the power supply.	X		
2.12	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider.				X	The vehicle shall utilize an ignition system designed for a 12V DC launch system.	X		
2.13	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).		X			The launch vehicle shall be designed to use standard launch services equipment. The vehicle design lead shall inspect all support equipment needed and verify it is within what is normally provided.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.14	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).		X			The motor shall be ordered from a verified vendor and utilize ammonium perchlorate composite propellant.	X		
2.14.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.		X			The final motor choice shall be listed in the Technical Design of the Launch Vehicle in the CDR milestone report.	X		
2.14.2	Any motor change after CDR must be approved by the NASA Range Safety Officer (RSO) and will only be approved if the change is for the sole purpose of increasing the safety margin. A penalty against the team's overall score will be incurred when a motor change is made after the CDR milestone, regardless of the reason.		X			The team shall use the motor choice given at the CDR milestone for all test flights and at competition			X
2.15	Pressure vessels on the vehicle will be approved by the RSO and will meet the following criteria:		X			The vehicle shall contain no pressure vessles.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.15.1	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.		X			The vehicle shall contain no pressure vessles.	X		
2.15.2	Each pressure vessel will include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank.		X			The vehicle shall contain no pressure vessles.	X		
2.15.3	Full pedigree of the tank will be described, including the application for which the tank was designed, and the history of the tank, including the number of pressure cycles put on the tank, by whom, and when.		X			The vehicle shall contain no pressure vessles.	X		
2.16	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).		X			No order shall be placed for any motor higher than an L-class.	X		
2.17	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	X				OpenRocket simulations shall be used to compute the stability margin throughout flight. This analysis shall verify the rocket achieves a margin of 2 at the point the first rail button clears the rail.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.18	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit	X				OpenRocket simulations of the vehicle's flight shall determine that the vehicle's off-rail velocity is at least 52 fps.		X	
2.19	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. Subscales are not required to be high power rockets.		X			The subscale flight shall be completed by the second week of December on one of two potential launch days partnering with Miciana Rocketry.		X	
2.19.1	The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.	X			X	OpenRocket simulations of the subscale shall confirm that it performs as similarly as possible to the full-scale vehicle. Data from the subscale flight shall be compared to simulations to evaluate accuracy of simulations.		X	
2.19.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.		X			An altimeter capable of recording the model's apogee altitude shall be selected for use in the subscale vehicle.		X	
2.19.3	The subscale rocket must be a newly constructed rocket, designed and built specifically for this year's project.		X			The team shall source all new components for the subscale. The rocket shall be a scale model of the competition vehicle.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.19.4	Proof of a successful flight shall be supplied in the CDR report. Altimeter data output may be used to meet this requirement.		X			The subscale vehicle shall record data with a single altimeter of the same make and model to be used in the competition vehicle.		X	
2.2	All teams will complete demonstration flights as outlined below.		X			Requirements 2.20.1 and 2.20.2 shall be verified.			X
2.20.1	Vehicle Demonstration Flight - All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown must be the same rocket to be flown on launch day. The following criteria must be met during the full-scale demonstration flight:		X			Requirements 2.20.1.1 through 2.20.1.9 shall be verified.			x
2.20.1.1	The vehicle and recovery system will have functioned as designed.		X			The vehicle and recovery system operation during demonstration flight shall be identified to meet all other system requirements.			X
2.20.1.2	The full-scale rocket must be a newly constructed rocket, designed and built specifically for this year's project.		X			The full-scale rocket shall be fully designed and built for this year's project.			X
2.20.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. The following requirements still apply:		X			Requirements 2.20.1.3.1 and 2.20.1.3.2 shall be verified.			X

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.1.3.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.		X			Ballast masses of the UAV payload shall be brought to launch day and secured in the body to simulate the payload.			X
2.20.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.		X			The payload CG and location in the rocket shall be used to locate the CG of the ballast.			X
2.20.1.4	If the payload changes the external surfaces of the rocket (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.		X			The camera mounts and Air Braking drag tabs shall be present and active on all demonstration flights.		X	
2.20.1.5	Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The RSO may approve use of an alternative motor if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances.		X			The motor selected for use in the demonstration/test flight will be the same motor used on the competition launch day.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.1.6	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the same amount of ballast that will be flown during the launch day flight. Additional ballast may not be added without a re-flight of the fullscale launch vehicle.		X			All ballast shall be calculated based on OpenRocket simulations and inspected to be present for all test flights.		X	
2.20.1.7	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO).		X			The final full-scale demonstration flight shall be prior to the FRR milestone. Any additional changes deemed necessary shall be identified and communicated to the NASA RSO for confirmation.		X	
2.20.1.8	Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement.		X			Altimeter data shall be included in the FRR report.			X
2.20.1.9	Vehicle Demonstration flights must be completed by the FRR submission deadline. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted. Teams completing a required re-flight must submit an FRR Addendum by the FRR Addendum deadline.		X			A demonstration flight will be performed before March 4th. Should a re-flight be needed, an addendum will be submitted by the date given by the Student Launch office.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.2	Payload Demonstration Flight - All teams will successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline. The following criteria must be met during the Payload Demonstration Flight:		X			Requirements 2.20.2.1 through 2.20.2.4 shall be verified.			X
2.20.2.1	The payload must be fully retained throughout the entirety of the flight, all retention mechanisms must function as designed, and the retention mechanism must not sustain damage requiring repair			X		The functionallity of the active retention system shall be confirmed to operate nominally. Post launch analysis shall be performed to assess the possibility of damage prior to a second test flight.			X
2.20.2.2	The payload flown must be the final, active version.		X			The UAV shall be fully constructed and been through all ground testing prior to the first demonstration flight.			X
2.20.2.3	If the above criteria is met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required.		X			No addendum will be written if all above criteria are met.			X

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.2.4	Payload Demonstration Flights must be completed by the FRR Addendum deadline. No extensions will be granted.		X			All payload demonstration flights shall be completed prior to March 25th, 2019.			X
2.21	An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASArequired Vehicle Demonstration Re-flight after the submission of the FRR Report.		X			The FRR addendum shall be submitted in the event that the demonstration flight scheduled in Feb. warrants addtional testing past the FRR milestone.			X
2.21.1	2.21.1. Teams required to complete a Vehicle Demonstration Re-Flight and failing to submit the FRR Addendum by the deadline will not be permitted to fly the vehicle at launch week.		X			All documents shall be submitted prior to the milestone deadline.			X
2.21.2	Teams who successfully complete a Vehicle Demonstration Flight but fail to qualify the payload by satisfactorily completing the Payload Demonstration Flight requirement will not be permitted to fly the payload at launch week		X			The team shall meet all requirements for Payload Demonstration Flight. Payload qualification shall be identified through ground testing and full scale flight.			X
2.21.3	Teams who complete a Payload Demonstration Flight which is not fully successful may petition the NASA RSO for permission to fly the payload at launch week. Permission will not be granted if the RSO or the Review Panel have any safety concerns.		X			A post launch assessment shall determine if the payload demonstration flight met all mission success criteria. If a not fully successful mission is identified, the petition shall be submitted.			X

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.22	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	X				The Air Braking System shall be located aft of the burnout center of gravity.		X	
2.23	The team's name and launch day contact information shall be in or on the rocket airframe as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle.		X			The team shall paint the team name and contact information on the launch vehicle.			X
2.24	Vehicle Prohibitions		X			Requirements 2.24.1 through 2.24.10 shall be verified.			X
2.24.1	The launch vehicle will not utilize forward canards. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the rocket's stability.	X	X			The vehicle design shall include no control surfaces and only fixed fins on the aft section of the vehicle. Camera housing shall be analyzed using CFD methods to prove minimal aerodynamic effects.		X	
2.24.2	The launch vehicle will not utilize forward firing motors.		X			The vehicle shall utitlize a single aft firing motor to generate thrust.	X		
2.24.3	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)		X			The motors under consideration shall be free of metal expelling sponges.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.24.4	The launch vehicle will not utilize hybrid motors.		X			The launch vehicle motor shall be a commercially available solid rocket motor.	x		
2.24.5	The launch vehicle will not utilize a cluster of motors.		X			The launch vehicle shall use a single motor.	X		
2.24.6	The launch vehicle will not utilize friction fitting for motors.		X			The launch vehicle shall use a commercially available active motor retention system.	X		
2.24.7	The launch vehicle will not exceed Mach 1 at any point during flight.	X				OpenRocket and RockSim models shall verify that the launch vehicle does not exceed Mach 1 at any point during flight.	X		
2.24.8	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad (i.e. a rocket with and unballasted weight of 40 lbs. on the pad may contain a maximum of 4 lbs. of ballast).	X	X			OpenRocket and CAD models shall verify the total unballasted weight of the launch vehicle. Ballasted flight shall consist of total ballast weight no more than 10% of the calculated weight.	X		
2.24.9	Transmissions from onboard transmitters will not exceed 250 mW of power	X				On board transmitters for GPS location tracking shall be chosen with a power rating ¡250 mW.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.24.10	Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses.	X				The launch vehicle shall utilize light weight metal solely where composite materials are unable to support stresses during flight.		X	

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.1	The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue-stage descent is reasonable, as deemed by the RSO.			x		A single parachute shall be deployed at apogee, acting as a streamer recovery by being held in a packed configuration by a chute released until 500ft AGL.			x
3.1.1	The main parachute shall be deployed no lower than 500 feet.				x	A test launch shall verify that the chute release deploys from the main parachute at an altitude no lower than 500 ft AGL.			x

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.1.2	The apogee event may contain a delay of no more than 2 seconds				x	Test launch data shall indicate that mecahnism deployment occurs no later than 2 seconds after apogee has been detected by the primary alitimeter.			x
3.2	Each team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full-scale launches.			x		Ground testing shall include fully packing the parachute prior to manually triggering deployment. This test shall demonstrate the system is capable of fully separating the body tubes and ejecting the chute prior to any flight tests.			x
3.3	At landing, each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf.	x				Matlab and Python codes shall be used to model the descent speed of each independent section of the vehicle. These programs shall show that the main parachute is capable of reducing landing kinetic energy to below 75ftlb	x		

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.4	The recovery system electrical circuits will be completely independent of any payload electrical circuits.		x			The recovery system shall be an independent subsystem. All electronics shall be wired independently from payloads and shall share zero connections or signals with payload electronics.		x	
3.5	All recovery electronics will be powered by commercially available batteries.		x			Commercially available 7.4V batteries shall be used to power recovery servos and altimeters.	x		
3.6	The recovery system will contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers.		x			2 independent Eggtimer altimeters shall be used in the recovery subaystem.	x		
3.7	Motor ejection is not a permissible form of primary or secondary deployment.		x			Primary and secondary deployment shall be attained through a mechanical system to induce launch vehicle separation and a chute release respectively.	x		
3.8	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.		x			Shear pins shall be used to hold the payload and the booster sections together.			x

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.9	Recovery area will be limited to a 2,500 ft. radius from the launch pads.	x			x	Matlab and Python code shall be used to verify that the drift of the rocket is less than 2500ft for up to 20 mph winds. A test launch shall be perfomed to show the distance from the launch rail falls into this category as well.	x		
3.1	Descent time will be limited to 90 seconds (apogee to touch down).	x			x	Matlab and Python code will be used to verify that descent time is less than 90s. This will also be verified with a test launch.	x		
3.11	An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.		x	x		All parts of the rocket shall be tethered with nylon shock chords, and a GPS transmitter shall be placed inside the nose cone of the launch vehicle.			x
3.11.1	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic tracking device.		x			The launch vehicle shall consist of two tethered sections which contain all payloads and the tracking device.			x

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.11.2	The electronic tracking device(s) will be fully functional during the official flight on launch day.			x		Ground testing shall be verified to give the location of the rocket prior to being taken out to the launch pad. Prior to any test flights, the ground testing shall establish the accuracy of the tracking device.			x
3.12	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).		x	x		A Faraday cage and carbon fiber shall be designed to encompass the recovery bay. Ground testing shall simulate the flight profile to ensure nominally no unexpected trigger in the system.		x	
3.12.1	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.		x			A Faraday cage and carbon fiber shall be placed around the recovery bay in order to shield it from other on-board electronics.			x
3.12.2	The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.		x			A Faraday cage and carbon fiber shall be placed around the recovery bay in order to shield the system.			x

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.12.3	The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.		x			A Faraday cage and carbon fiber will be placed around the recovery bay in order to shield the system.			x
3.12.4	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.		x			A Faraday cage and carbon fiber will be placed around the recovery bay in order to shield the system.			x

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.1.	Teams will design a custom UAV that will deploy from the internal structure of the launch vehicle.	X		X	X	The team shall perform all analysis and trade studies to construct a unique UAV for the mission. The demonstration flight shall show that the UAV can deploy from the vehicle.		X	
4.4.2	The UAV will be powered off until the rocket has safely landed on the ground and is capable of being powered on remotely after landing.		X			The UAV shall be confirmed to be powered off prior to standing the launch vehicle on the pad. Ground testing shall verify that the deployment mechanism is capable of closing a switch to provide power to the UAV.		X	

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.3.	The UAV will be retained within the vehicle utilizing a fail-safe active retention system. The retention system will be robust enough to retain the UAV if atypical flight forces are experienced.	X		X	X	The team shall calculate the most extreme loading conditions on the system in order to determine structural integrity and test the robustness of the system before being placed in the launch vehicle		X	
4.4.4.	At landing, and under the supervision of the Remote Deployment Officer, the team will remotely activate a trigger to deploy the UAV from the rocket.		X			The team shall verify that they have permission from the RDO prior to sending any signal to the launch vehicle.		X	
4.4.5.	After deployment and from a position on the ground, the UAV will take off and fly to a NASA specified location, called the Future Excursion Area (FEA). Both autonomous and piloted flight are permissible but all reorientation or unpacking maneuvers must be autonomous.			X		The UAV shall demonstrate autonomous deployments triggered soley from a single signal sent by the team. The UAV shall then enter autonomous flight to locate the FEA.		X	
4.4.6.	The FEA will be approximately 10 ft. x 10 ft. and constructed of a color which stands out against the ground.		X			The team shall verify the size of the FEA on the launch field prior to flight in Alabama at competition.			X

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.7.	One or more FEA's will be located in the recovery area of the launch field. FEA samples will be provided to teams upon acceptance and prior to PDR.		X			The team shall verify that the FEA is delivered to the team.	X		
4.4.8.	Once the UAV has reached the FEA, it will place or drop a simulated navigational beacon on the target area.			X	X	The UAV shall complete multiple ground test flights carrying the beacon to a predetermined area.		X	
4.4.9.	The simulated navigational beacon will be designed and built by each team and will be a minimum of 1 in W x 1 in H x 1 in D. The school name must be located on the external surface of the beacon.		X			The team shall custom design a 3D printed navigational beacon to be carried by the UAV.		X	
4.4.10.	Teams will ensure the UAV's batteries are sufficiently protected from impact with the ground.		X			The team shall place the battery in the middle of the UAV body to properly shield the battery from any impact.		X	
4.4.11.	The batteries powering the UAV will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other UAV parts.		X			The team shall verify that all batteries are clearly marked with the appropriate hazard and safety marking.		X	

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.12.	The team will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336; see https://www.faa.gov/uas/faqs).		X			The team shall work with the safety committee and mentor to ensure full compliance with FAA regulations. The UAV design team officer shall read the applicable FAA rule.		X	
4.4.13.	Any UAV weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.		X			Because the UAV weighs more than 0.55 lbs., the team shall go through the necessary procedures to register the UAV with the FAA as soon as possible.			X

Safety Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.		X	X		The team shall write and follow launch day checklists for pre-departure, pre-launch, and recovery activities. Launches shall occur only after design leads have signed off on all launch day checklists.			X
5.2	Each team must identify a student safety officer who will be responsible for all items in section 5.3.		X			The student safety officer shall be listed in the General Information section of the PDR and all stated responsibilities shall be communicated to said officer.	X		

Safety Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
5.3	The role and responsibilities of each safety officer will include, but are not limited to:		X			Responsibilities listed in requirements 5.3.1 through 5.3.4 shall be communicated to the safety officer and all other team officers.	X		
5.3.1	Monitor team activities with an emphasis on Safety during:		X			Responsibility shall be communicated to Safety Officer	X		
5.3.1.1	Design of vehicle and payload		X			"	X		
5.3.1.2	Construction of vehicle and payload		X			"	X		
5.3.1.3	Assembly of vehicle and payload		X			"	X		
5.3.1.4	Ground testing of vehicle and payload		X			"	X		
5.3.1.5	Subscale launch test(s)		X			"	X		
5.3.1.6	Full-scale launch test(s)		X			"	X		
5.3.1.7	Launch day		X			"	X		
5.3.1.8	Recovery activities		X			"	X		
5.3.1.9	STEM Engagement Activities		X			"	X		
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.		X			"	X		
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.		X			"	X		
5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.		X			"	X		

Safety Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.		X			The team shall work directly with the mentor and Michiana Rocketry club to ensure full compliance with local RSO for launch days. Intentions for launch shall be communicated in advance to the Michiana Club President.	X		
5.5	Teams will abide by all rules set forth by the FAA.		X			The team safety officer shall be aware of all FAA rules at launch, and defer to instructions of RSO and mentor.		X	

6.2.2 Team Derived Requirements

In order to further define the scope and detail of the system design, the team has derived additional requirements for the Launch Vehicle (LV), Air Braking Subsystem (AB), Recovery Subsystem (RC), and UAV Payload (PL). Some of these requirements are derived directly from a NASA given requirement, while others have been identified as necessary constraints to the design and created independently. These requirements are given in the subsequent tables, in which the parent requirements are listed as well as the justification for why each derived requirement is necessary.

Derived Vehicle Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS

Derived Vehicle Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
LV2.17-1	CAD Models shall be used to preduct CG	x				Models shall be created in CAD software with mass properties inputted.	2.17	Necessary to verify that the stability of the launch vehicle is above 2.0.		x	
LV2.17-2	CG predictions shall be verified prior to any launch				x	Prior to any launch, the CG shall be physically measured using a balancing tool.	2.17	Necessary to ensure that the CG predictions of the launch vehicle are accurate			x
LV2.19.1-3	Subscale dimensions shall be 40% ± 5% of the projected fullscale dimensions	x				Subscale will be an approximate 40% scale of the fullscale projections. This will be accomplished by sourcing the correct items and designing to this specificiation	2.19	Necessary to ensure that subscale is an accurate scale model of the full scale.		x	
LV2.20.1.3.2-4	Simulated masses' CG's shall be within 1 inch of the CG of the original mass	x				Any simulated mass shall be placed in an orientation that located the Cg within an inch of the Cg of the original mass.	2.20.1.3.2	Necessary to verify that the simulated mass correctly represents the mass in the vehicle and the test flight provides useful data.			x
LV2.20.1.4-5	All changes to the external surface of the rocket due to the payload must be simulated during the full-scale Vehicle Demonstration Flight		x			Any external feature, such as camera mounts and Air Braking drag tabs will be present and active on all demonstration flights.	2.20.1.4	Necessary to verify that demonstration flight accurately represents the final flight conditions.		x	
LV2.20.1.5-6	The motor used for the Vehicle Demonstration Flight shall be the same as the launch day motor.		x			The launch day motor will be used in all Demonstration flights.	2.20.1.5	Necessary to test how the motor will perform on Launch Day		x	

Derived Vehicle Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
LV2.20.1.6-7	Ballast must be calculated and configured in the rocket for the full scale test.		x			Use OpenRocket simulations to calculate and configure ballast in rocket for test day. Ballast will be inspected on launch day.	2.20.1.6	Necessary to fully simulate the conditions on launch day.		x	
LV2.22-8	The Air Braking System will be located aft of the burnout center of gravity.	x				The coupler with the tabs shall be located aft of the center of gravity.	2.22	Necessary for stability of rocket during flight.	x		
LV2.23-9	The team name and contact information shall be on the rocket and on each piece that separates from it.	x				The team will paint the team name and contact info on the launch vehicle.	2.23	Necessary so that rocket can be identified and returned to the team.			x

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB2.20.2-1	The Air Braking System shall be the final active version and demonstrate successful activation of the system in flight, meeting mission success criteria.			X		When ABS is active in demonstration flights, a reduction in apogee shall be shown. Flight data stored on the ABS microSD card shall indicate system performance.	2.20.2	The ABS shall qualify as an additional vehicle payload and thus will be subject to payload demonstration requirements.			X

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB2.24.1-1	The Air Braking System shall increment deployment of all drag tabs simultaneously.			X		The ABS shall demonstrate extending all tabs the same distance beyond the body tube when fed simulated flight data. The system response for flight events shall be predictable and observed when fed flight data.	2.24.1	Forward canards are prohibited to prevent attitude control. Drag tabs must be verified to deploy together to prevent imbalance of forces (as if by canards).	X		
AB-1	The location of the drag tab extensions shall be located within 4 inches of the post burnout center of presssure.	X				The team shall use OpenRocket to locate the post burnout center of pressure and size the body tube to satisfy this constraint.	N/A	Aerodynamic perturbances caused by the drag tabs should be located close to the center of pressure to minimize effects of flight stability.		X	
AB-2	The vehicle shall experience a stable and safe flight with the Drag tabs extended.				X	Subscale flights with a subscale drag tab coupler shall be used to verify preliminary stability. Full scale vehicle tests will verify flight stability.	N/A	The ABS must only impact the trajectory of the vehicle in the vertical direction resulting in a stable flight. Unstable flight presents a safety hazard to the vehicle and team personnel.		X	
AB-3	The ABS shall exhibit autonomous control over the full range of actuation during flight.			X		A single servo motor, shall provide continuous autonomous control of the mechanism to dictate actuation of tabs based on avionics data.	N/A	Continuous and autonomous control is necessary in order to precisely control the induced drag on the vehicle.			X

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-4	The ABS shall be integrated into the vehicle as a single removable payload.	X		X		CAD software shall be used to size tolerances for ABS. These dimensions shall be used in construction to demonstrate the final assembly fits within the body tube.	N/A	Designing the ABS as a single removable entity improves the efficiency of the integration strategy and reduces the risk of interfering with integration of other components.		X	
AB-5	The ABS power and arming switches shall be accessible from the external of the vehicle and shall have visible indicators to represent the control state the system is in.		X	X		The designed shall have arming switches accessible via the barometer hole on body tube. The LED indicators shall be inspected during integration to be both visible and change depending on simulated flight data.	N/A	The arming of all systems must be accessible externally to reduce risk of false triggers. The ability to visually confirm the status of the control system through changing LED's will improve system reliability.	X		
AB-6	ABS Electronics shall be directly soldered to the avionics PCB when possible, and all avionics shall be secured to prevent disconnection during flight.		X			The system shall be inspected before integration to ensure all fasteners and connections are secure. The system shall be subjected to shake tests before flight.	N/A	In order to ensure the continuous control described in Req. AB-2. the avionics system must be secure and reliably connected.		X	

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-7	The ABS shall be capable of determining the vehicle velocity and altitude within a maximum of ±5.0 m and ±5.0 m/s respectively.				X	The system shall record accelerometer and barometer data and pass it through a Kalman filter to calculate altitude and velocity within the given tolerances.	N/A	Accurate measurements are necessary to reliably control the apogee of the vehicle.		X	
AB-8	The ABS shall autonomously actuate its drag tabs and alter the drag of the rocket to achieve an apogee of 4,700 ± 25 ft.				X	The system's actuation shall be ground tested and the successful apogee control shall be determined by a test launch.	N/A	The ABS must operate independent of team personnel on the ground. The ABS must demonstrate successful operation in pursuit of achieving target apogee.			X
AB-9	The ABS shall be capable of reducing the apogee of the rocket by no less than 200 ft.				X	The vehicle will undergo a control flight with no drag tab extension, and a full braking test with full extension after motor burnout. The difference in apogee between the tests will be used to verify the requirement.	N/A	Considered vehicle motor options project an apogee of approximately 4,900 ft. To achieve the 4,700 ft. target apogee, the ABS must be capable of reducing apogee by 200 ft.			X
AB-10	The Drag Tabs shall not actuate beyond the mechanical limit of their enclosure.			X		A hollow shaft potentiometer shall be fixed to the shaft to provide positional feedback and ensure the servo motor does not over actuate.	N/A	Damage to the ABS and vehicle may occur if the tabs are over actuated and control of the tabs is lost or the tabs are jammed.		X	

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-11	The ABS shall contain redundant systems to ensure tabs are retracted in case of system failure.			X		The ABS shall include a hollow shaft potentiometer that will provide positional feedback that will be used to determine if system failure has occurred and the tabs need to be retracted.	N/A	ABS tab failure can induce unpredictable flight characteristics and new hazards. If failure is detected, tabs should retract into vehicle body.		X	
AB-12	ABS electronics shall be capable of being powered on for no less than 3 hours with all systems active.				X	The ABS current draw in documentation indicates system can remain powered for 9 hrs. Ground testing of the system shall verify the up to 3 hours in powered state.	N/A	The ABS must be capable of remaining powered on in the event of an extended waiting period before launch while on the launchpad.		X	
AB-13	The ABS must be capable of logging all raw data and calculated vehicle state data for post-launch review.				X	This requirement will be verified through ground and flight testing.	N/A	Data is necessary to evaluate the successful operation of the ABS as well as perform post-mission analysis to improve the system for future launches.			X
AB-14	The ABS must be inspected prior to every flight for signs of defects.		X			Pre- and post-flight safety checklists shall be created that require a visual inspection of the system.	N/A	System defects increase failure probability. Flight checks reduce chance defects will introduce new hazards.			X

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-15	The ABS components must be capable of surviving flight and landing forces.				X	This requirement will be verified through flight testing.	N/A	In order to ensure the ABS is reusable the system must be able to withstand flight forces.			X
AB-16	The ABS avionics module must be sealed from the lower section of the ABS to prevent pressure disturbances.				X	This requirement will be verified through ground and flight testing. Through holes for wiring from the lower section shall be sealed during assembly.	N/A	To ensure the ABS altimeter does not experience noise spikes, the avionics bay must be pressure sealed with the exception of the vehicle body vent holes.			X
AB-17	The Drag Tabs must be capable of fully extending in no less than 0.5 seconds.			X		This requirement will be verified through ground testing.	N/A	The ABS must have fast actuation in order to precisely control the drag tabs in the short time frame of the flight.			X

Derived Recovery Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
RC3.2-1	The mechanical recovery system shall expel the parachute from the body tube in static ground testing.			X		Ground tests shall be performed to show that the sizing of the latch mechanism supplies the force necessary to separate and release the parachute from inside the vehicle body. The chute release shall be tested in the same manner.	3.2	Necessary to ensure functionality and consistency of latch mechanism and chute release for deployment when subjected to simulated flight conditions.			X

Derived Recovery Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
RC3.3-1	The launch vehicle shall descend under a parachute with a surface area greater than 94 ft^2.		X			The parachute shall be chosen so that it has at least 94ft^2 of surface area.	3.3	Based on maximum vehicle mass, this ensures a maximum drag coefficient of 2.59 necessary to meet kinetic energy requirement 3.3		X	
RC3.3-1.1	The parachute shall be packed in a volume of body tube 6 inches diameter and 30 inches in length.				X	The team shall test multiple packing methods to verify that the chosen parachute can be packed into this volume. This method shall be documented to be used at all launches.	RC-3.3.1	Necessary to standardize parachute packing such that the chute will not get caught during deployment or be too tight for the ejection system to function.			X
RC3.4-1	The recovery system shall be a separate assembly from the rest of the launch vehicle		X			The recovery system shall be designed such that it can be removed from the launch vehicle.	3.4	Allows the subsystem to be independence of the launch vehicle to replace components (i.e batteries)		X	
RC3.7-1	Primary deployment shall be triggered by the recovery altimeters in the recovery subsystem when apogee is detected. Secondary deployment shall be triggered by a chute release when a designated altitude is reached.			X		A test launch will be performed in order to ensure that the main parachute is ejected at apogee and allowed to unfurl at 500 ft AGL	3.7	Ensures that the all pieces of the launch vehicle are recovered safely and within the kinetic energy requirements			X

Derived Recovery Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
RC3.9-1	The vehicle shall not drift more than 2,500 ft from the launch pad when subjected to winds not exceeding 20 mph.	X			X	Python programs shall analyze the flight behavior under a variety of wind conditions and shall calcultate drift radius based on wind speed and parachute size. Flight test shall confirm vehicle lands within 2,500 ft of launch rail.	3.9	Establishes the limit for drift radius under worst flight condition. Additionally, dictates that a common drift radius calcluation be used to verify with worst case flight performance.	X		
RC3.11-1	A GPS transmitter shall be installed in the nosecone section to transmit position of vehicle.		X	X		The GPS unit shall be placed in the nose cone prior to ground testing. The unit shall transmit position to a ground receiver during all test flights.	3.11	This ensures that the position of the launch vehicle is known at very point during flight and assigns responsibility of integrating the GPS unit to the Payload Team.			X
RC3.12-1	Recovery altimeters shall be enclosed in a compartment of the launch vehicle encased in carbon fiber.		X			Both ends of the servo bay as well as the outer wall shall be lined with carbon fiber.	3.12	Places the recovery electronics in a section that is insuled from external RF transmitting.		X	
RC-1	The recovery subsystem, including parachutes and deployment mechanism, shall weigh no more than 190 oz.		X			Component weights shall be approximated in flight simulations until actual mass is measured. Each component shall be weighed during construction to ensure max weight is not exceeded.	N/A	The vehicle design team has allocated maximum mass budgets for each subsystem. This requirement ensures the entire recovery subsystem is within the limits of the launch vehicle.		X	

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
PL4.4.1.-1	The team shall develop an Orientation Correction Mechanism and a Linear Transport Mechanism that shall allow for the complete clearance of the UAV for flight to the FEA.	X		X	X	The team shall demonstrate the functionality of the system for a variety of landing configurations. The system shall deploy the UAV such that it clears all external body frames.	4.4.1	The deployment mechanism must be capable of clearing all external components of the rocket so that the UAV can takeoff for any landing conditions.		X	
PL4.4.2.-1	The team shall utilize the Button-on-Arm power-on system to power on the UAV after the rocket has safely landed under the supervision of the Remote Deployment Officer.		X	X		The team shall verify that the system is configured to supply power. The system shall change the powered state of the UAV through operation of the deployment mechanism.	4.4.2	The UAV must be able to be powered on during deployment.		X	
PL4.4.3.-1	The team shall make the Locking Mechanism robust enough to ensure the security of the UAV throughout its launch and descent. The team shall test this mechanism before flight.			X	X	The team shall constrain the UAV in all directions during flight to ensure that it remains immobile. The team shall test the mechanism's durability at ground tests prior to launch to verify it can withstand the loads experienced during flight and landing.	4.4.3	The UAV must be immobile during flight. It is crucial that the Locking Mechanism can properly constrain the UAV to prevent damage.		X	

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
PL4.4.5-1	The team shall ensure the ability of the UAV to be both remotely piloted with the FrSky Taranis X9D Plus 2.4 GHz ACCST Radio and autonomously controlled with DroneKit-Python.			X	X	The team shall demonstrate the operational functionality of the UAV for each pilot condition. The demonstration shall show that the UAV is capable of completing all flight phases from take-off to beacon delivery for both flight controllers.	4.4.5	In the event that there is a malfunction with autonomous flight, the UAV must be proven to operate nominally for piloted flight as well.			X
PL4.4.6.-1	The team shall write a Python script using the OpenCV library that would run on the onboard Raspberry Pi to analyze the footage from the Pi camera and find the FEA using the hue, separation, value (HSV) color space.	X		X		The team shall test the code by running it multiple times during UAV flight tests in order to ensure reliability and proper target detection.	4.4.6	A primary goal of the UAV is to deploy the beacon on the FEA. It is critical that the camera is able to distinguish the FEA and that the script onboard the Raspberry Pi can analyze footage.			X
PL4.4.7.-1	The team shall use DroneKit-Python and the GPS coordinates of the FEA to set target positions. The software shall find the GPS coordinates of the closest Future Excursion Area to initially set waypoints for the drone.	X		X		The team shall generate input data for a simulated FEA location and verify the UAV will create a flight path to that location.	4.4.7	The GPS is not accurate enough to ensure FEA location alone. The UAV must instead go to the general known location of the FEA and create waypoints for autonomous flight while it detects the FEA.		X	

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
PL4.4.9.-1	The team shall design two 3D printed beacons to help ensure the successful delivery of a simulated navigational beacon to the FEA. The University of Notre Dame and the Notre Dame Rocketry Team logos shall be printed on both beacons.		X			The team shall 3D print two custom objects to represent a beacon with the Notre Dame logo clearly visible (per. Requirements 4.4.8 and 4.4.9)	4.4.8 and 4.4.9	The reasoning behind having two beacons is redundancy. If the first deployed beacon does not land upon the FEA, the small servo in the Beacon Delivery Subsystem will further rotate and deploy the second identical beacon.		X	
PL4.4.10-1	The team shall place the LiPo battery in the center of the UAV body in order to ensure that the LiPo will not be crushed or punctured upon landing a safe distance away from the FEA at the end of the mission.		X			The team shall inspect the body to verify that the body properly protects the LiPo battery.	4.4.10	The LiPo battery has a high severity hazard mode in the event of failure. Therefore, it must be placed in the most secure/stable location on the UAV to mitigate the likelihood of a failure.	X		

6.3 Project Budget

The Notre Dame Rocketry Team has budgeted $17,750 for the competition this year. The funding for this project comes from two primary revenue streams. The first is funding directly provided by the University of Notre Dame through club allocation funding for the student chapter of AIAA and departmental funds in the College of Engineering. The primary revenue stream, however, is charitable donations by the NDRT corporate sponsors. This year's sponsors include The Boeing Company, TimkenSteel, and Pratt & Whitney. A breakdown of the funds secured at this point in the competition is given in Table 68.

Table 68: Notre Dame Rocketry Team Funding Sources

Source	Amount
Remaining Balance (2017/18)	$ 2,516.54
The University of Notre Dame	$ 2,500.00
ND Day Fundraising	$ 876.46
The Boeing Company	$ 10,000.00
TimkenSteel	$ 1,000.00
Pratt & Whiney	$ 5,000.00
TOTAL	$ **21,893.00**

The current sourced funds total $21,893 and are more than sufficient for covering the costs of this year's project. Going forward, the team plans to continue building on its primary revenue stream and increase fundraising to support Research and Development within for the program. As the donation from Pratt & Whitney came after the PDR milestone, a portion of the donation has been allocated for this purpose. The funds raised for the 2018/19 competition have been allocated to each major program area and are given in Table 69.

Table 69: Notre Dame Rocketry Team Funding Sources

Allocation	Amount
Vehicle Design	$ 5,250
Recovery Subsystem	$ 1,750
UAV Payload	$ 3,000
Air Braking System	$ 1,450
Rocket Subtotal	$ **11,450**
Educational Engagement	$ 300
Competition Travel	$ 6,000
Miscellaneous	$ 500
Research & Development	$ 3,500
TOTAL	$ **21,750**

The largest expenditures for the team are the overall launch vehicle construction and traveling to competition. This budget allows for an overall project margin of $143 with holding $500 set aside for cost overrun or expedited shipping payments as unseen expenses. This plan also allows for funds to be already secured going into the summer for future development of the program.

The material acquisition plan for the team this year has relied heavily on vendors the team has partnered with in the past, such as Apogee Components. Additional sources for procuring components have been researched to reduce both cost and lead time on materials after being ordered. One final avenue, is to leverage the team's relationship with corporate sponsors, such as Boeing, to purchase excess composite materials from the company at a discounted rate. This is something the team is actively pursuing and will take into consideration for the competition vehicle.

A detailed breakdown of the itemized budget organized into allocation categories for the project is shown in Table 70.

Table 70: Itemized Budget

Vehicle Component	Vendor	Description	Qty	Price Per Unit	Total Cost ($)
Subscale Nose Cone	LOC Precision		1	20.74	20.74
Subscale Fore Body Tube	LOC Precision		1	10.44	10.44
Subscale Aft Body Tube	LOC Precision		1	18.26	18.26
Subscale Motor Mount	LOC Precision		1	9.6	9.60
Subscale Motor	Aerotech		1	29.99	29.99
Subscale Tabs	3D Print		1	30	30.00
Subscale Fin Plywood	LOC Precision		1	5	5.00
Subscale Transition	3D Print		1	20	20.00
Subscale Centering Rings (75 - 54mm)	Apogee Rockets		4	7.59	30.36
Subscale Centering Rings (54 - 29mm)	Apogee Rockets		4	10.38	41.52
Subscale Bulkheads (3")	Apogee Rockets		2	3.98	7.96
Subscale Bulkheads (2.16")	Apogee Rockets		2	2.89	5.78
Rail Buttons	Apogee Rockets	1010	1	7.83	7.83
Rail Buttons	Apogee Rockets	1515	1	11.17	11.17
Subscale Coupler ("2.16")	LOC Precision		1	4.35	4.35
RocketPoxy (2 Pint)	Glenmarc		1	43.75	43.75
Rail Button Offsets	3D Prints		2	10	20.00
Fiberglass Nose Cone	PML	29" long	1	121.79	121.79
RocketPoxy (2 Pint)	Apogee Components		1	43.75	43.75
Carbon Fiber Body Tube (6")	PML	45", 31", 21"	2	479.95	959.90
Carbon Fiber cutting (60" per tube)	PML	45", 31", 21"	3	6	18.00
Phenolic 6" coupler	Apogee	11.75"	1	94.95	94.95
Fin Can Slotting	PML		4	6	24.00
Fiberglass Body Tube (7.51")	PML	22"	1	199.99	199.99
Fiberglass Body Tube cutting	PML	48" –¿ 22"	1	2.5	2.50
Carbon Fiber Sheet (1/8")	DragonPlate	Fins	1	200	200.00
Fin Cutting	DragonPlate		4	20	80.00
JBWeld	JBWeld		2	29.99	59.98

ABS Slots	PML		1	50	50.00
Fiberglass Motor Centering Rings	Apogee Components	6/3/2019	3	19.95	59.85
Fiberglass Bulkheads	Apogee Components	6”	2	6.89	13.78
Fore Bulkheads	Apogee Components	7.5 - 6	2	13.01	26.02
Motor	Cesaroni / Aerotech		4	290	1160.00
Transition Section	Custom Order		1	200	200.00
Screw Pack	Home Depot		1	10	10.00
Various Shipping Costs			1	300	300.00
RockSim	Apogee		4	20	80.00
Motor Mount	PML		1	28.99	28.99
Miscellaneous			1	500	500.00
		TOTAL COST			$ 4550.25
		Allocation			$ 5250.00
		Margin			$ 699.75
Recovery System Components	Vendor	Description	Qty	Price per Unit	Total Cost ($)
Parachute	Rocketman Parachutes	Parachute	1	190	190.00
Altimeters	Eggtimer	Altimeters	2	35	73.00
Garolite Plates	McMaster Carr	Used for Bulkheads	2	44.1	88.20
3D Printing	Notre Dame	ABS Plastic	1	120	120.00
PC343-3031-5000-MW-4630-CG-N-IN	McMaster Carr	Spring	8	12.96	133.79
Safety Pins/ Holding rods	McMaster Carr	Aluminum Rods	1	5.48	5.48
Aluminum Sphere (latch)	McMaster Carr	Aluminum Sphere	1	11.48	11.48
Shock Cords	Us Cargo Control	28yd of Shock cords	2	41.52	83.04
Chute Release	Jolly Logic	Chute Release	2	155.94	311.88
Batteries (9V)	Walmart	Batteries	1	18.99	18.99
Batteries	Tenergy	Servo Batteries	2	17.99	35.98
Power HD High Voltage 6.0-7.4V #HD-1235MG	Power HD	Servo Motors	2	42.9	85.80
Eye Bolts	McMaster Carr	Eyebolts for bulkheads	2	6.16	12.31
5/16 In Threaded Link 1760lb Capacity Packaged	Del Cidt	Quick Links	4	3.12	12.48
Pipe Clamps	Home Depot	Pipe Clamps	4	16.76	67.06
Threaded pipes for clamps	Home Depot	Black Steel Pipe	1	23.75	23.75
BACOENG 3 Gallon Vacuum Chamber Kit	BACOENG 3	Vacuum Chamber	1	200	200.00
#29128 - 36” Nylon Parachute	Apogee Rockets	Drogue Parachute	1	21.8	21.80
		TOTAL COST			$ 1495.04
		Budget Allocation			$ 1750.00
		Margin			$ 254.96
UAV Payload Components	Vendor	Description	Qty	Price Per Unit	Total Cost ($)
Pixhawk 4 Autopilot and Neo-M8N GPS Combo	GetFPV	Pixhawk 4	1	219.99	219.99
Raspberry Pi 3 Model B	Micro Center	RPi3 B	2	29.99	69.98
Multirotor Carbon Fiber T-Style Propeller 7x2.4 Black (CW/CCW) (2pcs)	Hobbyking	Carbon Fiber Prop	4	4.75	19.00

Lumenier 18A 32bit Silk ESC OPTO (2-4s)	GetFPV	Electronic Speed Controller	6	9.99	68.41
Hobbyking #8482 Propeller 7x3.8 Black (CW/CCW) (2pcs)	Hobbyking	Plastic Prop	5	2.55	12.75
Adapter Rings (E)	APC Propellers	Thin Electric Adapter Rings	1	2.49	5.83
T-Motor MN1806 KV1400	T-MOTOR	Motor	6	25.9	155.40
Turnigy nano-tech 4500mAh 3S 35 70C Lipo Pack w/XT-90	Hobbyking	Battery	2	40.25	80.50
Keenstone Lipo Battery Charger/Discharger with Low Voltage Checker	Keenstone	Charger	1	49.99	49.99
Cable Zip Ties	NewMainone	Zipties	1	13.98	13.98
RJXHOBBY 20mmX300mm Non-Slip Silicone Battery Straps	RJXHOBBY	Velcro Straps	1	8.99	8.99
Adiyer Metric M3 Button Head Hex Socket Cap Screws Nuts Set	Adiyer	Metric Screws	1	11.99	11.99
500mW Transceiver Telemetry Radio Set V3 433 MHZ	Holybro	500mW Telemetry Set 433MHz	2	45	118.60
500mW Transceiver Telemetry Radio Set V3 915 MHZ	Holybro	500mW Telemetry Set 915MHz			–
Raspberry Pi Camera Board v2 - 8 Megapixels	Adafruit Industries	Raspberry Pi Camera	1	29.95	42.51
Everbilt 1/4" x 36" Aluminum Round Rod	Home Depot	Rods	2	4.37	8.74
1/2-13 Threaded Rod (.500" Diameter) #91847	United States Plastic Corporation	Leadscrew	1	14.78	14.78
1/4" Width MXL Series No. Ll025mxl Timing Belt	McMaster Carr	Timing Belt	4	2.32	9.28
FEETECH FS90R (2 Pack) - 360° Rotation — Continuous Rotation Robotic Servo	FEETECH	Beacon Servo for Delivery	1	11.94	11.94
MDS-Filled Cast Nylon Bulkhead (#2449T13) (12" x 12" x 3/8")	McMaster Carr	Front Linear & Back Rotational Bulkhead (Deployment)	2	58.09	116.18
Nema 14 Stepper Motor 0.9deg 0.4A 11Ncm/15.6oz.	STEPPER-ONLINE	Stepper Motor for Linear, Translational Motion (Deployment)	1	19.9	19.90
Continuous Rotation 360 Degree Ball Bearing Servo Arduino	FEETECH	Servo Motor for Rotational Motion (Deployment)	1	17.95	17.95
1/2 in.-13 Nylon Hex Nut	Home Depot	Nut for Leadscrew	4	0.71	2.84
Turnigy 2200mAh 3S 25C Lipo Pack	Hobbyking	Battery for Deployment	1	10.99	10.99
MDS-Filled Cast Nylon Bulkhead (#2449T13) (Tracks Around Bulkheads)	McMaster Carr	Tracks to Contain Bulkheads	4	58.09	232.36
L3GD20H Triple-Axis Gyro Breakout Board	Adafruit	Gyroscope for Orientation Correction	1	12.5	23.84

Microcontroller for Deployment System	Adafruit	Microcontroller to Connect Accelerometer to Stepper	1	22	22.00
Metal Supports for Aluminum Rods	Lowes	Placed on Back Bulkhead to Help Stabilize Deployment	2	7.75	15.50
Yellow Tarp 3.3 OZ, 12'x20'	Harpster Tarps	Practice FEA	1	22.99	22.99
MT60 Connectors	WST	10 Pairs MT60 3.5mm 3-wire 3-pole Bullet Connector Plug Set for RC ESC to Motor 10 Male Connectors & 10 Female Connectors	1	13.99	13.99
XT60 Bullet Connectors	LHI	LHI XT-60 XT60 Male Female Bullet Connectors Plugs for RC Lipo Battery	1	8.45	8.45
XT90 Connectors	WOAFLY	LHI XT90 Battery Connector Set for RC Lipo Battery Motor 6 Pairs Yellow,6 Male Connectors + 6 Female Connectors	1	9.89	9.89
Adafruit USB Cable	Adafruit	Power Cable for Arduino Board	1	5.65	5.65
Torsion Spring, 270 Degree Angle, Left-Hand Wound, 0.805" OD, Packs of 6	McMaster Carr	Torsion Spring	1	11.87	15.49
Torsion Spring, 270 Degree Angle, Left-Hand Wound, 0.600" OD, Packs of 6	McMaster Carr	Torsion Spring	1	8.91	12.53
MXL Series Lightweight Timing Belt Pulley, 0.63" OD	McMaster Carr	Pulley	5	35.75	39.37
Torsion Spring 225 Degree Angle, Left-Hand Wound, 0.556" OD	McMaster Carr	Torsion Spring	1	7.91	7.91
Torsion Spring 225 Degree Angle, Left-Hand Wound, 0.461" OD	McMaster Carr	Torsion Spring	1	7.54	7.54
		TOTAL COST			$ 1528.03
		Allocation			$ 3000.00
		Margin			$ 1471.97
Air Braking System Components	Vendor	Description	Qty	Price Per Unit	Total Cost ($)
Adafruit ADXL345	Excess Inventory	Triple Axis Accelerometer for testing	1	0	0.00
Adafruit BMP280	Excess Inventory	Barometer	1	0	0.00
Arduino MKR ZERO	Arduino	Microcontroller	1	21.9	21.90
Adafruit BNO055	Adafruit	Accelerometer & Orientation IMU	1	35.5	35.50
Adafruit LIS3DH	Adafruit	Triple Axis Accelerometer	1	5.5	5.50

Sparkfun MPL3115A2	Sparkfun	Altitude Pressure Breakout Board	1	22.81	22.81
Hollow Shaft Potentiometer (RH32PC R5K L2%)	P3 America, Inc.	Potentiometer for shaft encoding	1	15	15.00
Adafruit LED Sequins Multicolor Pack of 5	Adafruit	LED	2	4.5	9.00
Breakaway 0.1" 2x20 pin Strip Dual Male Header	Adafruit	Header Pins for Sensors	3	1.5	4.50
Small PCB Test Points (100 pack)	Adafruit	PCB Test Points	1	10.5	10.50
Small Alligator Clip to Male Jumper Wire Bundle 6 Pieces	Adafruit	Alligator Clip Leads	1	3.95	3.95
Hitech D980TW Servo	Servo City	Servo Motor to drive mechanism shaft	1	169.99	169.99
Spline Servo to Shaft Coupler	Servo City	Shaft coupler	1	12.99	12.99
Oil Embedded Mounted Sleeve Bearing (5912K13)	McMaster-Carr	Bearing for aft section of shaft	1	9.73	9.73
Female Header Pins	NBHP	Female header pins for circuit prototype	1	5.6	5.60
Prototype Circuit Boards	Paxcoo Direct	Prototype solder boards for subscale	1	8.99	8.99
PCB	OSH Park	Printed Circuit Board	3	25	75.00
Tenergy 30C 7.4V 2200 mAh (3-pack)	Tenergy	Battery (Note: 3 pack)	1	36.99	36.99
Tenergy TLP 2000 Universal Charger	Excess Inventory	Battery Charper for Li-Ion or LiPo batteries	1	0	0.00
Toggle Switch	Excess Inventory	Toggle Switch	2	0	0
Fireproof Battery Case	Colcase	Battery case for safe Li-Po storage	1	12.99	12.99
10 uF Electrolytic Capacitor - Pack of 10	Adafruit	Capacitors for voltage regulation circuit	1	1.95	1.95
5 V voltage regulator	Adafruit	voltage regulator	3	0.75	2.25
HDPE 0.375"x12"x12" Sheet	McMaster-Carr	High Density Polyethylene	1	11.03	11.03
Delrin Sheet 0.5"x12"x12"	McMaster-Carr	Delrin	1	46.71	46.71
Delrin Sheet 0.25"x12"x12"	McMaster-Carr	Delrin	1	30.57	30.57
Clear Polycarbonate 0.25"x12"x12"	McMaster-Carr	Polycarbonate for motor and bearing plates	1	15.89	15.89
Stand Offs	Excess Inventory	Stand offs for mounting motor and bulkheads	8	0	0
Steel Threaded Rods	Lowes	Threaded rods for integration	2	10.99	21.98
Lock Nuts	Excess Inventory	Lock nuts for integration rods	8	0	0
L-6", D-5/16" Drive Shaft (1497K2)	McMaster-Carr	Shaft connecting motor and mechanism	1	11.52	11.52
Machine Key Stock (3/32")	McMaster-Carr	Key stock for connecting keyed shaft to crosspiece. 3/32"	1	1.24	1.24

Ball Joint Rod End (60645K78)	McMaster-Carr	Male end of Tie Rod	6	5.81	34.86
Ball Joint Rod End (60645K61)	McMaster-Carr	Female end of Tie Rod	6	5.95	35.7
Steel-Nylon Lock Nuts (pack of 100)	McMaster-Carr	Lock Nut for tie rod	1	2.91	2.91
Krytox Grease	Chemours	Grease for drag tab bearing	1	27.99	27.99
microSD Card	Excess Inventory	SD card for datalogging	2	0	0
Nylon Screws	McMaster-Carr	Various sized screws for assembly	1	33.91	33.91
Nylon Standoffs	McMaster-Carr	Various sized standoffs for assembly	1	35.16	35.16
3D Printed Battery Case	Custom Machined	Case for battery	1	20	20.00
		TOTAL COST			$ 794.61
		Allocation			$ 1450
		Margin			$ 655.39
STEM Engagement Items	Vendor	Description	Qty	Price Per Unit	Total Cost ($)
Estes Viking Rockets (12 pack)	Estes Rockets	Model rockets	1	79.99	79.99
A8-5 Engines	Estes Rockets	Engines for remaing Estes Alpha Rockets	2	10.29	20.58
Miscellaneous Materials	N/A	Smaller items for activities	1	199.43	199.43
		TOTAL COST			$ 300.00
		Allocation			$ 300.00
		Margin			$ 0.00

6.4 Project Timeline

The timeline for this year's Student Launch project has been broken down into separate timelines for the various design teams. Overall project milestones for Student Launch are set at the highest level and serve as a baseline for setting team deliverables. The design of each of the subsystems was broken down into major design tasks with durations spanning 1 - 3 weeks. This is done to coincide with the weekly full team and subteam design reviews. Current deliverable deadlines are set for all test flights and NASA milestones. An overview of the project timeline is shown in the Gantt Chart in Figures 113 and 114.

Figure 113: Project Gantt chart, part I

NASA Student Launch 2018...	start	end
NASA SL 18/19	**08/22/18**	**04/26/19**
RFP	08/22	09/19
Preliminary Design	09/20	11/08
Proposals Awarded	10/02	10/02
Social Media Est.	10/26	10/26
PDR Documents Due	11/02	11/02
PDR Milestone Presentation	11/08	11/08
Critical Design	11/19	01/11
CDR Q&A	11/27	11/27
CDR Documents Due	01/11	01/11
CDR Teleconferences	01/14	01/30
Flight Readiness	01/23	03/25
FRR Q&A	01/25	01/25
Test Flight Deadline	03/04	03/04
FRR Documents Due	03/04	03/04
FRR Teleconferences	03/08	03/21
Re-Flight Deadline	03/25	03/25
SL Competition	04/02	04/08
Post-Launch Assessment	04/09	04/26
PLAR Documents Due	04/26	04/26
Vehicle Design	**08/31/18**	**03/25/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/04
Cumulative Model Validation	01/08	03/11
Requirements Derivation	09/10	10/15
Trade Studies	09/14	10/22
Sub-Scale Vehicle	10/19	12/12
Sub-Scale Construction	11/06	11/15
Sub-Scale Flight #1	12/01	12/01
Sub-Scale Performance Verification	12/03	12/11
OpenRocket Model Generation	10/01	10/25
CFD Analysis	11/16	01/20
Final Design Configuration	12/30	12/30
Full Scale Materials Ordered	01/08	01/08
Full Scale Performance Validation	01/01	02/26
Full Scale Construction	01/13	02/06
Mass Properties Analysis	01/12	01/20
Construction Safety Briefing	01/20	01/20
Payload Integration Testing	01/27	02/03
Launch Day Dry Run	02/04	02/07
Full Scale Flight #1	02/09	02/09
Full Scale Flight #2 (Backup)	03/09	03/09
Flight Demonstration Deadline	03/25	03/25
Air Braking Subsystem	**08/31/18**	**03/25/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/11
Requirements Derivation	09/10	10/15
Trade Studies	09/14	10/22
Mechanical Design	09/20	11/09
Avionics Design	10/01	11/02
Sub-Scale Testing	10/24	11/21
Performance Modeling	11/02	11/15
Sub-Scale Launch	12/01	12/01
Sensor Data Validation	12/03	12/23
Dynamic Analysis	11/14	01/02
Avionics Testing	11/28	01/20
All Material Received	01/17	01/17
Mechanical Construction	01/20	01/27
Ground Testing Phase	01/29	02/05
Full Scale Flight Testing	02/06	03/10
Flight Test #1	02/09	02/09
System Performance Validation	02/13	03/04
Flight Test #2 (Backup)	03/09	03/09
Flight Demonstration Deadline	03/25	03/25

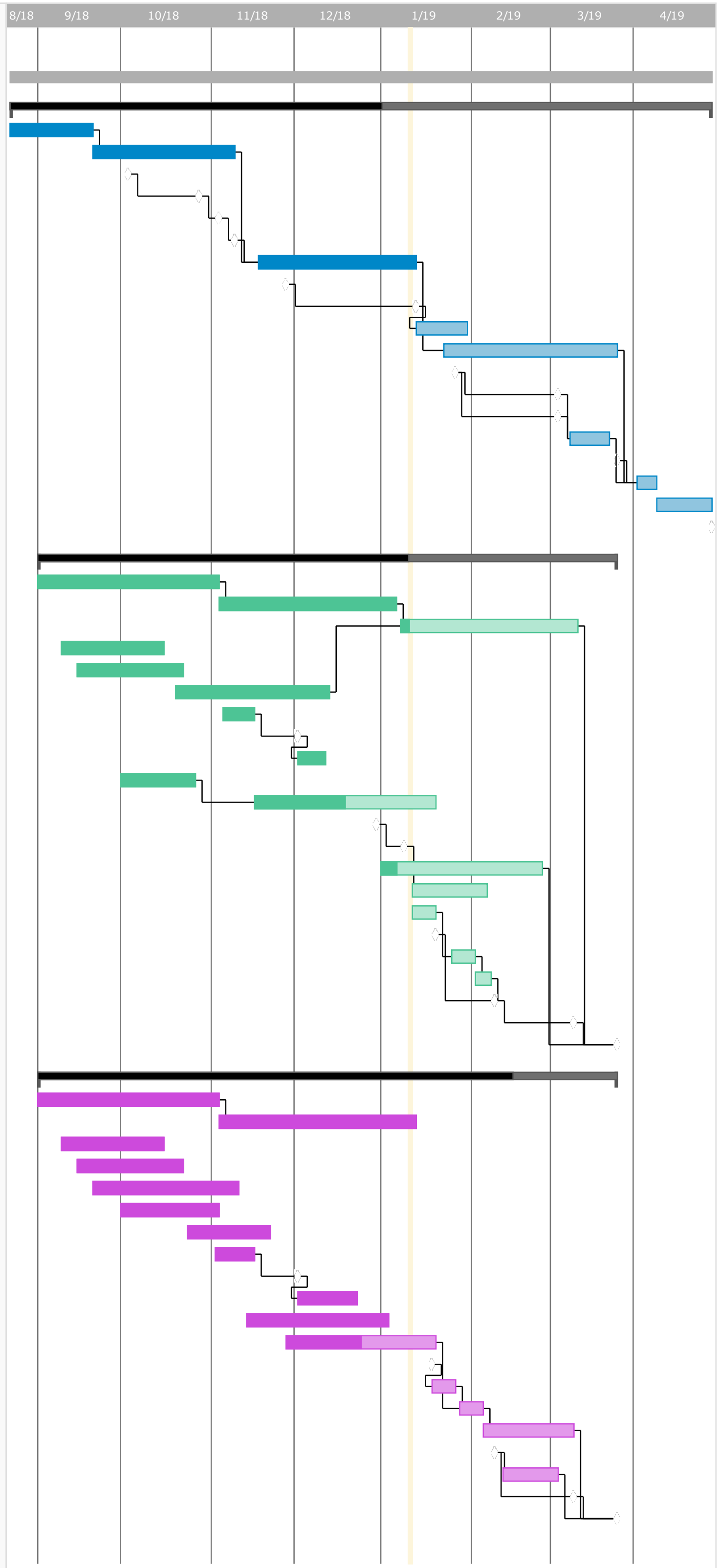
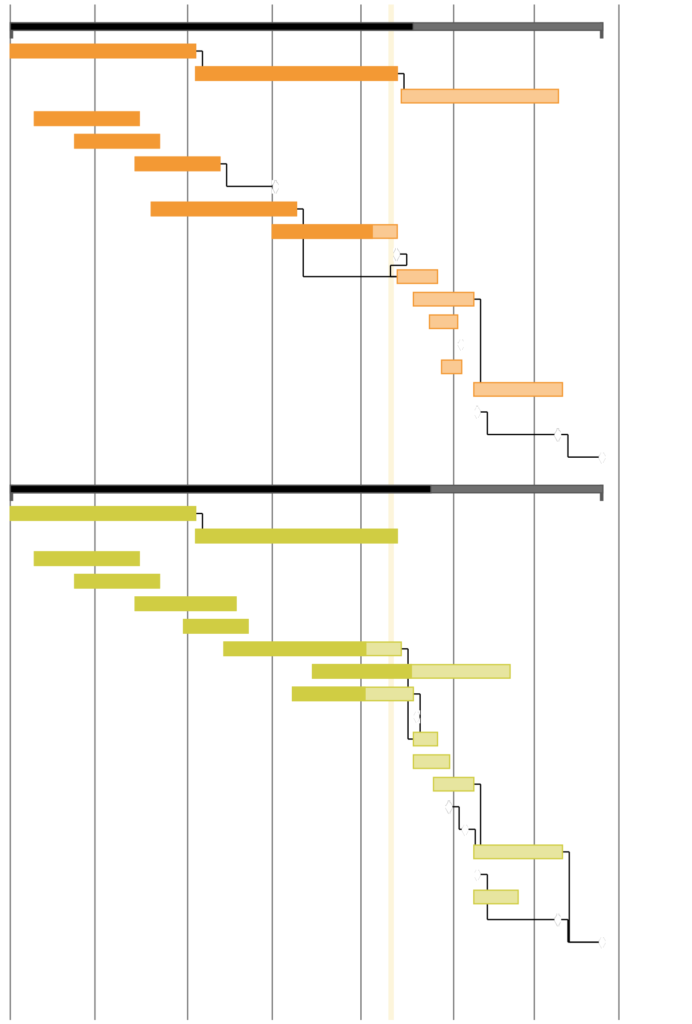


Figure 114: Project Gantt chart, part II

Recovery Subsystem	**08/31/18**	**03/25/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/11
System Validation	01/15	03/09
Requirements Derivation	09/10	10/15
Trade Studies	09/24	10/22
Sub-Scale Avionics Design	10/15	11/12
Sub-Scale Launch	12/01	12/01
Structural Analysis	10/19	12/09
Prototype Development	12/02	01/13
All Materials Ordered	01/12	01/12
Mechanical Construction	01/14	01/27
System Performance Test Phase	01/20	02/07
Component Testing	01/24	02/02
Simulated Flight Test	02/04	02/04
Separation Ground Testing	01/29	02/04
Full Scale Flight Testing	02/09	03/11
Flight Test #1	02/09	02/09
Flight Test #2 (Backup)	03/09	03/09
Flight Demonstration Deadline	03/25	03/25
UAV Subsystem	**08/31/18**	**03/25/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/11
Requirements Derivation	09/10	10/15
Trade Studies	09/24	10/22
CAD Mechanism Analysis	10/15	11/16
Neural Network Trade Study	10/31	11/21
Target Detection Develepement	11/14	01/14
Sub-System Validation Testing	12/16	02/20
Construction Procedure Developeme...	12/07	01/17
All Materials Received	01/18	01/18
UAV Construction	01/18	01/25
Payload Bay Integration	01/20	01/30
Ground Testing Phase	01/26	02/07
UAV Flight Test #1	01/30	01/30
UAV Flight Test #2	02/05	02/05
Full Scale Flight Testing	02/08	03/11
Flight Test #1	02/09	02/09
Post Launch Analysis	02/10	02/24
Flight Test #2 (Backup)	03/09	03/09
Payload Demo Flight Deadline	03/25	03/25



A Safety

A.1 Project Risks

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Timeline.	Insufficient planning or scheduling; failure to hold individual members accountable for responsibilities.	Falling behind schedule for construction or documentation; missing NASA deadlines.	3D	1. Trello, Overleaf, and Slack will be used to ensure team and squad coordination in writing, testing, and construction. 2. In the event that the team falls behind, members will put in extra work until the team is back on schedule. 3. Leads will hold their members, and each other, accountable to deadlines.	1. All NASA document submission dates will be met. 2. The subscale rocket will be ready to fly by the subscale date. 3. The subscale rocket will provide useful scaled information for all squads.	3C
Budget.	Insufficient planning or frugality of material purchases; insufficient annual team funding or sponsorship.	Inability to purchase materials or cover transportation costs; depleting team account or taking on debt.	2D	1. All material costs will be determined prior to construction. 2. Travel/transportation costs will be planned out. 3. The team will pursue additional sources of funding when necessary.	1. The team's yearly costs will be less than the team's yearly funds. 2. A running sum of all costs and funds up to the present day for that academic year is being kept. 3. The total costs incurred by the squads will stay within their respective allotted budgets.	2C
Personnel.	Team members quitting the team.	That team member's responsibilities will go unfulfilled.	1D	In the event that a team member quits, their responsibilities will be spread among other members.	The squad lead of the departed member will reassign construction and testing responsibilities.	1D
Equipment and Facilities.	Improper tool use; lack of experience with tools or surrounding facility.	Physical injury to personnel; denial of access to facilities and tools.	2C	1. Every team member will have proper knowledge and training of required tools. 2. A safety committee member will always be present in the workshop during build sessions. 3. Personal protective equipment will always be used.	1. Every member will be checked off for basic safety and tool training. 2. Personal protective equipment will be provided in every construction space.	2C
Launch.	Improper launch procedures; defective launch components such as igniters or motors.	Catastrophe at takeoff; failure to launch; excessively horizontal launch angle.	4B	1. Rocket will be thoroughly inspected before launch. 2. All launch checklists and procedures will be carried out. 3. The team mentor, David Brunsting, will assist the team at every launch.	1. Launch checklists will be created and reviewed. 2. Each squad will develop a proper procedure for inspecting and clearing their system for launch.	4B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Recovery.	Premature recovery system activation; no recovery system activation.	Damage to the rocket and its systems; physical injury to personnel; damage to private property.	3C	1. The recovery squad will ensure that the recovery system functions properly through construction, testing, and launch. 2. On launch days, the recovery checklists will be carried out. 3. Recovery functionality will be verified at a full-scale test launch.	1. Recovery will verify a $>90\%$ success rate for deploying the parachute through testing. 2. Recovery will develop a proper procedure for inspecting, arming, and clearing their system for launch.	3A
UAV.	Insufficient securing during flight.	Induced spin or tilt on rocket flight.	3B	1. The UAV squad will ensure that their system functions properly through construction, testing, and launch. 2. On launch days, the UAV and checklist will be carried out. 3. UAV functionality will be verified at a full-scale test launch.	1. UAV will verify a $>90\%$ success rate for remaining secure during flight. 2. UAV will verify a $>90\%$ success rate for success deployment and flight of the vehicle. 3. UAV will develop a proper procedure for inspecting, arming, and clearing their system for launch.	3A
ABS.	Unbalanced forces on rocket; insufficient securing during flight.	Induced spin or tilt on rocket flight; failure to hit precise apogee.	3B	1. The ABS squad will ensure that their system functions properly through construction, testing, and launch. 2. On launch days, the ABS checklist will be carried out. 3. ABS functionality will be verified at a full-scale test launch.	1. ABS will verify a $>90\%$ success rate for remaining secure during flight. 2. ABS will verify a $>95\%$ chance of no structural failure of their system, especially relating to the drag tabs or the load-bearing rods. 3. ABS will develop a proper procedure for inspecting, arming, and clearing their system for launch.	3A
Resources.	Failure of suppliers to provide materials; insufficient planning or communication of required materials, equipment, and facilities.	Inability to construct rocket or its systems; construction of rocket or its systems with suboptimal material; time delay in waiting for required facility access.	2C	1. Each squad will outline necessary materials, equipment, and facilities prior to construction. 2. Year-long budget and spending plans will be implemented.	1. Each lead has submitted a list of materials to the safety officer. 2. A running list of purchases of materials by individuals squads will be kept.	2C

A.2 Personnel Hazards

A.2.1 Construction Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Direct contact with strong adhesive, such as epoxy	Failure to use/improper use of gloves when working with adhesives	Skin irritation	2C	1. Nitrile gloves are available and required for any team member working with adhesives such as epoxy.	1. Procedures for using epoxy have been created and will be adhered to by all team members. 2. Procedures for using gloves have been created and will be adhered to.	2A
Contact with the spinning bit of a portable drill	Improper use of a portable drill	Cut or burn to the area of contact	2B	1. Team personnel must be certified to use a power drill before using one during construction.	1. The certification process involves the signing of a safety rules form and a quiz to ensure that the team members know how to properly use a tool before using one during construction.	2A
Contact with the spinning bit of a dremel	Improper use of a dremel	Cut or burns to the area of contact	2B	1. Team personnel must be certified to use a dremel before using one during construction.	1. The certification process involves the signing of a safety rules form and a quiz to ensure that the team members know how to properly use a tool before using one during construction.	2A
Contact with the sanding surface of a belt/disk sanding machine	Improper use of a belt/disk sanding machine	Sanding burns and cuts to the area of contact	3B	1. Team personnel must be certified to use the belt/disk sanding machine before using one during construction.	1. The certification process for the Belt/Disk sanding machine involves signing a safety rules from, passing a quiz on proper operation of the machine, and demonstrating competency with the machine to Notre Dame machine shop personnel.	3A
Projectiles/ Shrapnel in the eyes	Use of power tools, such as dremels, drills, or sanding machines without safety glasses	Potentially serious eye damage	3B	1. Safety glasses will be worn at all times when any machines or power tools are being used in the shop.	1. Safety glasses are available on a shelf just outside the machine shop. 2. Before being allowed to participate in construction, team members must be certified to do so. This certification process involves signing a safety rules form and passing a safety quiz on general shop rules, such as the use of safety glasses.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Dust inhalation	Sanding or cutting material without proper ventilation and/or respiratory protection.	Lung and sinus irritation of inflammation. Potentially serious long-term effects.	3C	1. A vacuum tube/shop vac must be attached to the debris duct of any dust-producing machine when in operation. 2. A dust mask must be worn at all times when performing an action that produces dust, such as sanding or cutting of raw materials.	1. Dust masks are available to team members in the workshop. 2. Team members must be certified on a machine to work with the machine. The certification process involves passing a quiz on safe operation and, in the case of the belt/disk sander, demonstrating competency with the machine.	3A
Contact with spinning blade of a miter saw	Lack of attention while cutting with a miter saw.	Serious cuts	4B	1. Personnel must be certified to use a miter saw before using one during construction.	1. The certification process for the miter saw involves signing a safety rules from, passing a quiz on proper operation of the machine, and demonstrating competency with the machine to Notre Dame machine shop personnel.	4A

A.2.2 Testing Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by projectile from unplanned spring decompression during testing	1. Latch mechanism or retainment cords break during recovery system ground testing. 2. Servo releases the latch mechanism prematurely.	Potential for serious injury to personnel	3B	1. During ground testing, the spring will be pointed away from all personnel at all times. 2. Latch mechanism has been designed to be capable of holding substantially more load than will be experienced during typical recovery operation. 3. An array of spring retainment cords will be used such that one broken cord will not compromise the retainment of the springs. 4. The spring retainment cords have been selected such they will be capable of holding substantially more load than would be experienced during normal operation.	1. Procedures for ground testing of the recovery system have been created and will be strictly adhered. 2. Analysis has been done on the latch mechanism and load bearing bulkheads to confirm that the mechanism is capable of taking greater than the expected loads. 3. The current recovery design calls for cordage with a tensile strength of 2100 lbs, 4 times the load at which the springs will be compressed.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel exposure to harmful chemicals or chemical fire	Contact with broken or exploded batteries from UAV	Chemical fire burns or skin irritation	3B	1. New batteries will be purchased and used in construction of the UAV 2. Personnel will use gloves when handling batteries 3. Batteries will not be overcharged	1. New batteries have a significantly decreased chance of breaking or exploding 2. Latex gloves can reduce the severity of, or prevent entirely a chemical burn 3. Overcharging significantly increases the chance of battery fire or explosion. Therefore, batteries which are not overcharged will be less likely to fail	3A
Overheated electronics cause fire	Battery, servo motor or other electronic device receives more current than it was designed to.	Battery, servo or other electronic device overheats and causes burns or fire.	3B	Microcontrollers and power distribution boards will prevent sensitive electronics from drawing or providing more current than they were designed.	All motors and electronics have been chosen such that the max current draw is less than the maximum current that the powering batteries can provide.	3A
UAV flies into personnel during testing.	UAV testing performed in close proximity to crowds of personnel.	Flying UAV could strike personnel, causing injury.	3B	All UAV testing will be done in an open area with adequate room for the UAV to fly away from personnel.	The UAV will only be tested at local drone fields or at rocket launch sites.	3A

A.2.3 Launch Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket launches at a large angle with the vertical	1. The rocket is unstable 2. The launch rail is set up incorrectly	1. The rocket could launch into the crowd, potentially causing severe injury 2. The rocket could drift outside the launch radius, causing property damage or injury to bystanders	4B	1. All launches will be done in accordance with NAR guidelines on proper rail setup and launch angle 2. RSO recommendations for launch angle and rail setup will be followed 3. The rocket will be constructed to have a static stability of between 2 and 2.8	1. All launches will be done with an experienced RSO present and giving recommendations. 2. The team mentor, a Tripoli member and level 2 HPR certified, will be present to aid with launch rail setup and recommendations for launch angle, taking into account wind and crowd location 3. Rocket launch procedures have been created and will be followed 4. The center of gravity of the rocket will be measured before all launches to confirm that the static stability of the rocket meets the requirements. If the stability is outside the safe range, the rocket will not launch	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Motor failure during launch	1. Motor dropped or incorrectly assembled 2. Motor igniter incorrectly installed in the motor	Potential for explosion that could cause injury to team personnel and bystanders	4B	1. Minimum distance tables will be enforced during all launches 2. Team mentor, David Brunsting, will the only one to handle and insert motor. Dave has level 2 High Power Rocketry certification through Tripoli Rocket Association 3. The motor and igniter will be visually inspected prior to launch	1. Only motors that pass visual inspection will be flown 2. Only motors approved by the team mentor will be flown 3. The rocket will launch only if everyone is complying with minimum distance tables and RSO recommendations 4. The rocket will launch only if the team mentor was the individual who inserted and secured the motor in the rocket	4A
Personnel hit by rocket falling in ballistic trajectory	1. Failure of altimeter to signal deployment to servo 2. Failure of servo to release latch mechanism 3. Battery failure during flight 4. Failure of the deployed spring to separate the rocket after latch release	Potential for death or severe injury to personnel if hit by falling rocket	4B	1. All recovery electronics (altimeters, servos, and batteries) will be designed in such a way that a single failure of any of the electronic devices will not impact the system's ability to separate the rocket and eject the parachute 2. The springs have been selected such that they are capable of producing more force than is necessary to separate the rocket 3. Ground tests will be done prior to launch to ensure that all components of the recovery system are in full working order 4. Batteries used for launch will be fully charged	1. The current design calls for two independent altimeter-battery-servo systems, with either system fully capable of releasing the latch mechanism and causing separation of the rocket 2. Ground testing will ensure that the system is in full working order and that redundancy exists within the system 3. Procedures and checklists for ground testing of the recovery system have been created and will be strictly adhered to 4. Procedures for checking and replacing batteries prior to launch have been created and will be strictly adhered to 5. For testing and launches, the springs will be compressed to approximately 450 lbs, greater than the 300 lbs that it is estimated to be required for rocket separation. The spring are capable of compression to greater than 1000 lbs	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by rocket falling at higher than intended speeds	1. Failure of the Chute Releases to allow the parachute to open during rocket descent 2. Improper folding of the parachute during assembly	Potential for severe injury to personnel if hit by rocket	4B	1. The Chute Releases will be set up in such a way that failure of one Chute Release will not impact the recovery of the rocket 2. The parachute will be folded in a consistent way that will allow it to easily open after the Chute Release as stopped restraining the parachute	1. The current design calls for two Chute Releases set up in series, such that the tension restraining the parachute will be released if either Chute Release activates 2. The Chute Releases will be tested on the ground prior to launch 3. Procedures for folding the parachute prior to launch have been created and strictly adhered to	4A
Personnel hit by rocket falling at intended speeds	Improper conduct during a launch	Potential for serious injury to personnel if hit by falling rocket	3C	1. All participants in launch procedures must demonstrate knowledge of the hazards and safety procedures associated with a launch	1. Participants in launch proceedings will sit through a launch safety briefing and be required to pass a quiz on launch safety before they will be allowed on the launch site	3A
Premature ignition of motor	1. Motor or motor igniter incorrectly handled 2. Ignition wires have live voltage during igniter instillation	Potential for burns to personnel installing motor igniter	3B	1. Team mentor, David Brunsting, will the only one to handle and insert motor. Dave has level 2 High Power Rocketry certification through Tripoli Rocket Association 2. The motor and igniter will be visually inspected prior to launch 3. All launches will be done in collaboration with a registered rocketry club	1. An experienced LCO, from the collaborating rocket club, will be operating the launch control unit during launch operations, assuring that the launch control unit will be operated properly 2. The collaborating club's launch control unit will be used during launches. Launching with a registered club's launch control unit ensures that the hardware is reliable 3. Procedures for motor instillation and rocket launch has been created and will be strictly adhered to.	3A

A.2.4 Recovery Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by projectile from unplanned spring decompression during testing	1. Latch mechanism or retainment cords break during recovery system ground testing. 2. Servo releases the latch mechanism prematurely.	Potential for serious injury to personnel	3B	1. During ground testing, the spring will be pointed away from all personnel at all times. 2. Latch mechanism has been designed to be capable of holding substantially more load than will be experienced during typical recovery operation. 3. An array of spring retainment cords will be used such that one broken cord will not compromise the retainment of the springs. 4. The spring retainment cords have been selected such they will be capable of holding substantially more load than would be experienced during normal operation.	1. Procedures for ground testing of the recovery system have been created and will be strictly adhered. 2. Analysis has been done on the latch mechanism and load bearing bulkheads to confirm that the mechanism is capable of taking greater than the expected loads. 3. The current recovery design calls for cordage with a tensile strength of 2100 lbs, 4 times the load at which the springs will be compressed.	3A
Personnel hit by projectile from unplanned spring decompression during launch operation.	1. Latch mechanism or retainment cords break during recovery system ground testing. 2. Servo releases the latch mechanism prematurely.	Potential for serious injury to nearby personnel	3B	1. Latch mechanism has been designed to be capable of holding substantially more load than will be experienced during typical recovery operation. 2. An array of spring retainment cords will be used such that one broken cord will not compromise the retainment of the springs. 3. The spring retainment cords have been selected such they will be capable of holding substantially more load than would be experienced during normal operation. 4. The servos, and the altimeters that control the servos, will not be powered on until the rocket is on the launch pad, in the vertical position. 5. External safety pins will be used to physically block the latch mechanism from opening after the spring has been compressed. These pins will be pulled after the rocket is on the launch pad and in the vertical position.	1. Procedures for and launch operation of the recovery system have been created and will be strictly adhered. 2. Analysis has been done on the latch mechanism and load bearing bulkheads to confirm that the mechanism is capable of taking greater than the expected loads 3. The current recovery design calls for cordage with a tensile strength of 2100 lbs, 4 times the load at which the springs will be compressed	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by rocket falling in ballistic trajectory.	1. Failure of altimeter to signal deployment to servo. 2. Failure of servo to release latch mechanism. 3. Battery failure during flight. 4. Failure of the deployed spring to separate the rocket after latch release.	Potential for death or severe injury to personnel.	4B	1. All recovery electronics (altimeters, servos, and batteries) will be designed in such a way that a single failure of any of the electronic devices will not impact the system's ability to separate the rocket and eject the parachute. 2. The springs have been selected such that they are capable of producing more force than is necessary to separate the rocket. 3. Ground tests will be done prior to launch to ensure that all components of the recovery system are in full working order. 4. Batteries used for launch will be fully charged.	1. The current design calls for two independent altimeter-battery-servo systems, with either system fully capable of releasing the latch mechanism and causing separation of the rocket. 2. Ground testing will be done to ensure that redundancy exists in the system. 3. Procedures and checklists for ground testing of the recovery system have been created and will be strictly adhered to. 4. Procedures for checking and replacing batteries prior to launch will be created and strictly adhered to. 5. For testing and launches, the springs will be compressed to approximately 450 lbs, greater than the 300 lbs that it is estimated to be required for rocket separation. The spring are capable of compression to greater than 1000 lbs.	4A
Personnel hit by rocket falling at higher-than-intended speeds.	1. Failure of the Chute Releases to allow the parachute to open during rocket descent. 2. Improper folding of the parachute during assembly	Potential for death or severe injury to personnel.	4B	1. The Chute Releases will be set up in such a way that failure of one Chute Release will not impact the recovery of the rocket. 2. The parachute will be folded in a consistent way that will allow it to easily open after the Chute Release as stopped restraining the parachute.	1. The current design calls for two Chute Releases set up in series, such that the tension restraining the parachute will be released if either Chute Release activates. 2. The Chute Releases will be tested on the ground prior to launch. 3. Procedures for folding the parachute prior to launch have been created and will be strictly adhered to.	4A
Personnel hit by rocket falling at intended speeds.	Improper conduct during a launch.	Potential for serious injury to personnel.	3C	1. All participants in launch operations must demonstrate knowledge of the hazards and safety procedures associated with a launch.	1. Participants in launch proceedings will sit through a launch safety briefing before they will be allowed on the launch site.	3A

A.2.5 Unmanned Aerial Vehicle Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel exposure to harmful chemicals or chemical fire	Contact with broken or exploded batteries	Chemical fire burns burns, or skin irritation	3B	1. New batteries will be purchased and used in construction of the UAV. 2. Personnel will wear latex gloves while handling batteries. 3. Batteries will not be overcharged.	1. New batteries have a significantly decreased chance of breaking or exploding. 2. Latex gloves can reduce the severity of, or prevent entirely, a chemical burn. 3. Overcharging significantly increases the chance of battery fire or explosion. Therefore, batteries which are not overcharged will be less likely to fail.	3A
Personnel struck by falling UAV	UAV separated from housing during flight	Death or severe personnel injury	4C	1. UAV will be fastened using 0.25" diameter stainless steel hairpin cotter pins. 2. UAV housing will be attached to the rocket via a double thickness bulkhead. 3. Nose cone will be secured by a locked lead screw.	1. Increased thickness of cotter pins, and the material choice significantly increase the failure shear load of the pin. 2. A double thickness bulkhead is far less likely to fracture and detach from the body tube or the connection to the UAV housing. 3. In the event of the UAV separating from housing, a locked nose cone will likely contain the loose UAV, preventing it from leaving the body tube.	4A
UAV flies into personnel during testing.	UAV testing performed in close proximity to crowds of personnel.	Flying UAV could strike personnel, causing injury.	3B	1. All UAV testing will be done in an open area with adequate room for the UAV to fly away from personnel.	1. The UAV will only be tested at local drone fields or at rocket launch sites.	3A
Overheated electronics cause fire	Battery, motor or other electronic device receives more current than it was designed to.	Battery, motor or other electronic device overheats and causes burns or fire.	4B	1. Microcontrollers and power distribution boards will prevent sensitive electronics from drawing or providing more current than they were designed.	1. All motors and electronics have been chosen such that the max current draw is less than the maximum current that the powering batteries can provide.	4A
Sparking inside UAV	Faulty wiring or electrical connection	Potential for fire	3B	1. All wiring connections will be soldered. 2. Electrical engineering students and advisers will check connections to ensure no errors have been made in construction.	1. Soldered wires have a significantly decreased chance of failure. 2. Checking wiring connections several times can greatly reduce the risk of negligent mistakes and faulty connections, which are the main modes of failure in wiring.	4A

A.3 Failure Modes and Effects Analysis

A.3.1 Vehicles FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket bulkhead failure	Structurally insufficient materials or improperly applied epoxy.	Rocket could shear, result in partial mission failure, or serious injury.	4B	1. Follow manufacturer instructions for mixing epoxy. 2. Stress tests will be performed on the materials in the structure of the bulkhead.	1. Verify strength of materials used for bulkhead structure. 2. Verify the quality of the assembly of the structure.	4A
Rocket is dropped	Improper handling and carrying of launch vehicle.	Fractures in body of rocket, resulting in partial mission failure.	3B	1. At least three people will carry the rocket at any given time that the rocket is being handled. 2. The inside of the rocket will be lined with carbon fiber sheets.	Procedures and checklists for rocket handling will be created and adhered to.	3A
Fin can malfunctions.	Improper construction or insufficient strength of the fin can.	Rocket can become aerodynamically unstable, and shear, possible total mission failure.	4B	The wings will be properly constructed and capable of max dynamic pressure.	1. Calculations will be run to ensure fin can strength 2. Construction will be inspected to ensure there were no errors	4A
Motor mount failure.	Improper installation of motor.	Could result in serious injury or death, total mission failure.	4B	The Team Mentor will ensure proper installation of motor and motor mount.	Pre-launch procedures will ensure that the motor mount is properly installed.	4A
Rocket descent faster than expected.	1. Improper folding of parachute. 2. Parachute does not open during rocket descent. 3. Rocket fails to separate.	Rocket reaches terminal velocity and breaks upon impact with ground, results in total mission failure.	4B	1. Parachute will be folded properly and checked by another member of recovery squad. 2. Ensure that rocket is capable of separating to release the parachute from the force provided by compressed spring system.	Procedures and checklists for parachute folding will be created and adhered to.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket engine misfire	Failure rocket firing system to ignite the engine at the proper time.	Could result in serious injury or even death. total mission failure.	4B	1. The electronic firing system will not be connected until the rocket is at the pad, and ready to launch. 2. Personnel will always remain clear of the rocket if it has the possibility of ignition. 3. The ignition system will be disconnected in the event that the rocket does not ignite when prompted.	1. In launch procedures, make sure firing system is connected when the rocket is ready to launch. 2. Make sure also it states to stay beyond the minimum safe distance from the rocket when it has the possibility of ignition. 3. Also specify if it does not ignite when planned, to wait 5 minutes before approaching it.	4A
Loss of UAV.	1. Structurally deficient UAV payload bay. 2. Improper installation of the UAV. 3. UAV Payload bay does not release UAV.	Possible loss of UAV functionality, resulting in partial mission failure.	3B	1. Materials and adhesives will capable of holding UAV payload bay. 2. A procedure will be created for installing the UAV safely during pre-launch. 3. UAV will be able to survive stresses placed upon it by the payload bay.	1. In launch procedures, make a standard and proven procedure for installing UAV. 2. In construction, verify proper materials, and adhesives are used in the making of the payload bay. 3. Test and verify design of UAV releasing mechanism before flight.	3A
Loss of Air Braking System.	1. Structurally deficient parts within the rocket that hold the Air Braking System. 2. Improper installation of the Air Braking System. 3. Installation impedes function of Air Braking System.	Possible loss of Air Braking System, resulting in partial mission failure.	2B	1. The materials that bind the air braking system in the body of the rocket will be secure during installation. 2. The installation will not interfere with the functionality of the air braking system.	Verify the installation of the Air Braking system is complete, and it is functional before the flight.	2A
Loss of Recovery System.	1. Structurally deficient parts within the rocket holding the Recovery System. 2. Improper installation of Recovery System.	Possible loss of Recovery System, resulting in total mission failure.	3B	1. The materials that bind the recovery system in the body of the rocket will be secure during installation. 2. The installation will not interfere with the functionality of the recovery system.	The recovery system, and its proper installation, will be fully inspected before flight.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Loss of Rocket Aerodynamic Stability	Aerodynamic forces lead to the rocket losing control.	Rocket could going in the wrong direction, leading to rocket destruction, total mission failure, and possible injury or death.	4B	1. The rocket will be aerodynamically stable. 2. The internals of the rocket and its payloads will not vastly alter the center of mass away from the geometric center of the the rocket.	Utilize the wind tunnel calculations, the center of mass calculations, and center of thrust to makes sure all three forces are aligned and not going to cause the rocket to be unstable.	4A

A.3.2 Recovery FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Failure of the rocket to separate at apogee	1. Failure of altimeter to signal deployment to servo 2. Failure of servo to release latch mechanism 3. Battery failure during flight 4. Failure of the deployed spring to separate the rocket after latch release	Rocket descends on a ballistic trajectory at a dangerously high speed.	4B	1. All recovery electronics (altimeters, servos, and batteries) are designed in such a way that a single failure of any of the electronic devices will not impact the system's ability to separate the rocket and eject the parachute. 2. Ground tests will be done prior to launch to ensure that all components of the recovery system are in full working order. 3. Batteries used for launch will be fully charged. 4. The springs have been selected such that they are capable of producing more force than is necessary to separate the rocket.	1. The current design calls for two independent altimeter-battery-servo systems, with either system fully capable of releasing the latch mechanism and causing separation of the rocket. 2. Ground testing will be done to ensure that redundancy exists in the system. 3. Procedures and checklists for ground testing of the recovery system have been created and will be strictly adhered to. 4. Procedures for checking and replacing batteries prior to launch will be created and strictly adhered to. 5. For testing and launches, the springs will be compressed to approximately 450 lbs, greater than the 300 lbs that it is estimated to be required for rocket separation. The springs are capable of compression to greater than 1000 lbs.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Failure of the parachute to open at the correct altitude	1. Failure of the Chute Releases to allow the parachute to open during rocket descent. 2. Improper folding of the parachute during launch setup.	Rocket descends with higher-than-designed speed, potentially causing damage to the fins or airframe.	3B	1. The Chute Releases will be set up in such a way that failure of one Chute Release will not impact the recovery of the rocket. 2. The Chute Releases will be individually tested prior to flight. 3. The parachute will be folded in a consistent way that will allow it to easily open after the Chute Release as stopped restraining the parachute.	1. The current design calls for two Chute Releases set up in series, such that the tension restraining the parachute will be released if either Chute Release activates. 2. Procedures and checklists for testing the Chute Releases prior to flight have been created and will be strictly adhered to. 3. Procedures for folding the parachute prior to launch have been created and strictly adhered to.	3A
Failure of the opened parachute to adequately slow down the rocket	Improper sizing of the parachute.	Rocket descends with higher-than-designed speed, potentially causing damage to the fins or airframe.	3B	The parachute has been chosen such that the rocket will descend at a safe speed.	The Cert 3-Series XXLarge parachute that will be used for all launches has been calculated to bring the kinetic energy of the largest rocket section to below 75 ft-lbs.	3A
Parachute separates from the rest of the rocket during descent	1. Broken shock cord. 2. Broken quick-link or eyebolt connection.	Rocket descends at high speed and likely severely damaged on impact with the ground.	4B	1. Shock cords have been selected such that they are capable of holding significantly greater loads than would be experienced in a normal flight. 2. Any sharp objects that could cut or weaken the shock cords during descent will be covered. 3. Eyebolts, quick-links and other load-bearing fittings have been selected such that they are capable of holding more load than would be experienced in a normal flight.	1. The 9/16 inch nylon shock cords that will be used have a break strength of 2400 lbs, significantly greater than the forces that will be experienced in flight. 2. The current design does not contain any sharp edges or other threats to the shock cord that needs to be covered. 3. The quick links that will be used have a max working load of 2100 lbs, significantly greater than the forces that will be experienced in flight. 4. The eyebolts that will be used have a strength of 1400 lbs, significantly greater than the forces that will be experienced in flight.	4A
Rocket drifts further than intended during descent.	1. Improperly sized parachute. 2. Chute Release allows the main parachute to open earlier than intended.	Rocket could drift outside of the launch field, complicating recovery or potentially causing damage to property or the environment.	2D	1. The descent of the rocket will be staged to reduce the descent time, and therefore the drift distance. 2. The parachute has been sized such that the drift radius of the rocket is within the mission specifications. 3. The Chute Releases will be individually tested prior to flight to ensure proper operation.	1. Calculations will be done to ensure that the rocket will not drift outside of a 2500 ft radius during descent in up to 20 mph winds. 2. Procedures and checklists for testing the Chute Releases prior to flight have been created and will be strictly adhered to.	2B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket separates during motor burn.	1. Latch mechanism breaks during flight, releasing compressed spring. 2. Restraining cords break during flight, prematurely releasing compressed spring.	Parachute opens during motor burn, likely causing an erratic and dangerous flightpath and causing severe damage to the airframe	4B	1. Latch mechanism has been designed such that it can take significantly higher loads than it will experience in flight. 2. Restraining cords have been chosen such that they are capable of sustaining significantly more load than they will be under during launch. 3. Multiple restraining cords will be used in a redundant fashion. 4. The entire recovery system will be tested prior to launch to confirm that the system is in full working order.	1. Load analysis has been done on the latch mechanism and load-bearing bulkheads to confirm that they will be capable of sustaining the required loads. 2. The current recovery design calls for 1/8th inch kevlar shock cords to retain the springs. With a tensile strength of 2100 lbs, each cord is capable of taking 4 times the load at which the springs will be compressed. 3. The entire parachute deployment system will be ground tested prior to flight to confirm that the system is in full working order.	4A

A.3.3 Air Braking System FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Power supply failure in electrical system.	Under charged batteries, poor electrical connections between components and PCB.	Tabs fail to extend and rocket over shoots apogee.	3C	1. Batteries will be chosen with adequate power to survive delays on launch pad. 2. Physical control switches will ensure system is only on when necessary. 3. All electrical connections will be made with solder or purpose-built connectors and electrical tape or shrink wrap if necessary. 4. Separate switches will power and fully arm the system so it does not run unnecessarily.	1. Trade study performed on available batteries to choose brand that meets our needs. 2. Team members will be trained in pre-launch operation of control switches and be able to identify if battery needs to be replaced/charged. 3. Connects will be tested prior to launch with multimeter and by running system. 4. Status LEDs will alert operator if system is not correctly enable or loses power during launch preparation.	3A
Incorrect or missing sensor data.	Malfunction in sensor sampling, improper component install, poor data filter code performance.	The system functions improperly by extending tabs too early or too late for correct apogee.	2D	1. Sensors will be securely integrated with microcontroller through soldered PCB. 2. Highest performing sensor will be chosen for given size and cost restraints. 3. Sensors will be installed in acceptable operating environment. 4. Kalman filter will be utilized to limit effects of bad sensor readings.	1. Trade study to be performed to choose sensors that best meet our needs. 2. Multiple sensors will be purchased and ground tested to find best data fidelity. 3. Physical needs (i.e. holes in rocket body for altimeter) will be accounted. 4. Filtering code will be peer-reviewed and tested for accuracy.	2B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Undesired microcontroller command signals.	Bad control code algorithm, mistaken connections with microcontroller.	Microcontroller takes good sensor input, but sends bad control commands to system extending tabs at wrong time.	3B	1. Reliable microcontroller will be researched and chosen. 2. Multiple peer reviews and tests used on control code. 3. Clearly labeled PCB connections ensure proper connections with sensors. 4. Component selection and written code ensure low latency between sensor input and tab motion.	1. Trade study done on best available device for our needs. 2. Control code will be verified through peer review and ground testing. 3. PCB reviewed prior to fabrication and schematic available during assembly to prevent incorrect connections.	2A
Broken mechanical system.	Excessive force to snap drag tabs, jammed gears, seized motor.	Tabs are unable to position themselves correctly to stop rocket at proper apogee.	4B	1. High strength materials chosen to withstand expected forces plus factor of safety. 2. Few gears will be used to avoid dangers of overly complex system. 3. Reliable motor brand will be chosen. 4. Fragile components (wires, plastic clips) will be securely fastened and covered to avoid damage during flight.	1. Trade study performed on motor brands. 2. Ground testing with physical components avoids unexpected launch failures. 3. Tight tolerances on components will prevent most jams.	3B
Operator error.	System arming and power switches toggled incorrectly in preparation for flight.	Air brake not ready for launch and does not deploy.	3C	1. Switches will be labeled and easily accessible within rocket body. 2. Status LEDs will provide feedback to user that system is correctly enabled.	1. System arming responsibility delegated in advance of launch. 2. Selected operator will be trained on all pre-flight procedures related to Air Braking System.	3A
Impossible target apogee.	Selected motor propels rocket to altitude outside of range compatible with drag tab guidance to target.	Drag tabs unable to slow rocket sufficiently to stop where specified, or rocket motor not powerful enough to reach desired altitude.	3B	1. Motor sizes will be researched to ensure choice will slightly overshoot target apogee and allow rocket to be adequately slowed by air brake. 2. Weight and shape analysis will be performed on rocket design to model system and predict apogee for system with no tab extension.	1. All significant changes in weight will be documented to recalculate predicted apogee, with ballasts used as necessary. 2. Drag tabs will be sufficiently large to accommodate large amount of overshoot by chosen motor.	3A

A.3.4 Unmanned Aerial Vehicle FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
UAV falls during flight or fails to start	Defective wiring	Mission failure	4C	1. All wiring connections will be soldered. 2. Electrical engineering students and advisors can check connections to ensure no errors have been made in construction.	1. Soldered wires have a significantly decreased chance of failure. 2. Checking wiring connections several times can greatly reduce the risk of negligent mistakes and faulty connections, which are the main modes of failure in wiring.	4A
UAV stops flying before beacon delivery	Insufficient battery charge	Mission failure	4C	1. Battery will be charged sufficiently before flight. 2. UAV team will select a battery with sufficient flight time.	1. A sufficiently charged battery has a significantly decreased chance of losing power during flight. 2. By selecting a battery with ample power and running time, the chances of a dead battery during flight are greatly reduced.	4A
UAV crashes to ground	Motor failure	Mission failure or personnel injury	4C	Motors will be thoroughly tested before flight.	Increased motor testing reduces the risk of motor failure. Flight tests and practices can be conducted on campus with an advisor, which will allow for extensive testing.	4B
Beacon is not deployed	Servo motor failure	Mission failure	4C	Motors will be thoroughly tested before flight.	Increased motor testing reduces the risk of motor failure. Flight tests and practices can be conducted on campus with an advisor, which will allow for extensive testing.	4B
UAV is unable to launch	Stepper or servo motor failure	Flight and mission failure	4C	Motors will be thoroughly tested before flight.	Increased motor testing reduces the risk of motor failure. Flight tests and practices can be conducted on campus with an advisor, which will allow for extensive testing.	4B
UAV is unable to launch	Locking mechanism on the UAV legs is unable to be disengaged	Flight and mission failure	4B	1. Unlocking mechanism will be tested several times. 2. Multiple redundancies will be built into the unlocking mechanism. 3. The servo motor driving the UAV out of the body tube will deliver sufficient power.	1. Increased testing reduces the risk of failure of the locking mechanism. 2. Adding redundancy reduces the risk of total system failure, as a backup will be present. 3. The selected servo motor can deliver far more force than the shear pins require to disengage from the legs.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
UAV is unable to launch	Switch and/or remote mechanism fails to power on the UAV	Flight and mission failure	4C	1. Unlocking mechanism will be tested several times. 2. Multiple redundancies will be built into the system that powers on the UAV.	1. Increased testing reduces the risk of failure of the system which powers on the UAV. 2. Adding redundancy reduces the risk of total system failure, as a backup will be present.	4A

A.3.5 Launch Operations FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Airframe pieces out of alignment	Improper assembly of the rocket	Potential for damage to the couplers or airframe.	3B	1. Stands will be created to ensure that the rocket pieces are all at the same level during assembly. 2. The airframe will be assembled according to defined procedures.	Procedures and checklists for rocket assembly have been created and will be adhered to.	3A
Airframe dropped during or after assembly	Lack of care during launch operations	Potential for damage to the airframe, nosecone, fins or payloads.	4B	1. Stands will be constructed to rest the rocket on during transport and assembly. 2. The rocket airframe will be assembled according to defined procedures.	Procedures and checklists for rocket assembly have been created and will be adhered to.	4A
Payload or subsystem improperly integrated into rocket	Improper assembly of rocket or rocket subsystem	Potential for damage to rocket airframe, subsystem or payload	4B	Launch operations personnel must be aware of how the rocket subsystems fit together and secure into the rocket airframe.	Procedures and checklists for rocket assembly, payload/subsystem assembly, and payload/subsystem integration have been created and will be followed during launch operations.	4A
Parachute folded improperly during rocket assembly	Mistake made during parachute folding.	Parachute could become stuck in rocket during descent.	4B	Recovery personnel must follow defined procedures for folding a parachute.	Specific, consistent procedures for folding the parachute have been created and will be strictly followed before and during launch operations.	4A
Recovery spring unexpectedly decompresses during assembly or launch setup	1. Latch mechanism or spring restraining cords break 2. Improper assembly / handling of the recovery subsystem	Potential for airframe damage if spring is not properly braced / compressed	3B	1. Safety pins that physically block the latch mechanism from releasing will be installed during recovery assembly. 2. Assembly and integration procedures will be followed at all times.	Procedures for recovery subsystem assembly and recovery integration have been created and will be adhered to before any test flights of the vehicle.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Motor is damaged during assembly	Motor is dropped or improperly assembled	Potential for motor explosion	4B	Motors will be assembled and installed by the team mentor, who is certified to do so.	Our team mentor, Dave Brunsting, will be present at all launches of the rocket and will assemble the motors. He is Level 2 HPR certified through Tripoli Rocket Association.	4A
Motor igniter installed incorrectly	Personnel installing the igniter do not know how to do so	Potential for motor explosion	4B	Igniters will be installed by the team mentor, who is certified to do so.	Our team mentor, Dave Brunsting, will be present at all launches of the rocket and will install the igniters. He is Level 2 HPR certified through Tripoli Rocket Association.	4A
ABS subsystem set up incorrectly	Mistake made during subsystem assembly or integration.	ABS does not function properly, causing rocket to achieve incorrect apogee.	2B	ABS assembly and setup procedures will be followed at all times.	Procedures for ABS assembly and and setup have been created and will be followed during all launches in which the ABS is active.	2A
UAV payload incorrectly assembled or set up	Mistake made during UAV assembly, setup, or integration.	UAV fails to function properly when activated	3B	UAV assembly, setup and integration procedures will be followed at all times.	Procedures for UAV assembly and setup have been created and will be followed during all launches in which the UAV is active.	3A
Rocket incorrectly loaded onto rail	Lack of care during launch operations	1. Failure to launch and potential damage to the airframe 2. Rocket could come off the pad at an angle, resulting in further mission failure	3B	Procedures for proper operation of the assembled launch procedures will be followed during all launches of the vehicle.	Procedures for the loading of the rocket onto the launchpad have been created and will be strictly adhered to.	3A

A.3.6 Launch Support Equipment FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Launch rail at high angle with vertical	1. Launch rail and pad set up improperly. 2. Rocket improperly loaded onto launch pad.	1. Rocket will not reach target apogee. 2. Rocket could drift further than expected.	3B	1. All launches will be done in accordance with NAR guidelines on proper rail setup and launch angle. 2. RSO recommendations for launch angle and rail setup will be followed.	1. All launches will be done with an experienced RSO present and giving recommendations. 2. The team mentor, a Tripoli member and level 2 HPR certified, will be present to aid with launch rail setup and recommendations for launch angle, taking into account wind and crowd location. 3. Rocket launch procedures have been created and will be followed.	3A
Launch controller unit fails to ignite motor	Faulty wire, wire connection, or battery in the launch control unit or the ignition circuitry.	Rocket will not launch	2B	All launches will be done in collaboration with a registered rocketry club. The club's launch control unit will be used.	The rocketry clubs the rocket will be launched at have an excellent track record of successful launches. The hardware they provide can be assumed to be reliable.	2A
Launch ignition wires are live during igniter installation	1. Faulty launch controller unit. 2. Improper operation of the launch controller unit.	Motor could ignite prematurely, injuring personnel	4B	All launches will be done in collaboration with a registered rocketry club.	1. An experienced LCO, from the collaborating rocket club, will be operating the launch control unit during launch operations, assuring that the launch control unit will be operated properly. 2. The collaborating club's launch control unit will be used during launches. Launching with a registered club's launch control unit ensures that the hardware is reliable.	4A

A.3.7 Payload Integration FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Subsections are not properly secured	Shear pins and/or assembly screws not properly installed during assembly	Rocket sections, payloads or subsystems could separate from the rocket in flight, causing damage to the rocket or preventing operation of one or more subsystems.	4B	An inspection of the entire rocket will be done prior to flight, specifically to ensure that the subsystems and payloads are secured and operable.	1. Team officers and subsystem leads will perform inspection, looking primarily to confirm proper securing of sections and operation of each individual subsystem 2. A pre-launch inspection checklist and procedures have been created and will be properly filled out	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Premature separation of the rocket	1. Shear pins are not inserted 2. Incorrect number of shear pins used	Possible damage to the rocket airframe, parachute, parachute rigging, and other rocket subsystems and payloads.	4B	Inspection of the rocket will be done before the rocket is on the launch pad to confirm presence of proper numbers of shear pins.	Rocket assembly procedures and checklists have been created to ensure that the appropriate number of shear pins are used prior to launch. Checklists must be checked off by appropriate officers and team personnel prior to launch.	4A
Rocket payload or subsystem separates from main rocket airframe during flight.	Assembly screws not properly installed	Rocket subsections separate from airframe during descent, causign damage to the rocket airframe or subsystems.	4B	Full inspection of the rocket will be done before the rocket goes to the launch pad to ensure that it is properly assembled	1. Assembly procedures have been created and will be strcitly followed 2. Assembly checklists will require the signiture of the appropriate team personnel before the rocket is placed on the launch rail	4A
Epoxy failure during flight	Epoxy is improperly mixed or set	Bulkhead or centering ring detaches from the rocket airframe during flight	4B	1. Specific time will be set aside during construction to allow the epoxy to properly set before more work is done on the airframe 2. Epoxy will be mixed according to manufacturer recommendations	Procedures and checklists for rocket construction have been created and will be and adhered to.	4A
Centering Ring failure during flight	Centering rings are improperly epoxied or misaligned	1. Motor causes damage to the rocket airframe 2. Motor creates moment on the rocket, altering the flight path and therefore the rocket apogee and drift distance.	4B	1. During manufacturing, care will be taken to properly align the centering rings 2. Before flight, the centering rings will be inspected for damage	Procedures and checklists for construction and instillation of centering rings have been created and will be strictly adhered to	4A
Bulkhead failure during flight	1. Bulkheads improperly aligned during construction 2. Bulkheads improperly epoxied during construction	Rocket payloads or subsystems could separate from the airframe during flight, causing damage or preventing operation	4B	1. Care will be taken to ensure that the bulkheads are properly aligned during construction. 2. Epoxy will be mixed and applied in accordance with manufacturer instructions	Procedures for bulkhead installation have been created and will be strictly adhered to during construction.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Airframe Couplers fail to keep rocket together in flight	1. Couplers are not the proper length 2. Couplers are improperly epoxied	Rocket shears or slips during the motor burn, causing severe damage to the airframe and altering the rocket apogee and drift distance	4B	1. Couplers will be made to be at least 1 caliber in length 2. Care will be taken to ensure that the couplers are properly epoxied into the body tube. 3. Epoxy will be mixed according to manufacturer guidelines	Procedures for airframe construction and coupler installation have been created and will be adhered to during construction.	4A

A.4 Environmental Hazards

A.4.1 Environmental Hazard to Rocket

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rain	Local weather patterns	Damage to electrical systems, potential for battery leakage, inability to launch	4C	1. Launch will be conducted on day with less than or equal to 30% chance of precipitation 2. Waterproof bags will be used to protect sensitive equipment	At least one member of safety team will check local forecast for predicted launch day precipitation.	1B
High Winds	Local weather patterns	Adverse effects on launch angle, reduction of altitude, increased drifting, inability to launch	4C	Launch will be conducted on day with low chance of winds in excess of 15 mph or gusts greater than 20 mph.	At least one member of safety team will check local forecast for predicted launch day winds.	2C
Trees, moist ground, man-made obstacles in drift radius	Local terrain and built environment	Damage to rocket systems, potential for battery puncture and leakage, inability to recover rocket	3B	Launch will be conducted on day with low chance of winds in excess of 15 mph to prevent excessive drifting if trees are in estimated drift radius.	At least one member of safety team will check local terrain and mark obstacles in the predicted drift radius.	2B
Low Cloud Cover	Local weather patterns	Inability to launch	4C	Launch will be conducted on day of no cloud cover or cloud cover in excess of 1 mile above ground level.	At least one member of safety team will check local forecast for predicted launch day cloud cover.	1B
High Humidity	Local weather patterns	Excessive moisture can prevent motor ignition, cause battery leakage	4C	Electronics, motor will be stored in waterproof bag until launch time if the dew point is within 30 degrees of the actual temperature.	At least one member of safety team will check local forecast for predicted launch day humidity.	2B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Extreme Temperatures	Local weather patterns	Battery depletion or explosion, prevent electrical components from functioning, induce critical failures, reduce separation of rocket, melt/damage adhesives	4C	1. Batteries will be checked for charge immediately prior to launch 2. Batteries will be removed from direct sunlight until launch time 3. Adhesive, mechanical components (eg. springs) will be tested in conditions less than 0 degrees Celsius and greater than 90 degrees Celsius for reliable performance	The team will comply with all decisions made by NASA representatives	2C
UV Exposure	Limited cloud cover with direct exposure to sunlight	Can weaken materials, adhesive failure	3B	Rocket will be removed from direct sunlight until launch time	At least one member of safety team will check local forecast for predicted launch day cloud cover and UV index.	2B

A.4.2 Rocket Hazard to Environment

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Release of hydrogen chloride	Burning of motors	Hydrogen chloride dissociates to form hydrochloric acid in water	2E	The amount of hydrochloric acid produced over one season is negligible.	Used motors will be properly disposed of according to SDS sheets from the manufacturer and in accordance with applicable local, state, and federal waste guidelines.	1E
Release of reactive chemicals	Burning of motors	Chemicals react and deplete ozone	2E	The amount of reactive chemicals produced over one season is negligible.	Used motors will be properly disposed of according to SDS sheets from the manufacturer and in accordance with applicable local, state, and federal waste guidelines.	1E
Release of toxic fumes	Burning of motors	Biodegradation of ammonium perchlorate	2E	The amount of ammonium perchlorate burned causes negligible degradation.	Used motors will be properly disposed of according to SDS sheets from the manufacturer and in accordance with applicable local, state, and federal waste guidelines.	1E
Carbon dioxide emission	Travel to and from launch site	Addition of greenhouse gas, heat to atmosphere	2E	Carpooling and commercial air travel produce a negligible effect of carbon dioxide emission per capita.	Occupancy in each vehicle used for transportation to and from events will be maximized.	1E

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Production of styrene gas	Fiberglass in vehicle	Toxic emissions	2E	The manufacturer of fiberglass produces toxic pollutants, including styrene, which evaporates into the atmosphere. The quantity of fiberglass used has a negligible effect on the environment.	NDRT will verify that suppliers of fiberglass are following best practice and producing responsibly with regard to toxic emissions.	1E
Grass fire	Burning of motors, electrical component short circuit	Ignition, electrical systems, motor all create heat and have potential to spark, causing a fire	3B	Appropriate fire extinguishing materials will be present at launch, wire connections will be checked before launch.	At least one member of safety team will verify that fire extinguishing materials are present as part of pre launch sign off and in accordance with NASA guidelines.	3A
Groundwater contamination	Leakage, improper disposal of batteries	Chemicals react in water, potentially leading to human ingestion and illness	2B	NDRT will follow procedures outlined in SDS sheets should chemical spills, leaks occur, and will follow SDS guidelines on disposal of used batteries and chemicals	Used batteries, motors will be properly disposed of and all leaks will be immediately reported to local, supervising organization that has jurisdiction over launch site. Note that any leaks from used motors are harmless to the environment according to the manufacturer's specifications.	2A
Spray paint inhalation or ingestion	Use of spray paint in construction	Paint dissolves in water, evaporates in air leading to ingestion or inhalation	3D	Spray painting will be conducted in a ventilated laboratory isolated from water systems or outside air.	All members working in the lab will possess appropriate certification to conduct spray painting and will be supervised by at least one officer.	3A
Soldering material waste	Wires soldered to electrical components	Air, ground contamination	3D	Vapor produced from soldering causes negligible effects on environment so long as proper laboratory ventilation is in place.	All members working in the AME lab will possess Level 1 certification to conduct soldering and will be supervised by at least one officer.	3C
Battery leakage	Excessive heat, excessive humidity, battery puncture, damaged casing	Chemicals react in water, potentially leading to human ingestion and illness, potential reaction to cause fire	4B	Proper precautions, including those recommended by the manufacturer, will be used to prevent the leakage of batteries	At least one member of safety team will verify that fire extinguishing materials are present and verify that launch conditions are NOT favorable for battery leakage or explosion.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Plastic waste	Plastic scraps used in soldering	Sharp plastic waste can lead to harm to animals upon ingestion, humans upon entry into groundwater supply	2E	Plastic will be disposed of according to applicable SDS, local standards	1. All members working in the lab will possess appropriate certification to conduct soldering and will be supervised by at least one officer 2. Material disposal will follow all applicable SDS guidelines and local, state, and federal laws	1E
Wire waste	Waste made during production of electrical components	Sharp wire waste can lead to harm to animals upon ingestion, humans upon entry into groundwater supply	2E	Wire will be disposed of according to applicable SDS, local standards	1. All members working in the lab will possess appropriate certification to build electrical components and will be supervised by at least one officer 2. Material disposal will follow all applicable SDS guidelines and local, state, and federal laws	1E

A.5 NAR High-power Rocket Safety Code

Topic	NAR Description	Team Compliance
Certification	I will only fly high power rockets or possess high power rocket motors that are within the scope of my user certification and required licensing.	Team mentors are Level 2 certified and the team will only use a maximum of L class motors.
Materials	I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or when necessary ductile metal, for the construction of my rocket	All design squads, especially the vehicle design squad, will refrain from using materials that do not meet the lightweight requirement. If there is uncertainty, the team will check with the NASA competition officials.
Motors	I will use only certified, commercially made rocket motors, and will not tamper with these motors or use them for any purposes except those recommended by the manufacturer. I will not allow smoking, open flames, nor heat sources within 25 feet of these motors.	The team will not use any motors, other than those used by certifiable and trusted rocket motor manufacturers. Motor use will be supervised by team mentors, will be only for the purpose of launching the rocket, and will be under controlled and safe condition.
Ignition Systems	I will launch my rockets with an electrical launch system, and with electrical motor igniters that are installed in the motor only after my rocket is at the launch pad or in a designated prepping area. My launch system will have a safety interlock that is in series with the launch switch that is not installed until my rocket is ready for launch, and will use a launch switch that returns to the "off" position when released. The function of onboard energetics and firing circuits will be inhibited except when my rocket is in the launching position.	The team's mentors will install all ignition systems and will only do so properly, and according to the NAR regulations outlined here.

Topic	NAR Description	Team Compliance
Misfires	If my rocket does not launch when I press the button of my electrical launch system, I will remove the launcher's safety interlock or disconnect its battery, and will wait 60 seconds after the last launch attempt before allowing anyone to approach the rocket.	Team mentors, Safety officer, and Captain must all approve any attempts to approach the rocket in the case of misfires. Even then, it will only be done well after a 60 second waiting period, and will be done only by the team mentors and essential personnel after the area has been determined to be safe.
Launch Safety	I will use a 5-second countdown before launch. I will ensure that a means is available to warn participants and spectators in the event of a problem. I will ensure that no person is closer to the launch pad than allowed by the accompanying Minimum Distance Table. When arming onboard energetics and firing circuits I will ensure that no person is at the pad except safety personnel and those required for arming and disarming operations. I will check the stability of my rocket before flight and will not fly it if it cannot be determined to be stable. When conducting a simultaneous launch of more than one high power rocket I will observe the additional requirements of NFPA 1127.	The team will follow all launch instructions given by the Range Safety Officer, and will comply with all rules stipulated here. Additionally, the Safety officer will give a 5 second warning to all personnel in the area prior to launch.
Launcher	I will launch my rocket froma stable device that provides rigid guidance until the rocket has attained a speed that ensures a stable flight, and that is pointed to within 20 degrees of vertical. If the wind speed exceeds 5 miles per hour I will use a launcher length that permits therocket to attain a safe velocity before separation from the launcher. I will use a blast deflector to prevent the motor's exhaust from hitting the ground. I will ensure that dry grass is cleared around each launch pad in accordance with the accompanying Minimum Distance table, and will increase this distance by a factor of 1.5 and clear that area of all combustible material if the rocket motor being launched uses titanium sponge in the propellant.	The team will only use rails provided by NAR, and will fully comply with this rule.
Size	My rocket will not contain any combination of motors that total more than 40,960 N-sec (9208 pound-seconds) of total impulse. My rocket will not weigh more at liftoff than one-third of the certified average thrust of the highpower rocket motor(s) intended to be ignited at launch.	Rocket design and motor selection will comply with this rule.
Flight Safety	I will not launch my rocket at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site, and will not put any flammable or explosive payload in my rocket. I will not launch my rockets if wind speeds exceed 20 miles per hour. I will comply with Federal Aviation Administration airspace regulations when flying, and will ensure that my rocket will not exceed any applicable altitude limit in effect at that launch site.	Weather and wind conditions will be evaluated in the week prior to a launch day, as well as on launch day, if conditions are determined to be unsafe, the team will not launch. All necessary FAA waivers and notices will be acquired and in place prior to launch. The team will comply with all launch day determinations made by the Range Safety Officer.
Launch Site	I will launch my rocket outdoors, in an open area where trees, power lines, occupied buildings, and persons not involved in the launch do not present a hazard, and that is at least as large on its smallest dimension as one-half of the maximum altitude to which rockets are allowed to be flown at that site or 1500 feet, whichever is greater, or 1000 feet for rockets with a combined total impulse of less than 160 N-sec, a total liftoff weight of less than 1500 grams, and a maximum expected altitude of less than 610 meters(2000 feet).	Team launches will only take place at NAR/TRA events. The Range Safety Officer has final say on all matters regarding safety issues.

Topic	NAR Description	Team Compliance
Launcher Location	My launcher will be 1500 feet from any occupied building or from any public highway on which traffic flow exceeds 10 vehicles per hour, not including traffic flow related to the launch. It will also be no closer than the appropriate Minimum Personnel Distance from the accompanying table from any boundary of the launch site.	The team will comply with this rule and any determination the Range Safety Officer makes on the day of launch.
Recovery System	I will use a recovery system such as a parachute in my rocket so that all parts of my rocket return safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my rocket.	The Recovery Design Squad will be responsible for designing, testing, constructing, and verifying a safe recovery system that will fully comply with this rule. A pre-launch checklist must be checked off by recovery and signed by the Captain and Safety Officer.
Recovery Safety	I will not attempt to recover my rocket from power lines, tall trees, or other dangerous places, fly it under conditions where it is likely to recover in spectator areas or outside the launch site, nor attempt to catch it as it approaches the ground.	The team will comply with this rule and any determinations made by the Range Safety Officer on launch day. If a safe recovery is not possible for the team, proper authorities will be contacted to ensure a complete and safe recovery.

A.6 Launch Concerns and Operation Procedure Checklists

These checklists have been approved by the Safety Officer, Technical Design Leads, and Team Captains such that together they outlines the necessary steps to complete a safe and successful test launch of the full scale rocket. Checklists should be carefully read so that whenever noted, proper caution and cognizance can be exercised.

In the case of an unforeseen situation or nonstandard event such as (but not limited to) a Catastrophe at Take Off (CATO), a punctured or damaged battery, improperly assembled (too tight or too loose) payload, see the Troubleshooting Safety Checklist, which is not completely exhaustive, but does offer instructions for a variety of situations ranging in severity and probability of occurrence. Should an event or situation that is not covered in the safety checklists be encountered during launch exercises, members should exercise their best discretion and approach an officer, the team mentor, the team's graduate student advisor, or the range safety officer for instructions on how to proceed.

A.6.1 General Safety Checklist

A.6.1.1 Pre-Departure

☐ **Ensure the following items are packed**

- ☐ 1 Fully Stocked First Aid Kit

- ☐ 2 Pair Leather gloves
- ☐ 1 Pair Antistatic Gloves
- ☐ 6 Pairs Safety Glasses
- ☐ 1 Pair Safety Goggles
- ☐ 1 Large Lab Coat
- ☐ 1 Pair Heat Resistant Gloves
- ☐ 2 Dust Masks
- ☐ 1 Box Nitrile Gloves
- ☐ 1 Pair Cut Resistant
- ☐ Fire Resistant Battery Bags
- ☐ 3 Fully Stocked Rocket Team Tool Boxes
- ☐ 1 Hand Drill with Fully Charged Battery (in carrying case)
- ☐ Drill bit case with standard range of bit
- ☐ 1 Copy of each checklist in possession of respective technical lead
- ☐ 1 Copy of all checklists in possession Safety Officer (back up)

☐ **Following actions must be completed**

- ☐ Team Captain reminds all drivers of destination and necessary instructions for arriving at the launch site
- ☐ Safety Officer should remind all members of basic launch day safety
- ☐ Account for all members expected to attend the launch and ensure that each member has a seat in a car
- ☐ Safety Officer ensures that all attending members attended pre-launch ORR and passed necessary competency quiz
- ☐ Safety Officer must sign off with technical leads to ensure that pre-departure checklists have been filled out

A.6.1.2 Pre-Flight

- ☐ Team mentor instructs team on procedures and rules specific to launch site and overseeing rocketry club
- ☐ Safety Officer reminds team members of procedure for catastrophic events such as CATO and Ballistic events
- ☐ Safety officer ensure that a team member is assigned to follow assembly of each subsystem and fill out the respective checklist in order to ensure that the procedure is being properly followed

☐ **Once rocket is assembled, follow procedures outlined for bringing rocket to launch pad and performing final pre-flight preparations**

- ☐ All team members watch rocket during flight in order to ensure that it is being safely tracked

A.6.1.3 Post-Flight

- ☐ Locate Rocket
- ☐ Safety Officer should inspect landing site for any potential hazards, then give the go-ahead if site is determined to be safe
- ☐ If site is not safe, see troubleshooting checklist, or consult officer for instruction
- ☐ Document landing site
- ☐ Collect rocket and transport back to base of operations

A.6.2 Vehicle Squad Safety Checklist

A.6.2.1 Pre-Departure

- ☐ **Items to bring:**
  - ☐ Nose Cone
  - ☐ Fore Body Tube
  - ☐ Aft Body Tube
  - ☐ Fin Can
  - ☐ Shear Pins
  - ☐ Locking Screws
  - ☐ 5 Minute Epoxy
- ☐ **Inspection:**
  - ☐ Inspect the body tubes and couplers to ensure they have not been damaged during storage
  - ☐ Ensure the items are stored in such manner as to not cause physical damage
  - ☐ Ensure the fin can is stored on the rocket holder so as not to damage the fins during transportation

A.6.2.2 Pre-Flight

- ☐ Insert ABS System along rails into fin can
- ☐ Ensure tabs are not obstructed by airframe
- ☐ Secure UAV system into fore body tube
- ☐ Insert nose cone onto top of body tube
- ☐ Secure nose cone with screws onto the body tube
- ☐ Secure Recovery System
- ☐ Screw Fore body tube and main parachute bay together
- ☐ Connect vehicle Sections I and II
- ☐ Insert shear pins to complete connection

- ☐ **The following steps should be performed by the Vehicle Design Lead Riley Mullen. If not careful while finding Cg, the rocket body and payloads could be damaged from being bent or dropped.**
  - ☐ Perform Center of gravity (Cg) test to ensure the center of gravity matches the simulated center of gravity
  - ☐ Mark these the measured Cg and simulated Cg on the rocket
  - ☐ Ballast as necessary to keep the stability margin
- ☐ **This concludes the steps that must be completed by Riley Mullen**

- ☐ **The following steps must be performed the team's mentor Dave Brunsting. The Motor is highly energetic, and Dave is the only one on the team who is qualified to handle and install the motor.**
  - ☐ Remove motor from packaging
  - ☐ Check that motor is properly assembled according to manufacturer's instructions
  - ☐ Remove pre-installed ejection charge
  - ☐ Properly dispose of black powder
  - ☐ Insert motor into casing
  - ☐ Ensure two spacers precede motor
  - ☐ Screw on rear closure
  - ☐ Insert motor into rocket
  - ☐ Attach motor retainer
  - ☐ Check for secure fit
- ☐ **This concludes the steps that must be completed by Dave Brunsting**
  - ☐ Check rocket stability (at least 1-2 calibers) and final weight
  - ☐ Register with LCO and RSO at launch site

- ☐ **The following steps must be performed by the team's mentor Dave Brunsting. Installing the igniter is a process that involves an energetic (the motor), and thus should be performed by qualified personnel.**

    - ☐ Remove igniter clips from igniter
    - ☐ Remove igniter from rocket
    - ☐ Ensure igniter has properly exposed ends which are split apart
    - ☐ Insert igniter into motor
    - ☐ Attach clips to igniter, ensuring good contact
- ☐ **This concludes the steps that must be completed by Dave Brunsting**
    - ☐ Clear launch area and retreat to spectating area

A.6.2.3 Post-Flight

- ☐ **Wait for approval from an officer to approach the rocket. They must first determine if the landing site and rocket are safe for recovery, or if there is a hazard present.**
    - ☐ Ensure only trained members are approaching vehicle
    - ☐ Assess there is no harmful physical damage before removal
    - ☐ Ensure nothing is on fire
    - ☐ Document state of rocket with photographs before moving any part
    - ☐ Remove any quick link where possible so that rocket can be transported in multiple parts.


- ☐ **Note that either leather gloves or heat resistant gloves can be used for the next step, but at least one must be used**
    - ☐ Handle fin can with PPE, but put fin can down if hands start to feel hot through gloves.
- ☐ **Dave Brunsting will dispose of used motors**

A.6.3 Recovery Squad Safety Checklist

A.6.3.1 Pre-Departure

- ☐ **Ensure the following items are packed**
    - ☐ Servo Bay (top and bottom pieces)
        - ☐ Top section

- ☐ Bottom Section
- ☐ Power HD servo motors (2)
- ☐ Aluminum plates (2)
- ☐ Aluminum rods (6)

- ☐ CRAM
  - ☐ CRAM body
  - ☐ CRAM core
  - ☐ Eggtimer altimeters (2)
  - ☐ Tenergy Batteries (2)
  - ☐ CRAM bulkhead+ eyebolt
- ☐ Garolite Bulkhead
- ☐ Compression Springs (4)
- ☐ Main Parachute
- ☐ Drogue Parachute
- ☐ Shock cords (39ft)
- ☐ Quick links
- ☐ Parachute Couplers
- ☐ Bar Clamps (4)

☐ **Inspect all wires and batteries for defects**

A.6.3.2 Pre-Flight

☐ **CRAM Assembly**

- ☐ The CRAM core should have the recovery batteries, switches and altimeters already mounted. If they are not mounted, attach them to the CRAM core through small screws and/or zip ties.
- ☐ Ensure that the altimeters and batteries are properly wired to each other and to other electrical connections.
- ☐ Insert the CRAM core into the body of the CRAM. The CRAM is now ready for connection with the Servo Bay.

☐ **Servo Bay/spring assembly**

- ☐ Insert the servos into the bottom portion of the Servo Bay, ensuring that the shaft of the servos properly mesh with the gears in the servo bay.
- ☐ Ensure that the angled plates of the latch mechanism are fully retracted and are meshing properly with the gears.
- ☐ Place the upper portion of the servo bay (with attached springs) on top of the lower portion of the servo bay. You should now have the full servo bay, with uncompressed springs on top. The spherical stopper and spring retainment cords should be hanging in the center of the servo bay.
- ☐ Using spring compressors placed on the bottom of the servo bay and top of the springs to compress the springs to the appropriate length.

- ☐ Using the servos, move the angled plates forward such that they prevent the spherical stopper from moving forward. The springs are now locked in place.
- ☐ Insert the safety pins into the safety pin holes
- ☐ Remove the spring compressors from the servo bay. The servo bay is now ready for connection to the CRAM.

☐ **System installation**

- ☐ Connect the batteries and altimeters from the CRAM to the servos in the Servo Bay.
- ☐ Using the long bolts and hex nuts, bolt the Servo Bay to the CRAM.
- ☐ Run the small section of the shock cord through the combined system. Connect one end to the eyebolt in place in the recovery bulkhead.
- ☐ Insert the system into the rocket, taking care to ensure that the orientation of the system is correct.
- ☐ Once the system is all the way inserted, install the assembly screws in the appropriate places from the outside of the rocket body. The system should now be installed in the rocket and ready for parachute instillation.

☐ **Folding of Parachute**

- ☐ Ensure that the shroud lines form a loop at the connection end. If they do not, make one using an overhand knot.
- ☐ Connect the parachute to the shock cord using a quick link
- ☐ Stretch parachute out on flat surface and straighten shroud lines. No shroud lines should be twisted together.
- ☐ Tether the Jolly Logic Chute Releases to individual shroud lines.
- ☐ "Accordion Fold" the parachute by folding the gores of the parachute panel-by-panel, gathering the shroud lines of the parachute into a single, straight bundle. The parachute should be flat and resemble a large pennant flag.
- ☐ Tuck the straight bundle of shroud lines up, so that the majority of the shroud line bundle is resting on the folded parachute. The connection end of the shroud line bundle should be sticking out of the bottom of the folded parachute.
- ☐ "Z-fold" the parachute onto itself by folding the top 1/3 of the parachute downward, under itself, then folding the remaining top $\frac{1}{2}$ upwards, on top of itself. At this point, the folded parachute should be 1/3 of its original length and should have the majority of its shroud lines safely tucked inside the folded parachute, with only a small loop sticking out of the bottom.
- ☐ At this point, the parachute can be rolled or further folded to the point in which it loosely fits inside the rocket body tube.

☐ **Prepare Chute Release**

- ☐ Attach the tether of the Chute Release by tying the tether cord onto the attachment point on the bottom of the Chute Release and to one of the shroud lines of the parachute.
- ☐ Choose an elastic band to wrap around the parachute. Ensure that this band has no damage and is correctly sized for the parachute in use.
- ☐ Attach the Chute Release pin to the elastic band by tying a knot. Attach the other end of the elastic band to the mounting point on the chute release by tying a knot.
- ☐ Wrap the elastic band around the parachute and attach the pin to the release point on the Chute Release.

- ☐ Repeat this for the second redundant Chute Release
- ☐ Ensure that the chute release is turned on

☐ **Installing the parachute**

- ☐ Ensure that the parachute coupler pieces are tethered to the mobile bulkhead, attached to the springs
- ☐ Encase the folded parachute and extra shock cord in the parachute coupler pieces
- ☐ Ensure the shock cord is connected to both pieces of the rocket through the eyebolts.
- ☐ Insert the parachute bundle into the rocket until the pieces of the rocket can be assembled together.
- ☐ After the recovery Sections are mated, insert shear pins

☐ **On the Pad**

- ☐ Flip the switch connected to the first altimeter-battery-servo system. Wait for it to go through its automatic pre-flight check. Once it starts chirping, it is taking data and is good for launch.
- ☐ Repeat for second altimeter-battery-servo system.
- ☐ Remove safety pins retaining the angled plates in the latch mechanism. The recovery system is now ready for launch.

A.6.3.3 Post-Flight

☐ **Post Flight inspection:**

- ☐ The Eggtimer altimeters constant beep out the altitude at apogee until another flight has begun, so that can be recorded upon finding the launch vehicle.
- ☐ Make sure to inspect the launch vehicle careful before handling, in case any part of the spring system did not deploy.
- ☐ In the unlikely event that a spring has failed to decompress, use a bar clamp to ensure that the system is under control, unlock the latch mechanism, and slowly decompress the spring using the clamp.

A.6.4 ABS Safety Checklist

Launch procedures for the Air Braking System (ABS) shall begin under the discretion of ABS lead Eric Dollinger. ABS power and integration steps will begin under the discretion of Vehicles lead Riley Mullen. This shall be done to minimize the time between loading the ABS into the fin can and the time of launch to reduce the risk of draining the battery prematurely. ABS launch procedures shall consist of inspection of the payload for defects, powering of the system, inspection of the status LEDs for proper controller startup, and installation into the fin can of the rocket.

A.6.4.1 Pre-Departure

- ☐ Assembled ABS
- ☐ Wrench set
- ☐ L Wrench set
- ☐ Screwdriver set

- ☐ Battery case
- ☐ Digital Multimeter
- ☐ Wire Strippers
- ☐ 6-32 nylon screws
- ☐ 10-32 nylon screws

A.6.4.2 Pre-Flight

- ☐ Inspect Air Braking System for proper construction assembly and material defects. After ensuring power is disconnected, inspect the mechanical system for loose screws and bent components, particularly the drag tabs.
- ☐ Hazards: -Damage to the ABS and rocket may occur as a result of dangerous conditions created if a mechanical defect is not identified.
- ☐ If physically inspecting the mechanism, ensure power is disconnected to reduce risk of pinching of fingers.
- ☐ With the battery disconnected from the printed circuit board, Inspect electronics for secure connections and component mounting. Inspect the battery for punctures, swelling, chemical odors, or other signs of defects.

☐ **If a battery defect is detected, the battery should immediately be placed in the fire proof battery case and the ABS lead and Safety officer should be notified. A backup battery should be inspected and installed in the event of a defective battery. Under no circumstances should a potentially defective battery be flown.**

- ☐ Install the battery and ensure the snap cover battery case cover is secured.
- ☐ Ensure the proper control code has been installed on the Arduino MKR Zero.
- ☐ Ensure the SD card is inserted in the Arduino prior to powering the system.

☐ **Hazards: if the SD card is not inserted prior to powering the Arduino, data cannot be stored to the SD card and system failure will occur.**

- ☐ After receiving confirmation from Vehicles lead Riley Mullen that the vehicle is prepared for the installation of the Air Braking System, connect the battery's molex connector to the printed circuit board and flip the power switch.
- ☐ Confirm that the power-LED has lit.
- ☐ Inspect the status LEDs for the sensors and SD card to ensure the Arduino controller is properly receiving sensor data and writing to the SD card.
- ☐ In the event that these lights do not turn on, notify ABS lead Eric Dollinger or a member of the ABS control coding group immediately.

☐ **Hazard: If data is not properly measured and stored, mission failure occurs.**

- ☐ If ABS is to be active for this flight, turn on the Arming switch. Ensure that the arming LED turns on.
- ☐ Check that the drag tabs are flush with the support plates.
- ☐ Under the direction of Vehicles lead Riley Mullen, begin installing the ABS into the fin can. The ABS integrates via 4 threaded steel rods which run through dedicated holes in the bulkheads of the ABS.

- ☐ Ensure that the ABS fully slots into the fin can and sits evenly.
- ☐ Inspect the drag tab cutouts in the fin can to ensure that the tabs are visible and have clearance to extend.

☐ **Hazard: If the tabs do not fit properly in the cut slots of the fin can, jamming is likely to occur which leads to mission failure and potential motor stalling, increasing the risk of damage to mechanical components, the motor, and the battery.**

- ☐ Place one #10 washer and a locknut on each of the threaded rods at the top of the forward ABS bulkhead to secure them to the fin can.
- ☐ Inspect through the barometric vent holes to ensure that the LEDs are still lit and indicate the system is not prematurely in the launched state.
- ☐ Make a final inspection of the system's installation for any obvious defects or abnormalities.
- ☐ Get a signature of approval from ABS lead Eric Dollinger, Vehicles lead Riley Mullen, and Safety lead Jed Cole.

A.6.4.3 Post-Flight

☐ **Post launch inspection**

- ☐ Use a wrench to unscrew the lock nuts from the integration rods at the forward bulkhead of the ABS. Remove the locknuts and washers.
- ☐ Check that the drag tabs are fully retracted to avoid jamming the ABS in the fin can while removing. Note if that tabs are not retracted.
- ☐ Carefully remove the ABS from the fin can by lifting with the U bolt at the forward bulkhead of the ABS inspect the avionics system for power and status LED indication to determine if power was lost during flight or landing. Flip the power switch to turn off the system. Remove the battery and inspect for damage. Place in the fire-proof battery case for safe storage. Inspect and note any damage to the mechanical system or payload assembly. Remove the micro SD card from the Arduino MKR Zero. Insert the microSD card into the SD card adapter and plug into a laptop. Open the data log file on the SD card and verify successful flight metrics.

A.6.5 UAV Safety Procedure

A.6.5.1 Pre-Departure

!!! Deployment electronics

- ☐ Nema 14 stepper motor
- ☐ FS5106R servo motor
- ☐ Turnigy 2200mAh LiPo
- ☐ BNO055 sensor
- ☐ Arduino UNO (board model: UNO R3)
- ☐ BJT transistors
- ☐ 433 MHz RF transmitter and receiver kit

- ☐ 6 stainless steel cotter pins
- ☐ Roll of polyethylene fiber wire
- ☐ Scissors

☐ **UAV frame (arms, supports, and struts already attached) with mounted electronics:**

- ☐ 5 motors (1 is a backup)
- ☐ ESCs (2 are backups)
- ☐ Pixhawk 4
- ☐ Raspberry Pi 3 Model B
- ☐ 5 props (1 is a backup)
- ☐ Turnigy 4500mAh LiPo
- ☐ 2 Raspberry Pi Camera Module V2 (1 is a backup)
- ☐ Power Distribution Board
- ☐ BEC voltage regulator
- ☐ Belt and pulley system
- ☐ 5 pulleys (1 is a backup)
- ☐ 2 belts (1 is a backup)
- ☐ 5 torsion springs (1 is a backup)

☐ **Beacon Delivery Subsystem**

- ☐ 2 NDRT beacons
- ☐ 2 FS90R servos (1 is a backup)
- ☐ Raspberry Pi 3 Model B
- ☐ Adapter Rings
- ☐ Battery charger/low-voltage checker
- ☐ Cable zip ties
- ☐ Velcro straps
- ☐ Metric screws
- ☐ 500mW Transceiver Telemetry Set V3 433 MHz
- ☐ 500mW Transceiver Telemetry Set V3 915 MHz
- ☐ MT60 Connectors
- ☐ XT60 Bullet Connectors
- ☐ XT90 Connectors
- ☐ FrSky Taranis X9D Plus 2.4 GHz ACCST Radio
- ☐ Laptop

A.6.5.2 Pre-Flight

Battery Checklist:

☐ Battery is properly charged

☐ Insert Lithium-Polymer voltage reader into the balance charging connector on the battery.

☐ Verify each cell has a 4.2 voltage potential.

☐ Balance charge on a balance charger if voltage is between 3.0 V and 4.2V.

☐ Do not use batteries with voltages below 3.0 V.

☐ Do not use batteries with unbalanced cell voltages.

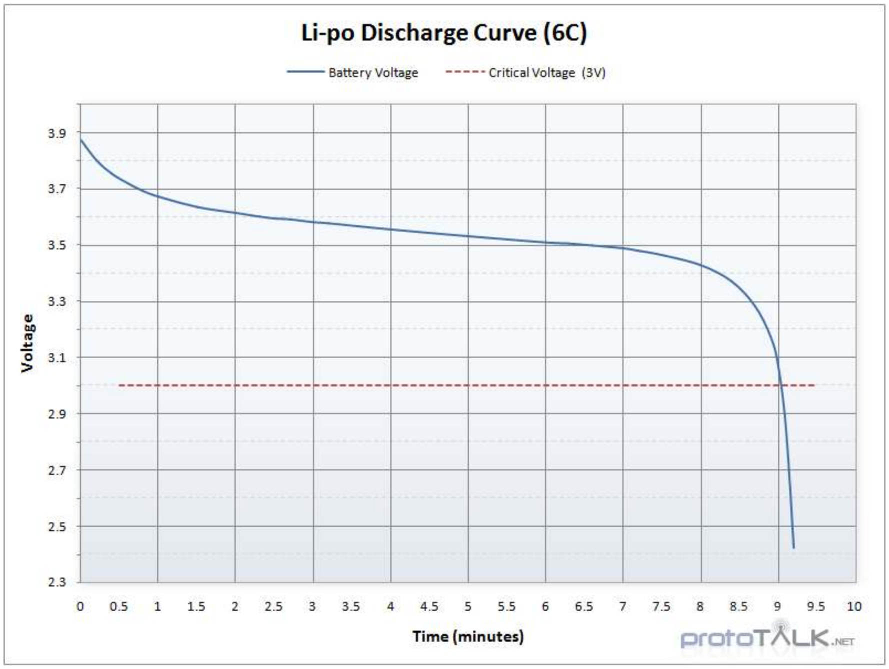


Figure 115: Lithium-polymer voltage discharge curve

Startup:

☐ Ensure ESCs are wired correctly

☐ Disconnect battery.

☐ Follow motor and ESC numbering according to Figure **??**.

☐ Connect each signal wire to the correct location on the Power Distribution Board. The Power Distribution Board has pins M1, M2, M3, and M4 that control the corresponding motor.

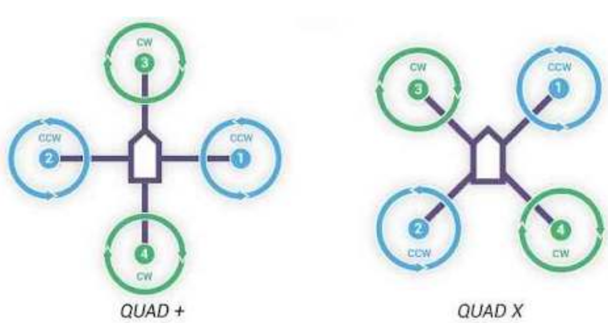


Figure 116: Lithium-polymer voltage discharge curve

- ☐ **Ensure Motors are spinning in correct directions**
  - ☐ Remove propellers from UAV
  - ☐ Apply masking tape to motors
  - ☐ Turn on transmitter with throttle at zero power.
  - ☐ Connect battery
  - ☐ Provide power to motors
  - ☐ Check the direction of rotation by examining the masking tape
  - ☐ Reverse rotation direction on incorrect motors by swapping two wires between the ESC and motor.
- ☐ **Ensure propellers are mounted correctly**
  - ☐ Disconnect battery
  - ☐ Following Figure 116, mount two clockwise propellers and two counterclockwise propellers.
  - ☐ Ensure propellers are mounted correctly

  Putting the UAV in the rocket:
  - ☐ Ensure that the aft rotating bulkhead and track mechanism is locked in place via the FS5106R servo.
  - ☐ Ensure that the belt and pulley system is in working order via a short test to check that the movement of one arm is synchronized with the movement of the remaining three arms of the UAV.
  - ☐ Fold the arms of the UAV into the proper position, ensuring that the torsion springs are in place and in compression. At this time, also ensure that both buttons for the button-on-arm electronic trigger are compressed via the two contacts.
  - ☐ Check that all electronics are mounted properly and safely to the top plate of the UAV.
  - ☐ Check that the 4500mAh LiPo is properly and safely secured between the two plates of the UAV.
  - ☐ Check that the Beacon Delivery Subsystem contains both beacons.
  - ☐ Check that the Raspberry Pi Camera Module V2 is mounted on the UAV and can stream video to the CPU on the ground.
  - ☐ Make sure that each of the four props has enough clearance to spin.
  - ☐ Tie the polyethylene fiber wire to the four eyebolts mounted on the aft rotating bulkhead, and tie the other end of the wire to four stainless steel cotter pins.
  - ☐ Secure each of the four aluminum struts of the UAV into each of four 3D-printed custom pipe flanges mounted on the UAV platform for deployment.
  - ☐ Insert the four stainless steel cotter pins through the flanges and the struts to ensure that the UAV will be properly restrained during flight.
  - ☐ Complete a brief shake test to ensure that the pins were inserted correctly so that the UAV will not move during flight.

A.6.6 Troubleshooting Safety Checklist

A.6.6.1 Catastrophic Motor Failure (CATO)

A catastrophic motor refers to any major failure of the rocket motor that occurs while the motor is burning. It is typically characterized by some form of explosion or fire on the rocket.

- ☐ **DO NOT attempt to catch or be near the falling rocket. A rocket that has undergone a motor failure may be on fire and could be in an uncontrolled, rapid descent. Take care and precaution when following the proceeding steps**
  - ☐ After the rocket lands, ensure it is not on fire. If it is on fire, put the fire out with a portable fire extinguisher.

- ☐ **The following steps should be performed with heat resistant gloves. Any parts handled after a CATO event will most likely be very hot, which can cause severe burn and injuries. If handling any parts with jagged edges, handle with leather gloves, as these will provide protection from sharp and jagged edges and heat.**
  - ☐ DO NOT touch the motor end of the rocket. It is likely to still be hot after the motor burn. Carry the rocket back by the shock cord or very top of the fin can section.
  - ☐ Using heat-resistant gloves, take the motor retainer off and pull the motor out of its mount.
  - ☐ Examine the motor to ensure that all of the propellent has burned off.
  - ☐ Occasionally, slivers of propellent will be left in the motor casing after an motor failure. If there is propellent, consult the team mentor for the best way to remove and dispose of the propellent.
  - ☐ Carefully remove all batteries from the rocket. DO NOT use these batteries in another launch. Even if they appear fine, the batteries may be internally damaged.
  - ☐ Recover what data can be recovered from the rocket and begin making repair plans.

A.6.6.2 Failure to Separate at Apogee

If the rocket fails to separate into its pieces at apogee, it will descend in a rapid, nose-down, ballistic trajectory that can cause severe injury if it strikes a person.

- ☐ **Always be looking at the rocket as it comes down. It is helpful to point at the rocket as it descends to alert others to the trajectory.**
- ☐ **If the rocket appears to be coming in your direction, quickly but calmly walk away from your current area.**
  - ☐ Wait for the team Safety Officer and team mentor to confirm that the rocket is safe before touching the rocket.

- ☐ After bringing the rocket back to the launch preparation area, remove the motor casing and all batteries.

☐ **DO NOT use these batteries in another launch, as they may be internally damaged.**

- ☐ Recover what data can be recovered from the rocket and begin making repair plans.

A.6.6.3 Altimeter issue on the launch pad

The Eggtimer altimeter goes through a self-checking phase after it is turned on. If an issue is detected, the Eggtimer will not operate properly and the issue will have to be corrected.

- ☐ Turn the altimeter off and back on. Occasionally this will solve the problem. If so, note the anomaly and proceed as you would with a normal launch.
- ☐ Double check to ensure that the recovery safety pins are still in place. If so, lower the launch rail and take the rocket off the pad. Take the rocket back to the preparation area.
- ☐ Take the shear pins out of the rocket and separate the sections.
- ☐ Remove the parachute, shock cords and parachute coupler from the rocket.
- ☐ Unscrew the retaining screws in the side of the rocket that keep the recovery system in place.
- ☐ Slide the recovery system out of the rocket.
- ☐ Unbolt the CRAM from the Servo bay.
- ☐ Take the CRAM core out of the CRAM body.
- ☐ Plug the faulty Eggtimer into a laptop and run diagnostics through any standard SSH terminal. Consult the Eggtimer user's manual for more information.

A.6.6.4 Tight parachute

If the folded parachute is very tight inside the parachute bay, it may not slide out upon separation, which will result in the rocket descending much faster than normal.

☐ **DO NOT attempt to force the parachute into the bay. This can prevent clean separation at apogee and potentially damage pieces of the rocket.**

- ☐ Take the parachute out of the rocket.
- ☐ Unhook the shock cords from the rocket.
- ☐ Unfold the parachute and refold according the standard procedures.
- ☐ Ensure that all folds are crisp and that the finished parachute is very tightly rolled.
- ☐ Reattach the Chute Releases.
- ☐ Proceed to reinstall the parachute in the rocket using standard procedure. A layer of talcum powder on the parachute and coupler may also help the parachute to slide out.

A.6.6.5 Stuck Subsystem

A subsection or payload of the rocket may bind and become stuck while attempting to install it. This can happen to the ABS, recovery system, UAV payload or the rocket couplers.

- [ ] **DO NOT attempt to force the piece into the rocket. This may cause damage to the rocket or the stuck payload.**
  - [ ] Carefully take the system out of the rocket.
  - [ ] Ensure that the system is rotated and oriented correctly.
  - [ ] Attempt to reinsert the system, paying careful attention to the orientation of the system and exactly what pieces are causing the issue.
  - [ ] If the system still binds or becomes stuck, take the system out and use sandpaper to sand away the section that is binding. Repeat until the system fits into the rocket smoothly.

A.6.6.6 Ignition failure

Occasionally, a rocket motor will fail to ignite on the pad. This can be caused by numerous issues, such as faulty ignitors, incorrect installation, faulty launch equipment, and damaged motor.

- [ ] After a failed ignition, the LCO of a launch range will typically attempt another ignition. If this one fails, proceed to step 2.
- [ ] Carefully remove the ignitor from the motor. This step should be performed by team mentor.
- [ ] Install another igniter, paying careful attention to standard procedure, and attempt another ignition. TEAM MENTOR PERFORMED
- [ ] If this ignition fails, take the rocket off the pad, take the motor out and inspect it for damage or incorrect assembly.
- [ ] If the motor appears in good condition and properly assembled, inspect the launch system to ensure that it is properly set up, in good condition, and has a charged battery. The range LCO should perform this inspection.
- [ ] Put the rocket back on the pad and attempt another ignition with a fresh igniter. If this fails, consult the team mentor for further troubleshooting.

A.6.6.7 Safe recovery system decompression

Ensure the safety pins are in the servo bay. If they aren't, put them in. If the rocket is fully assembled, remove the shear pins and separate the sections.

- [ ] Remove the parachute and unhook the shock cords
- [ ] Unscrew the recovery system retainment screws in the side of the rocket
- [ ] Unbolt the CRAM from the Servo Bay and springs
- [ ] Place the spring compressors on the servo bay and screw them down until they are touching the bottom of the bay and the top of the compressed springs.
- [ ] Remove the safety pins

- ☐ Use the servos to retract the angled plates that make up the latch mechanism
- ☐ Unscrew the spring compressors until the springs are fully uncompressed. The system is now safe to operate on.

A.6.6.8 Exposed and/or severed wire

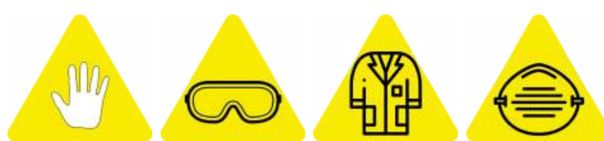
Sometimes wires can become damaged or even severed. This can interfere with the wires ability to transmit current, and can pose a danger, as some wires transmit danger levels of power, which would be unsafe for personnel to be exposed to.

☐ **For personnel safety, ensure that power source is turned off and disconnected from wire being operated on**

- ☐ Inspect wire to see if damage is repairable
- ☐ If so, make repair, if not proceed to next step
- ☐ Inspect to see if wire can be easily replaced with a spare wire
- ☐ If so, replace wire, if not proceed to next step
- ☐ Carefully pack system up so that it does not become further damaged, and transport back to university, where system can be repaired.

A.6.6.9 Punctured or damaged battery

Extremely dangerous, if believed to be damaged at all, battery should not be used AT ALL. Instead, they should be safely rendered inert and disposed of.



☐ **PPE required is leather gloves (for heat and general protection), safety goggles (for eye protection from fumes and particulate), lab coat (to protect skin from particulate and fire), and dust mask (to help protect from inhalation hazards)**

- ☐ If battery is believed to be damaged, approach with caution, as it should be considered an exploding hazard. Only personnel chosen to handle it, and wearing proper PPE, should approach it.
- ☐ Battery should be handled with care, and held away from face and body.
- ☐ Place battery in fireproof battery disposal bag
- ☐ Bring battery to qualified and authorized disposal site

B Unmanned Aerial Vehicle Payload Technical Design

B.1 Future Excursion Area Detection Subsystem Codes

The following is the program used for the manual annotation of FEA footage.

```
import cv2
import numpy as np

cam = cv2.VideoCapture('crop3.mp4')
frame = 0
imgset = []
maskset = []

def click_and_crop(event, x, y, flags, param):
    global refPt

    if event == cv2.EVENT_LBUTTONUP:
        refPt.append([x,y])

        cv2.circle(image, (refPt[-1][0], refPt[-1][1]), 2, (0,255,0), 2)
        cv2.imshow("image", image)
        if len(refPt) >= 4:
            pts = np.array(refPt, np.int32)
            cv2.fillPoly(image, pts.reshape((1,-1,1,2)), (255,255,255))
            cv2.imshow('image', image)

def roi(img, vertices):
    mask = np.zeros_like(img)
    cv2.fillPoly(mask, vertices, 255)
    masked = cv2.bitwise_and(img, mask)
    return masked

print("""Controls: click on boundaries to create polygon
      r-reset annotations
      n-skip frame
      c-finished with frame
      q-quit annotating
      s-skip ahead
""")

while True:
    stay1 = True
    stay2 = True
    if frame % 10 == 0:

        retval, image = cam.read()
        refPt = []

        clone = image.copy()
        cv2.namedWindow('image')
        cv2.setMouseCallback('image', click_and_crop)

        while True:
            cv2.imshow('image', image)
            key = cv2.waitKey(1) & 0xFF

    #if r is pressed, reset cropping region
            if key == ord('r'):
                image = clone.copy()
                refPt = []
            elif key == ord('n'):
                stay1 = False
                break
            elif key == ord('c'):
                break
            elif key == ord('q'):
                np.save('images.npy',np.array(imgset))
                np.save('masks.npy', np.array(maskset))
                stay2 = False
                break
            elif key == ord('s'):
                frame += 1000
                stay1 = False
                break

        if stay1:
            pts = np.array(refPt, np.int32)
            result = roi(clone.copy(),pts.reshape(1,-1,1,2))
            maskset.append(result)
            imgset.append(clone)
    frame += 1
    if not stay2:
        cv2.destroyAllWindows()
        break
```

The following is the program used to detect the FEA.

```
import cv2
import numpy as np

cam = cv2.VideoCapture('video4.mp4')

while (True):
    retval, img = cam.read()
    res_scale = 0.5  # rescale the input image if it's too large
    img = cv2.resize(img, (0, 0), fx=res_scale, fy=res_scale)
    # detect selected color (OpenCV uses BGR instead of RGB)
    # when tuned to blue, in a relatively dark room:
    # lower = np.array([50, 0, 0])
    # upper = np.array([100, 50, 50])
    # objmask = cv2.inRange(img, lower, upper)

    # for HSV:
    hsv = cv2.cvtColor(img, cv2.COLOR_BGR2HSV)
    lower = np.array([10, 50, 200])  # modified because it is bright outside
    upper = np.array([40, 150, 255])
    objmask = cv2.inRange(hsv, lower, upper)

    # debugging:
    cv2.imshow("Binary image", objmask)
    # Resulting binary image may have large number of small objects.
    # You may check different morphological operations to remove
    # unnecessary elements.

    # check your ROI defined in to determine how many pixels you have.
    kernel = np.ones((5, 5), np.uint8)
    objmask = cv2.morphologyEx(objmask, cv2.MORPH_CLOSE, kernel=kernel)
    objmask = cv2.morphologyEx(objmask, cv2.MORPH_DILATE, kernel=kernel)
    cv2.imshow("Image after morphological operations", objmask)

    # find connected components
    cc = cv2.connectedComponents(objmask)
    ccimg = cc[1].astype(np.uint8)
    # find contours of these objects
    imc, contours, hierarchy = cv2.findContours(ccimg,
                                                cv2.RETR_TREE,
                                                cv2.CHAIN_APPROX_SIMPLE)
    # display contour points:
    #cv2.drawContours(img, contours, -1, (0,255,0), 3)
    # ignore bounding boxes smaller than "minObjectSize"
    minObjectSize = 20

    for cont in contours:
        # test shape to see if it is a square
        peri = cv2.arcLength(cont, True)
        approx = cv2.approxPolyDP(cont, 0.04 * peri, True)

        if len(approx) == 4:
            # compute the bounding box of the contour and use the
            # bounding box to compute the aspect ratio
            (x, y, w, h) = cv2.boundingRect(approx)
            ar = w / float(h)
            # a square will have an aspect ratio that is approximately
            # equal to one, otherwise, the shape is a rectangle
            square = 1 if ar >= 0.5 and ar <= 1.5 else 0
            # prove it loosely resembles a square
        else:
            square = 0

        if square:
            # use just the first contour to draw a rectangle
            x, y, w, h = cv2.boundingRect(cont)
            # do not show very small objects
            if (w > minObjectSize or h > minObjectSize) and square:
                cv2.rectangle(img, (x, y), (x + w, y + h), (0, 255, 0), 3)
                cv2.putText(img,  # image
                            "ISSA TARP!",  # text
                            (x, y - 10),  # start position
                            cv2.FONT_HERSHEY_SIMPLEX,  # font
                            0.7,  # size
                            (0, 255, 0),  # BGR color
                            1,  # thickness
                            cv2.LINE_AA)  # type of line
        cv2.imshow("Live WebCam", img)
        action = cv2.waitKey(1)

    if action == 27:
        break
```