University of Notre Dame
2018-2019

Notre Dame Rocket Team
Preliminary Design Review

NASA Student Launch 2018
UAV and Air Braking Payloads

Submitted November 2, 2018

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Contents

Contents i

List of Tables v

List of Figures vi

1 Summary of Report 1
1.1 General Information . . . 1
1.2 Mission Statement . . . 2
1.3 Vehicle Summary . . . 2
1.3.1 Size Statement . . . 2
1.3.2 Mass Statement . . . 3
1.3.3 Motor Selection . . . 4
1.4 Payload Summary . . . 5

2 Changes Since Proposal 5
2.1 Changes to Vehicle Criteria . . . 5
2.2 Changes to Payload Criteria . . . 5
2.3 Changes to Project Plan . . . 5

3 Technical Design: Launch Vehicle 6
3.1 Mission Success Criteria . . . 6
3.2 System Level Design . . . 6
3.2.1 Nose Cone . . . 6
3.2.2 Fins . . . 7
3.2.3 System Integration . . . 9
3.2.3.1 Integration Techniques . . . 9
3.3 Leading Vehicle Design . . . 10
3.3.1 Materials Selection . . . 10
3.3.2 Detailed Mass Statement . . . 11
3.3.3 Propulsion . . . 13
3.3.4 Vehicle Layout . . . 16
3.4 Air Braking Subsystem . . . 18
3.4.1 Air Braking System Overview . . . 18
3.4.2 ABS Aerodynamics Design . . . 18
3.4.2.1 Equations and Drag Tab Sizing . . . 18

3.4.2.2 Drag Tab Material 20
3.4.3 ABS Mechanical Design 21
3.4.3.1 Derivation of Mechanical Design Approach 21
3.4.3.2 Drive Mechanism 22
3.4.4 ABS Electronical Design 23
3.4.4.1 Accelerometer Trade Study 23
3.4.4.2 Barometer Trade Study 25
3.4.4.3 Microcontroller Selection 27
3.4.4.4 Servo Motor Selection 27
3.4.4.5 Battery Selection and Allocation 28
3.4.4.6 Printed Circuit Board Design 31
3.4.5 ABS Control System Design 32
3.4.5.1 Overview of ABS Control Structure 32
3.4.5.2 Kalman Filter 33
3.4.6 ABS Integration Strategy 35
3.4.7 ABS Sub-scale Flight Testing 36
3.5 Recovery Subsystem 37
3.5.1 Overview 37
3.5.2 Mechanical Parachute Deployment System 37
3.5.2.1 Mechanical Parachute Deployment System 37
3.5.2.2 CRAM Assembly 38
3.5.2.3 CRAM Body 38
3.5.2.4 CRAM Core 39
3.5.2.5 Shock Cords and Recovery Fittings 40
3.5.2.6 Spring 41
3.5.2.7 Spring Support 42
3.5.2.8 Redundant Mechanical Latch Comparison and Selection . . 43
3.5.2.8.1 Rotating Bar Release 43
3.5.2.8.2 Plate Release 44
3.5.2.8.3 Angled Plate Release 44
3.5.2.8.4 Selection 45
3.5.3 Black Powder Deployment Mechanism 46
3.5.4 Compressed CO_2 Separation Method 47
3.5.5 Recovery Deployment System Trade Study 47
3.5.6 Chute Release 48
3.5.7 Altimeter Trade Study 50
3.5.8 Recovery Staging 51

3.5.9 Electronics 52
3.5.10 System Design 52
3.5.10.1 Parachute Sizing Requirements 52
3.5.11 Subscale Vehicle Recovery 54
3.5.11.1 Vehicle Integration 55
3.6 Mission Performance Prediction 55
3.6.1 Flight Profile Simulations 55
3.6.2 Static Stability Margin 57
3.7 Subscale Vehicle 57
3.7.1 Comparison to Full Scale Vehicle 57

4 Safety **59**
4.1 Safety Officer 59
4.2 Safety Analysis 59
4.2.1 Project Risk Analysis 63
4.2.2 Personnel Hazard Analysis 63
4.2.2.1 Construction 63
4.2.2.2 Testing 63
4.2.2.3 Launch 63
4.2.2.4 Recovery 63
4.2.2.5 Unmanned Aerial Vehicle 63
4.2.3 Failure Modes and Effects Analysis 64
4.2.3.1 Vehicles 64
4.2.3.2 Recovery 64
4.2.3.3 Air Braking System 64
4.2.3.4 Unmanned Aerial Vehicle 64
4.2.3.4.1 Launch Operations 64
4.2.3.5 Launch Support Equipment 64
4.2.3.6 Payload Integration 64
4.2.4 Environmental Hazards 65
4.2.4.1 Environmental Hazard to Rocket 65
4.2.4.2 Rocket Hazard to Environment 65
4.3 Safety Manual 65
4.3.1 Material Safety Data Sheets 66
4.4 Procedures 66
4.4.1 Competency Quizzes 66
4.4.2 Operation Readiness Reviews 67
4.5 Sub-Scale Rocket Plan 67

4.5.1 Construction . . . 67
4.5.2 Launch . . . 67
4.5.3 NAR Safety Code Compliance . . . 68

5 Technical Design: Payload 68
5.1 Payload Overview . . . 68
5.1.1 Mission Success Criteria . . . 68
5.2 System Level Trade Studies . . . 68
5.2.1 UAV Electrical Design . . . 69
5.2.2 Deployment System . . . 70
5.2.3 Target Delivery System . . . 71
5.3 Payload Subsystems . . . 72
5.3.1 UAV Mechanical Design . . . 73
5.3.2 UAV Electrical Design . . . 79
5.3.3 Deployment System . . . 88
5.3.3.1 Deployment Drive System . . . 88
5.3.3.2 Orientation Correction System . . . 89
5.3.3.3 Locking Mechanism . . . 91
5.3.4 Flight Control System . . . 92
5.3.5 Target Delivery System . . . 97
5.3.5.1 Target Detection . . . 97
5.3.5.2 Beacon Deployment . . . 100

6 Project Plan 105
6.1 Requirements and Verifications . . . 105
6.1.0.1 NASA Requirements . . . 105
6.1.0.2 Team Derived Requirements . . . 134
6.2 Project Budget . . . 142
6.3 Project Timeline . . . 149

Appendix A Safety A1
A.1 Project Risks . . . A1
A.2 Personnel Hazards . . . A2
A.2.1 Construction Hazards . . . A2
A.2.2 Testing Hazards . . . A4
A.2.3 Launch Hazards . . . A5
A.2.4 Recovery Hazards . . . A6
A.2.5 Unmanned Aerial Vehicle Hazards . . . A8

A.3 Failure Modes and Effects Analysis . . . A9
A.3.1 Vehicles FMEA . . . A9
A.3.2 Recovery FMEA . . . A10
A.3.3 Air Braking System FMEA . . . A12
A.3.4 Unmanned Aerial Vehicle FMEA . . . A13
A.3.5 Launch Operations FMEA . . . A14
A.3.6 Launch Support Equipment FMEA . . . A15
A.3.7 Payload Integration FMEA . . . A16
A.4 Environmental Hazards . . . A17
A.4.1 Environmental Hazard to Rocket . . . A17
A.4.2 Rocket Hazard to Environment . . . A18
A.5 NAR High-power Rocket Safety Code . . . A21

List of Tables

1 List of acronyms . . . ix
2 Vehicle Dimensions and Characteristics . . . 3
3 Mass Statement . . . 4
4 Motor Comparisons . . . 4
5 Nose Cone Projected Dimensions . . . 7
6 Fin Design Analysis . . . 8
7 Fin Design Considerations . . . 9
8 Leading Fin Design Dimensions . . . 9
9 Detailed Section and Part Masses . . . 12
10 Material Densities . . . 13
11 Motor Choices . . . 14
12 Motor Considerations . . . 15
13 Vehicle Layout . . . 17
14 Comparison of Drag Tab materials . . . 21
15 Comparison of accelerometer specifications . . . 24
16 Trade study of select accelerometers . . . 24
17 Comparison of Barometer Specifications . . . 25
18 Trade study of potential barometers . . . 26
19 Servo Motor Technical Specifications . . . 28
20 Battery Technical Specifications . . . 29
21 Current Consumption of ABS . . . 31
22 Spring Characteristics . . . 42

23 Kepner Tregoe trade study table for recovery system design. 48
24 Parachute release method trade study 50
25 Recovery Staging 51
26 Weights of Vehicle Sections 53
27 Characteristics of the Cert 3-Series XX Large 53
28 Flight Simulations 56
29 Stability Margins 57
30 Subscale to Full Scale Comparison 58
31 Probability of hazard occurrence classification 60
32 Severity of hazard classification 61
33 Risk assessment matrix 62
34 Description of Risk Levels and Management Approval 62
35 Power-On Sequence trade study for the UAV electrical design. 70
36 Deployment method trade study for the linear motion of the UAV exiting the rocket. 71
37 Orientation method trade study to properly ensure the UAV can take off vertically. 71
38 Beacon body trade study to determine the best shape for beacon. 72
39 Beacon deployment method trade study to compare mechanisms. 72
40 Weighted criteria for the Target Detection System. 99
48 Notre Dame Rocketry Team Funding Sources 143
49 Notre Dame Rocketry Team Funding Sources 143
50 Itemized Budget 144

List of Figures

1 Leading Fin Design 8
2 Leading Vehicle Design Drawing 10
3 Thrust Curve for Cesaroni L1395 15
4 Thrust Curve for Cesaroni L1115 16
5 Thrust Curve for Aerotech L1120 16
6 Vehicle Section Breakdown 18
7 Top view of drag tab area 19
8 Free Body Diagram of ABS Drag Tabs 20
9 Model of Air Braking System 21
10 Model of ABS Mechanism 23
11 Bosch BNO055 IMU 25

12 Bosch BMP280 Barometer . . . 26
13 Arduino MKR ZERO . . . 27
14 PowerHD 1235MG Servo Motor . . . 28
15 Tenergy 7.4 V, 2200mAh battery . . . 30
16 ABS PCB Schematic . . . 32
17 ABS PCB Layout . . . 32
18 ABS Control Code Flow Chart . . . 33
19 ABS Kalman Filter Flow Chart . . . 34
20 Kalman filtering of 2018 accelerometer data . . . 34
21 Kalman filtering of 2018 barometer data . . . 35
22 Subscale drag tab model . . . 36
23 Deployment system as assembled (left) and exploded view (right) . . . 37
24 Deployment system as assembled (left) and exploded view (right) . . . 38
25 Design of mounting bulkheads . . . 39
26 Design of CRAM core . . . 40
27 Design of CRAM core . . . 40
28 Rotating bar for latch mechanism . . . 44
29 Angled Plate Release Latch Mechanism . . . 45
30 Black Powder Legacy System . . . 47
31 Jolly Logic Chute Release . . . 49
32 Archetype Rocketry Cable Cutter . . . 49
33 Main parachute ejection and chute release activation . . . 52
34 Drift Estimations . . . 54
35 Subscale Vehicle Design . . . 59
36 Subsystem breakdown of the payload experiment. . . . 69
37 Further breakdown of the payload experiment subsystems. . . . 73
38 Carbon fiber props for use at competition. . . . 73
39 H-Formation of the UAV. . . . 74
40 Folded formation of the UAV. . . . 75
41 X formation of the UAV. . . . 76
42 Frame design that allows for beacon delivery clearance with battery shelving. 78
43 Iterative design process. . . . 80
44 Central Processing Unit of the UAV. . . . 82
45 Pixhawk 4 flight controller. . . . 83
46 Pi Camera Module V2 that interfaces with the Raspberry Pi 3B. . . . 84
47 Communication system architecture. . . . 85
48 A cross section of the the deployment system. . . . 89

49 The deployment system with orientation correction viewed from behind. . . . 91
50 An orthogonal view of the flange, hairpin cotter pin, and UAV strut configuration. 92
51 The diameter and pitch of a propeller. 92
52 The "X configuration" allows for increased rotational acceleration. 93
53 The "+ configuration" of a UAV. 93
54 A simplified model of a manual flight controller. 96
55 FrSky uses frequency-hopping ACCST technology across the entire 2.4GHz band for excellent range. 96
56 A convolutional neural network. 98
57 Tetrahedron shaped beacon design. 101
58 Cubic beacon design with NDRT acronyms. 101
59 Side view of the first beacon deployment design. 102
60 Phase I of the first beacon deployment design. 102
61 Phase II of the first deployment system. 103
62 Phase III of the first deployment design. 103
63 Second beacon deployment design. 104
64 Project Gantt chart, part I 150
65 Project Gantt chart, part II 151

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 Report

1.1 General Information

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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 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 Vehicle Summary

1.3.1 Size Statement

The preliminary design of the launch vehicle for this year's Student Launch competition is a variable diameter rocket with a length of 134 inches and fore and aft diameter of 7.71 and 6 inches respectively. Additional general vehicle dimensions are given in Table 2.

Table 2: Vehicle Dimensions and Characteristics

Characteristic	Dimension
Length of Rocket (in.)	134
Fore Diameter of Rocket (in.)	7.708
Aft Diameter of Rocket (in.)	6
Transition Length (in.)	4
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.)	77.595
Weight without Motor (oz.)	676
Weight with Motor (oz.)	831
Estimated Stability Margin without Motor	4.11
Estimated Stability Margin with Motor	2.81

1.3.2 Mass Statement

The mass of general sub-sections are listed below, in Table 3. These sections and masses are important to understand the weight distribution across the vehicle and its impact on the center of gravity location, as well as total mass of the launch vehicle.

Table 3: Mass Statement

Section	Weight (oz)
Nose Cone	30
UAV Payload	149
Transition Section	27.6
Recovery	272.3
ABS	91.5
Fin Can	105
Motor	155.6
TOTAL:	**831**

1.3.3 Motor Selection

Motor selection is an important step that, once fixed, will impose constraints on other aspects of the vehicle. Through OpenRocket databases, the characteristics of potential motor choices were determined. These specifications are shown below in Table 4.

Table 4: Motor Comparisons

Motor	Cesaroni L1395-BS	Cesaroni L1115	Aerotech L1120
Apogee (ft)	5036	5140	4823
Diameter (in)	2.95	2.95	2.95
Length (in)	24.45	24.45	24.45
Cost ($)	292.99	292.99	292.99

After Proposal, the team decided not to consider the Aerotech L1365-M motor due to its lower predicted altitude. This motor has been replaced by the Aerotech L1120.

1.4 Payload Summary

The payload experiment chosen for this year's competition is the unmanned aerial vehicle with simulated navigational beacon delivery. The payload experiment has been broken down into five subsystems: UAV Mechanical Design, UAV Electrical Design, Deployment System, Flight Control System, and Target Delivery System. Deployment System is further broken down into Locking Mechanism, Deployment Drive System, and Orientation Correction System.

2 Changes Since Proposal

2.1 Changes to Vehicle Criteria

Due to material sourcing constraints, the aft body diameter of the launch vehicle has been changed from 5.54" to 6". This should also provide less aerodynamic concerns with flow disruption with respect to the transition section as well. In addition to the increase in diameter, the nose cone has been changed from polypropylene to fiberglass to increase the robustness of the vehicle and provide a greater margin for survivability. The projected vehicle apogee has been lowered from 5,000 ft. to 4,700 ft. due to updated and more accurate mass budgets for different payloads.

2.2 Changes to Payload Criteria

Since Proposal, the payload experiment has undergone several design changes. These include a change in the flight controller to a Pixhawk 4, the removal of the PIC32 microcontroller, a change in the UAV orientation system, and a total redesign of the UAV body design. The new orientation system avoids the use of ball bearings completely and shall instead use an accelerometer and a stepper motor for rotation inside the UAV payload bay. A convolutional neural network is being considered for target detection, and a two beacon redundancy system shall be utilized at competition.

2.3 Changes to Project Plan

The primary change to the project plan since Proposal was to set milestones for all test flights. The targeted sub-scale flight has been set for November 17^{th}, 2018 with a backup launch day of December 8^{th}. The full scale flight is targeted to be February 9^{th}, 2019 with a re-flight launch day of March 9^{th} if necessary. Additionally, the team has derived additional requirements based on those provided by NASA to better guide the project. Finally, additional funding from the University of Notre Dame has been secured and a full itemized budget was generated for predicted project expenses.

3 Technical Design: Launch Vehicle

3.1 Mission Success Criteria

The following criteria are the team's main design drivers for mission success throughout this process and will be considered with all future design changes and verification methods.

The relevant criteria for a successful mission are: Altitude: The vehicle must reach an apogee of as close to 4700 feet as possible. Success on this criterion will be determined based on readings from an altimeter onboard the rocket. Stability: The rocket must maintain an acceptable degree of stability for the duration of its flight of at least 2.0 calibers. Stability is determined theoretically with OpenRocket and RockSim models. Structural Integrity: The vehicle must remain intact for the duration of its flight. Each component of the rocket from the motor retention and the internal bulkheads to the drag tabs on the air braking system and the onboard rover must survive the flight. Recovery: The vehicle must be reusable upon recovery without requiring repairs. Recoverability is predicted by kinetic energy calculations of each section upon landing based on terminal velocity. Recoverability of the rocket will be determined based on the condition of each component after the rocket lands.

3.2 System Level Design

3.2.1 Nose Cone

The full scale launch vehicle will have an ogive-shaped fiberglass nose cone from Mad Cow Rocketry. Nose cones of different material and source were considered. Carbon fiber was considered due to consistency with the main body of the rocket, and polypropylene was considered due to its use in the past. However, there have historically been issues with the polypropylene nose cone warping and not fitting into the body tube. Using fiberglass - which matches the material of the payload bay it is fitted to - will result in a more secure and effective fit. Due to the material selected being fiberglass, it was considered that the team may create their own nose cone, but this introduces a risk that there would be an error in fabrication. Therefore, there is no significant benefit over simply purchasing one. The nose cone satisfies the team's standards for a nose cone, in that it is lightweight and and reliable. Reasoning for the use of this specific design of cone is based on the team's use of similar cones in the past, with a great degree of success. Fiberglass is a synthetic resin made from a filament matrix. Additionally, this material is stronger than polypropylene. Previous nose cones have experienced damage while undergoing recovery, so a stronger material will provide a higher order of strength. The projected dimensions of the nose cone can be found below in Table 5.

Table 5: Nose Cone Projected Dimensions

Parameter	Value
Length (in)	22
Shoulder Length (in)	5
Weight (oz)	30
Outer Diameter (in)	7.708
Inner Diameter (in)	7.51

3.2.2 Fins

In order to retain dynamic stability during flight, fins will be attached at the fin can. Fins serve to position the Center of Pressure (CP) aft of the Center of Gravity (CG), resulting in a corrective aerodynamic moment to stabilize the rocket in flight. Without fins, unpredictable moments from wind disturbances would induce perturbations in the rocket's flight path. To reach an optimal fin design, we considered different options for the material, planform shape, airfoil shape, and number of fins.

The material for the fins needed to be chosen to be strong enough to withstand a hard impact at landing and aerodynamic forces during flight without breaking, without adding too much weight to the rocket or being too expensive. Considerations for the fin material included carbon fiber and plywood. Plywood is both light and cost-effective, but it is a comparatively weak material. Carbon fiber is light and very strong, but it is more expensive than plywood. In order to ensure structural integrity at the expense of some additional cost, the fins will be constructed using carbon fiber.

When selecting a planform shape, the options considered included ellipse, trapezoid, and parallelogram. The factors contributing to the chosen shape are summarized in Table 6.

Table 6: Fin Design Analysis

	Ellipse	Trapezoid	Parallelogram
Effectiveness at low Reynolds numbers	Low drag	Moderate drag	Low drag
Difficulty of construction	Difficult	Moderate	Simple

In order to minimize the profile drag created by the fins, and to use a shape that is easy to construct and attach to the rocket, the parallelogram is the clear choice for the fin planform shape. Tabs of length 1 in. will be added in addition to the parallelogram profile, which will be used to insert the fins into the fin can, where they will be secured using epoxy. In order to reduce drag further, the leading and trailing edges of the fins will be rounded, as shown in the dimensioned image in Figure 1.

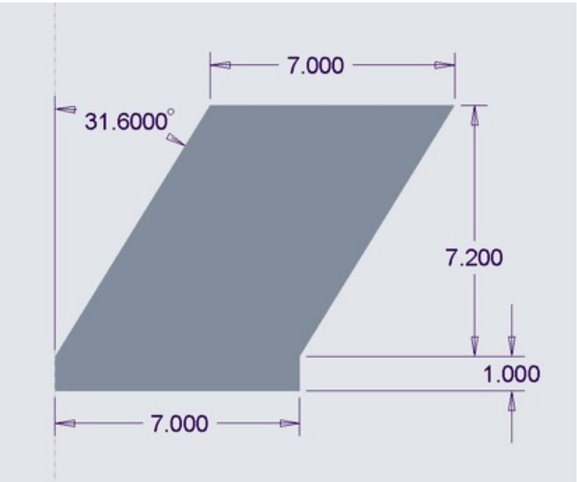


Figure 1: Leading Fin Design

At low Reynolds numbers, the optimum airfoil shape is a rounded leading edge leading to a pointed trailing edge, with a neutral camber to prevent uneven lift forces from acting on the fin surfaces. Therefore, this is the cross section shape that will be sanded onto the fins.

In order to ensure stability, the rocket must have at least three fins, and any more than four fins would be redundant. The contributing factors in choosing a number of fins are summarized in Table 7.

Table 7: Fin Design Considerations

3 Fins	4 Fins
Less additional interference drag	Higher additional interference drag
Difficult to attach symmetrically around the rocket	Easy to attach symmetrically around the rocket

Though it will add more drag to the rocket, four fins will be attached in order to ensure easy assembly and symmetry in the alignment of the fins.

An overview of the design choices for the fins is shown in Table 8.

Table 8: Leading Fin Design Dimensions

Material	Carbon Fiber
Platform 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

3.2.3 System Integration

3.2.3.1 Integration Techniques

All bulkheads and centering rings will be made of fiberglass. Fiberglass provides several structural and performance advantages over the materials of previous year, namely plywood. Through the use of fiberglass, the team will be able to build much stronger bulkheads and centering rings while decreasing overall thickness. The couplers and the motor mount will be made of carbon fiber. Previous NDRT iterations of carbon fiber construction proved sounder and more powerful than phenolic coupler design, and this year the team will continue to trust in that trend. The same logic applies to the motor mount; the carbon fiber serves as a sturdy, reliable material for the mount. Additionally, the carbon fiber material can adequately stand up to heat from the motor because of its ideal thermal properties. The team has and will continue to use a variety of epoxies and attachment hardware on the rocket. For sub scale construction, where different materials will be used, the team will use Great Planes 30 minute epoxy for the attachment of phenolic components. On the full size rocket, Glenmarc RocketPoxy will be used for carbon fiber and fiberglass pieces. The team will use this RocketPoxy to adhere the fins and centering rings to the body of the rocket, ensuring full stability and strength throughout the flight. As for the motor mount, a number of options will be considered, but JB weld will be the primary adhesive because of its extremely high heat tolerance. This heat tolerance will create a robust adhesion from the motor mount to the centering ring and fins, even throughout flight events. As the payload design is still in its development stages, more specific information on attachment hardware will be included in later reports. The team will continue to use hardware materials much stronger than necessary to ensure the safety of all involved.

3.3 Leading Vehicle Design

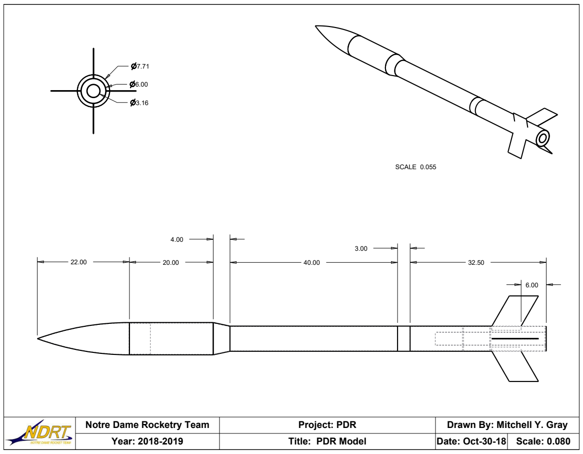


Figure 2: Leading Vehicle Design Drawing

3.3.1 Materials Selection

Fiberglass will be used for the nose cone. Polypropylene has been used traditionally in the past, due to it being inexpensive in comparison to materials such as fiberglass and carbon fiber. Polypropylene is also very easy to manipulate in necessary so it can be warped to accommodate multiple diameters. However, polypropylene nose cones in the past have provided difficulties with sizing, and so a sturdier fiberglass nose cone has been selected. The materials selected for construction of the body tube are fiberglass and carbon fiber. These materials were chosen because of their strength and their previous success in similar scenarios. The reason that fiberglass is used in conjunction with carbon fiber is that the carbon fiber would block radio signals to the UAV payload, which requires such a signal. Fiberglass provides a similar strength to carbon fiber but with a weight penalty, so it is only used for the UAV payload bay. The material selected for the fins is carbon fiber. As with the rest of the rocket, carbon fiber was selected because it is strong, responds well to shock, and durable. Another material considered is plywood. However, while plywood is much lighter, carbon fiber is much stronger and was therefore selected, also with consideration with consistency to the main body tube. The material selected for the centering rings and bulkheads is fiberglass. Fiberglass was selected for its strength and durability, an improvement from last year's plywood centering rings and bulkheads. For the couplers and motor mount, the team will be using carbon fiber. Carbon fiber provides more strength and reliability than other materials the team has used in the past, namely phenolic tubing. The team will also use various adhesives when constructing both the subscale and and full scale rocket. Great Planes 30 minute epoxy will be used for the attachment of the phenolic portions for subscale production and Glenmare RocketPoxy will be used for attaching the carbon fiber and fiberglass pieces to the full scale rocket. The motor will be attached with JB weld because of its high heat tolerance, an important factor when choosing motor adhesive.

3.3.2 Detailed Mass Statement

A detailed mass statement of parts and subsystems is listed below in Table 9

Table 9: Detailed Section and Part Masses

Part	Mass (oz)	Material
Nose cone	30	G10 Fiberglass
UAV bay	67	G12 Fiberglass
UAV and related systems	80	—-
Transition	35	G10 Fiberglass
Secondary Recovery tube	16.1	Carbon fiber
Bulkhead (each)	17.2	G10 Fiberglass
Tube coupler	3.66	Kraft Phenolic
Recovery tube	40.2	Carbon fiber
Parachute	57	—-
Recovery System	120	—-
ABS (total system not including bulkhead)	95.8	—-
Fin can	43.5	Carbon fiber
Fin (each)	6.575	Carbon fiber
Motor mount	10.6	Carbon fiber
Motor retainer	5.6	6061 Aluminum
Centering ring (each)	2.07	G10 Fiberglass

Material Properties can be found below in Table 10

Table 10: 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

3.3.3 Propulsion

To make a preliminary motor selection, a number of motor configurations were simulated on a model of the launch vehicle created in the simulation software OpenRocket. This motor selection process focused mainly on estimated apogee. To estimate the altitude at apogee, OpenRocket takes into account many parameters, including the vehicle shape, material finish, weight, and component density. For this preliminary design, weights were updated from the proposal based on continued design from payloads. Due to increases in mass from proposal, the target altitude has been shifted from 5000 ft. to 4700 ft. Considering the air braking system and a target altitude of 4700 ft, motors were selected with an estimated apogee range between 4800 ft and 5000 ft. The air braking system will be used to decrease the apogee altitude ultimately achieved by the rocket. After many simulations with a number of Cesaroni, Loki Research, and Aerotech motors, the three motors selected for the current configuration are the Cesaroni L1395-BS, Cesaroni L1115-P, and Aerotech L1120, which have predicted apogees of 4975 ft, 4879 ft, and 4823 ft respectively. Though these altitudes are higher than the target altitude, they are within range that can be accounted for by changes in weight or aerodynamic qualities prior to launch. The L1395 has a total impulse of 1101.46 lbf with a maximum and average thrust of 400.48 lbf and 314.03 lbf respectively. The L1115-P, on the other hand, has a total impulse of 1128.38 lbf with a maximum and average thrust of 385.48 lbf and 251.56 lbf respectively. The L1120 made by Aerotech, has a total impulse of 1106.51 lbf with a maximum and average thrust of 349.58 lbf and 243.69 lbf respectively. These and some other important characteristics of these motors are shown below in Table 7. The thrust curves from these two motors are shown below in Figures 5, 6, and 7. To check the simulations, these thrust curves were compared to published thrust curves for these motors and found to show the same trends. Maximum acceleration is important to the launch vehicle due to the forces it could apply to the payloads in the rocket, as well having the potential to exaggerate any unequal forces that the vehicle experiences through burnout. For this reason, maximum acceleration and burn time are important features to consider. Apogee is another important consideration to address the competition challenge, so the presence of three potential motors gives the assurance of compliance even with unexpected design changes. Below, Table 11 shows the relevant data for each considered motor.

Table 11: Motor Choices

Manufacturer	Cesaroni	Cesaroni	Aerotech
Classification	L1395-BS	L1115-P	L1120
Predicted Apogee (ft)	4975	4879	4823
Diameter (in)	2.95	2.95	2.95
Length (in)	24.45	24.45	24.45
Propellant Weight (lb)	5.17	5.24	6.06
Maximum Acceleration (ft^2/s)	224	212	187
Loaded Weight (lb)	13.24	9.63	10.25
Average Thrust (lbf)	314.03	251.56	243.69
Maximum Thrust (lbf)	400.48	385.48	349.58
Total Impulse (lbf*s)	1101.46	1128.38	1106.51
Burn Time	3.51	4.48	4.52

Each motor has benefits and negatives to its selection, and table of these considerations can be found in Table 12.

Table 12: Motor Considerations

	Cesaroni L1395-BS	Cesaroni L1115	Aerotech L1120
Overall Pros	1. This motor has a higher maximum and average thrust. 2. This motor requires a lesser weight of propellant. 3. This motor's predicted apogee is closer to the team's projected apogee.	1. This motor is the lighter option, with a loaded weight of 9.63 lbs. 2. This motor has a greater total impulse.	1. This motor has a moderate loaded weight. 2. This motor has a moderate total impulse. 3. This motor has the lowest maximum acceleration.
Overall Cons	1. This motor is the heavier option, with a loaded weight of 13.24 lbs. 2. This motor has a smaller total impulse.	1. This motor has a lower maximum and average thrust. 2. This motor requires a larger weight of propellant. 3. This motor has a predicted apogee that is farther away from the team's estimated apogee 4. This motor has a higher maximum acceleration	1. This motor provides the lowest projected apogee

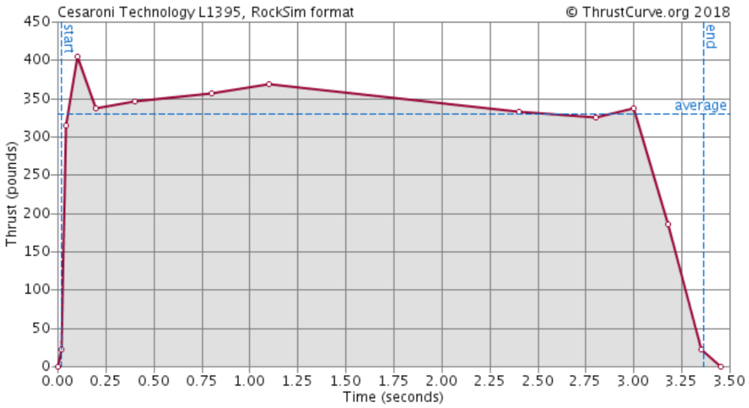


Figure 3: Thrust Curve for Cesaroni L1395

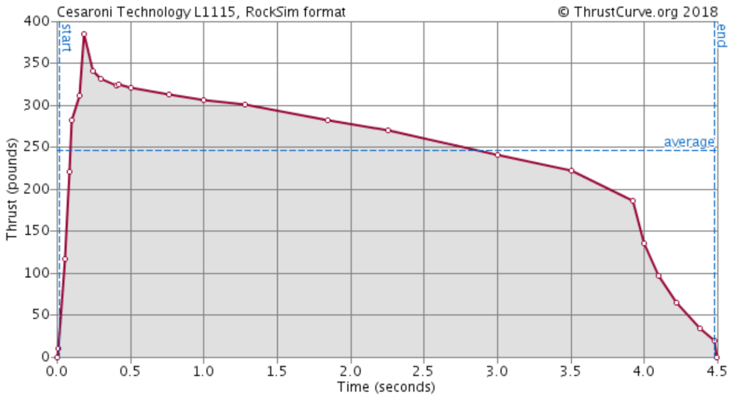


Figure 4: Thrust Curve for Cesaroni L1115

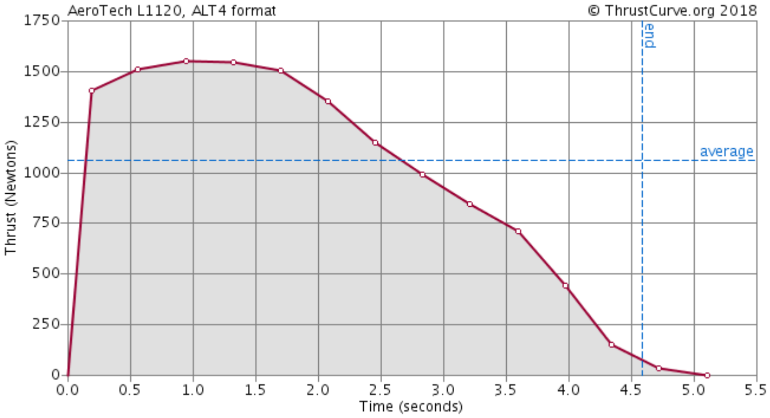


Figure 5: Thrust Curve for Aerotech L1120

3.3.4 Vehicle Layout

Table 13 shows the breakdown of the launch vehicle into subsections. These subsections are shown in Figure 6.

Table 13: Vehicle Layout

Section	Sub-Section	Label	Composition	Description
I	Nose Cone	A	Hollow fiberglass nose cone, 22" tall and 7.708" diameter	Foremost component, connected to the UAV payload bay (B)
	UAV Payload Bay	B	20" long fiberglass body tube 0.12" thick with a 7.708" diameter	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	E	Carbon fiber body tube	Holds CRAM (Compact Removable Avionics Module), as well as parachute. Measures 6" in diameter and 40" in length, with a thickness of 0.08"
II	ABS	F	Carbon Fiber body tube	Houses ABS and physical tabs
	Fin Can	G	Carbon fiber body tube and four fins	Secures four fins, Air Braking System, and motor mounting components to launch vehicle. Measures 32.5" in length and 6" in diameter

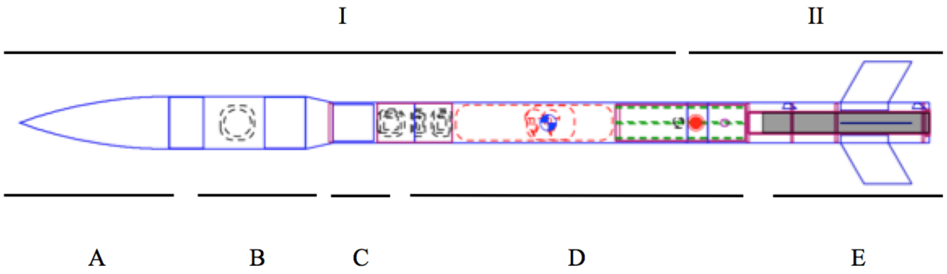


Figure 6: Vehicle Section Breakdown

3.4 Air Braking Subsystem

3.4.1 Air Braking System Overview

The purpose of the Air Braking System, hereby abbreviated ABS, is to implement a closed loop control of the apogee of the rocket. Drag control surfaces, hereby called drag tabs, will be extended from the side of the vehicle body 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 onboard avionics. These electronics will implement a closed loop PID control system using feedback from onboard 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 results of the system will be evaluated and determined to be a success based on the below 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 are only actuated if the vehicle was overshooting the designed target apogee. That is, if data is accurate and indicates the rocket shall not reach the designated apogee the tabs should not actuate.

3.4.2 ABS Aerodynamics Design

3.4.2.1 Equations and Drag Tab Sizing

Calculation of necessary drag force to control the apogee of the rocket begins with a simple force balancing equation 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/deceleration of the rocket, $F_{drag,rocket}$ 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 are calculated using the drag equation shown in 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. The drag coefficient of the tabs used for preliminary design was approximated as a flat plate and therefore was 1.28, while the drag coefficient used for the rocket was approximated as a bullet and therefore was 0.295, both according according to NASA online resources on the topic.

Based on these equations and the limiting factors of the area of the vehicle, the drag tabs are designed with an extended area of 2 in^2. Because of changes in the density of air, velocity, and other perturbations the full deployment of the tabs is not necessary throughout the entire time period in which the system will be active. Therefore, implementation of a control system provides continuous autonomous control of the tab extension to the induce the proper drag force.

The tab is shaped to sit flush with the body tube when fully retracted as shown in the model displayed in Figure 7

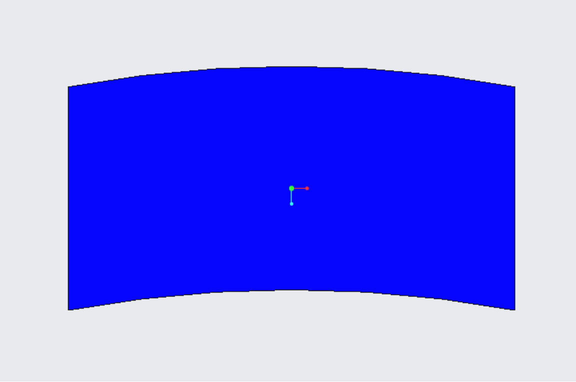


Figure 7: Top view of drag tab area

Computational Fluid Dynamics (CFD) analysis shall be performed before CDR to further quantify the impact of the tabs on the system and provide justification for the tab sizing to allow modification if deemed necessary.

3.4.2.2 Drag Tab Material

The material of the drag tabs must be able to endure the stresses and strains that it will be subjected to. An initial simplistic analysis was performed to estimate the max stress that the drag tab would be subject to with the drag tab is designed approximately as a rectangular cross section with a thickness of a quarter inch, width of 2 inches, and length of 2.5 inches achieving a maximum extension of 1 inch from the vehicle body. Based on a maximum velocity of about 450 mph, a maximum dynamic pressure of about 3.6 psi is estimated, which combined with a coefficient of drag of about 1.28 for a flat plate results in a pressure distribution of 4.6 psi on the tab. Modelling the tab as a cantilever beam at maximum extension yields a maximum bending stress of about 855 psi, which is assumed to be the max stress that the tab will be subject to. A free body diagram of the tabs is depicted in Figure 8.

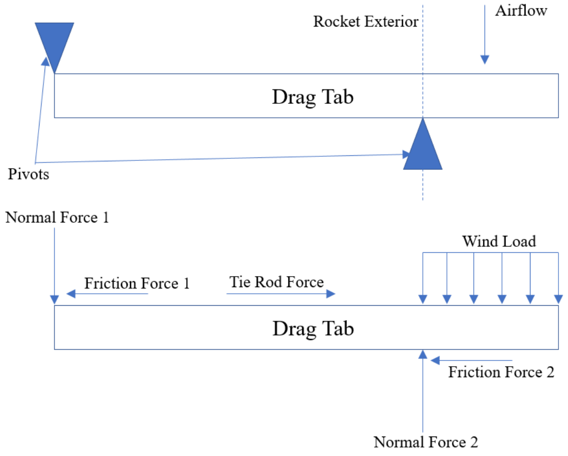


Figure 8: Free Body Diagram of ABS Drag Tabs

A table of easily machinable materials has been compiled and is displayed below in Table 14. All of the listed materials have a maximum yield stress that would provide a high factor of safety for the yield stress of the design. Other important factors that will be important to the material selection are also displayed, such as cost, weight, and machinability. Based on the low friction and easy machinability of Delrin, it is the preliminary choice for the tab material. Prior to CDR, Finite Element Analysis and Computational Fluid Dynamics analysis shall be performed on the tab design for Delrin and other materials to make a final selection.

Additionally, in order to improve the factor of safety of the supplied vs. required torque, lubricating grease such as Krytox will be applied to decrease the coefficient of friction to approximately 0.12 based on Krytox specifications.

Table 14: Comparison of Drag Tab materials

Material	Density g/cm^3	Yield Stress psi	Coefficient of Friction	Cost/kg
Alumide	1.36	6900	1.05-1.3	1.59
Polyamide	1.13-1.35	5800	0.15-0.25	4.3
HDPE	0.95	3600	0.29	1.2
Al 7075-T6	2.7	72k	0.7-1.35	1.8
Delrin	1.42	5200	0.2	3.1

3.4.3 ABS Mechanical Design

The objective of ABS mechanical system is to accurately and reliably control the drag tabs used to induce drag and control the apogee of the vehicle. To this aim, the system should not induce a moment on the rocket except for a drag force directly opposite the direction of flight precisely slowing to the selected apogee. A model of the Air Braking System is shown in Figure 9.

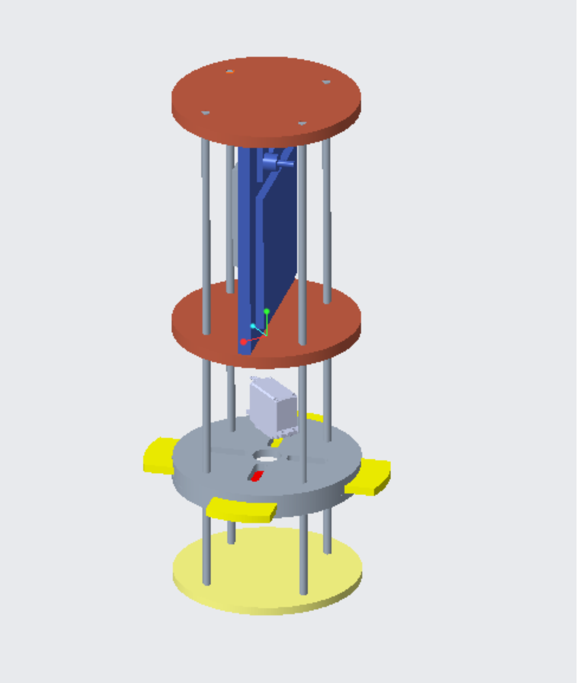


Figure 9: Model of Air Braking System

3.4.3.1 Derivation of Mechanical Design Approach

For tab distribution, two designs were considered which can both be driven about a central axis of rotation by a servomotor. One option considered was to extend the tabs non-linearly via a rotational extension of circular sector tabs from the body driven by a central gear. This system would provide the advantage of allowing for a greater area of the drag tabs which can utilize more of the vehicle's cross sectional area due to the direct rotational extension.

The second design considered focuses on linearly extending drag tabs from the vehicle of the body. This is the approach used in previous iterations of the ABS. This system provides a major advantage in that the drag induced can be considered approximately linear as the tabs extend compared to a rotational extension which has a nonlinear increase in area with motor rotation. This greatly simplifies the calculation of induced drag and provides for a more precise control system. Drawbacks of the system are that is that it limits the area of the tabs due to the required space for a the mechanism to convert rotational motor motion to linear extension. However, due to the advantage of linear extension in calculating the drag for control purposes and the advantage of using a similar system in the past, the preliminary design is to apply a linear extension approach to the mechanism.

3.4.3.2 Drive Mechanism

The servo motor driving the system will be secured above the bulkhead of the drag tab enclosure and directly connected to a central shaft. The central shaft driving the mechanical system will be bolted to a centrally located cross-arm, which is connected to each of the four drag tabs via a tie rod. This ensures that all four drag tabs will actuate at the same time, creating a symmetrical distribution of induced drag maintaining the stability of the rocket. A model of the mechanical system is shown in Figure 10 with two drag tabs removed to showcase the slots which ensure the linear extension.

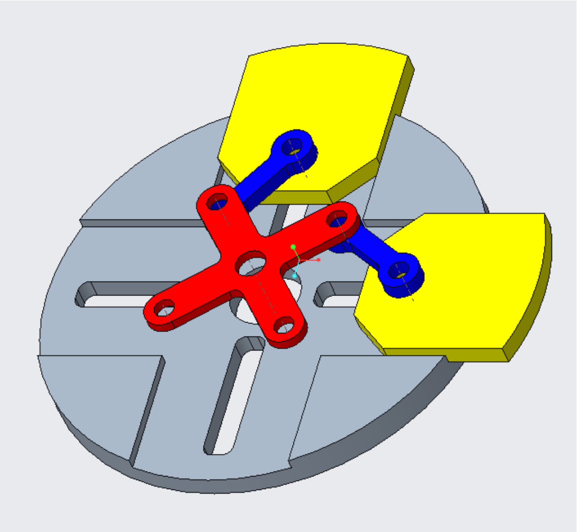


Figure 10: Model of ABS Mechanism

3.4.4 ABS Electronical Design

The electronics of the Air Braking System are designed as a comprehensive avionics module for recording flight data, filtering the data, and actuating the system based on a control algorithm maintained on board a microcontroller. Avionics electrical connections shall be condensed through the use of a custom Printed Circuit Board (PCB) and shall be securely mounted to a vertically oriented deck manufactured from High Density Polyethylene (HDPE) located fore of ABS mechanism section.

3.4.4.1 Accelerometer Trade Study

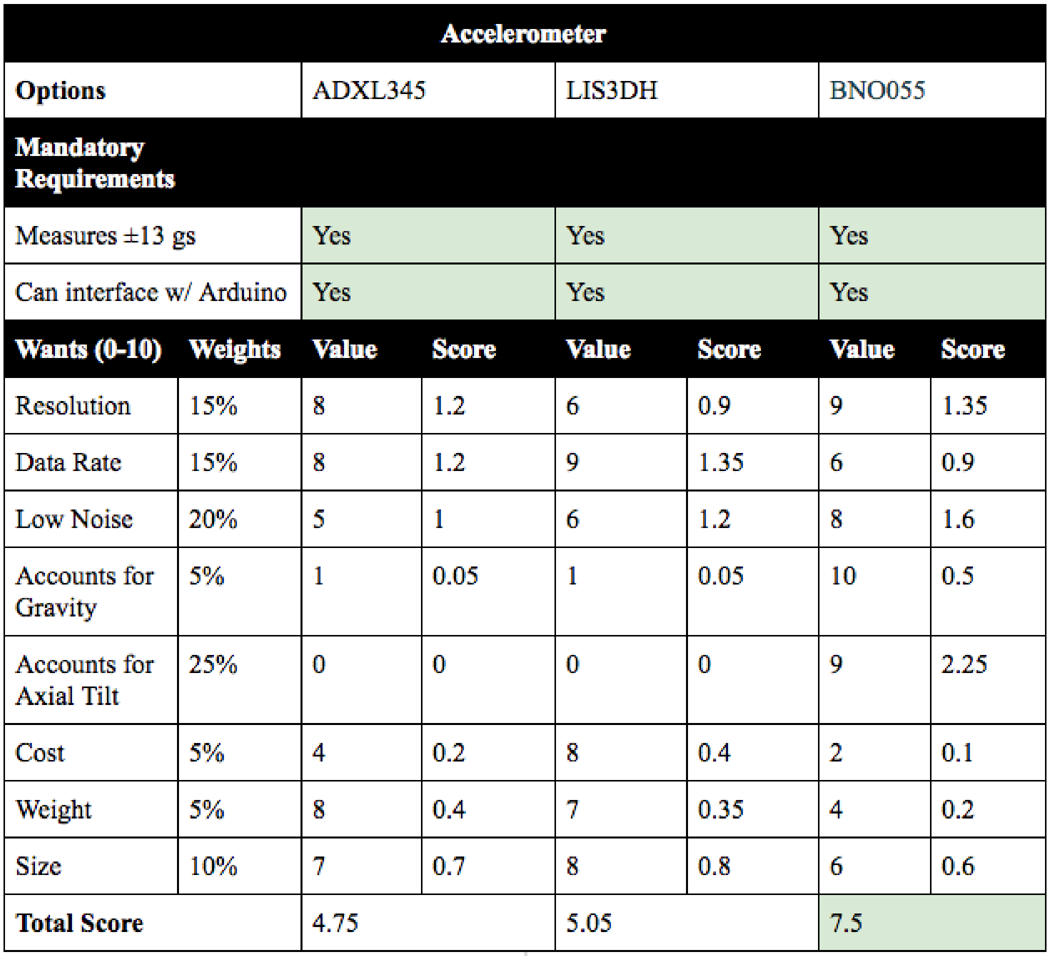
Data for the accelerometers under consideration is listed in Table 15 below. Primary considerations were measurement range, data resolution, data rate (frequency), weight, and cost. The ADXL345 is the accelerometer flown on previous years' ABS. The LIS3DH is an alternative accelerometer model considered for the benefit of its comparable technical specifications at a significantly lower cost.

The third option considered is the BNO055 which is an inertial measurement unit (IMU). This IMU provides several features including 3-axis acceleration, absolute 3-axis orientation, linear acceleration isolated from the effect of gravity, and Angular Velocity measurement. Specifications for the three accelerometers are shown in Table 15, and a trade study is conducted in Table 16.

Table 15: Comparison of accelerometer specifications

Sensor	Range (±g)	Resolution	Output Rate (kHz)	Protocol	Weight (g)	Size (mmxmm)	Cost
ADXL 345	16	13-bit	3.2	SPI, I2C	1.27	25x19	17.50
LIS3DH	16	10-bit	5	SPI, I2C	1.5	20x20	4.95
BNO055	16	14-bit	0.1	I2C	3	20x27	34.95

Table 16: Trade study of select accelerometers



Accelerometer							
Options		ADXL345		LIS3DH		BNO055	
Mandatory Requirements							
Measures ±13 gs		Yes		Yes		Yes	
Can interface w/ Arduino		Yes		Yes		Yes	
Wants (0-10)	**Weights**	**Value**	**Score**	**Value**	**Score**	**Value**	**Score**
Resolution	15%	8	1.2	6	0.9	9	1.35
Data Rate	15%	8	1.2	9	1.35	6	0.9
Low Noise	20%	5	1	6	1.2	8	1.6
Accounts for Gravity	5%	1	0.05	1	0.05	10	0.5
Accounts for Axial Tilt	25%	0	0	0	0	9	2.25
Cost	5%	4	0.2	8	0.4	2	0.1
Weight	5%	8	0.4	7	0.35	4	0.2
Size	10%	7	0.7	8	0.8	6	0.6
Total Score		4.75		5.05		7.5	

Based on the above trade study table, the BNO055 IMU is the leading choice. It keeps a clear account of the effects of gravity on measured acceleration, and even more critically provides true vertical acceleration rather than just axial acceleration (which increasingly deviates from vertical throughout flight). Additionally, it has the highest-resolution data of any of the accelerometers under consideration. It has a notably slower frequency but this is a negligible drawback since 100Hz is sufficient for an accurate flight profile. Therefore, the BNO055 is the preliminary choice for the ABS accelerometer. This choice will be verified through bench testing before CDR to confirm the performance meets manufacturer specifications. A picture of the BNO055 IMU is shown in Figure 11.

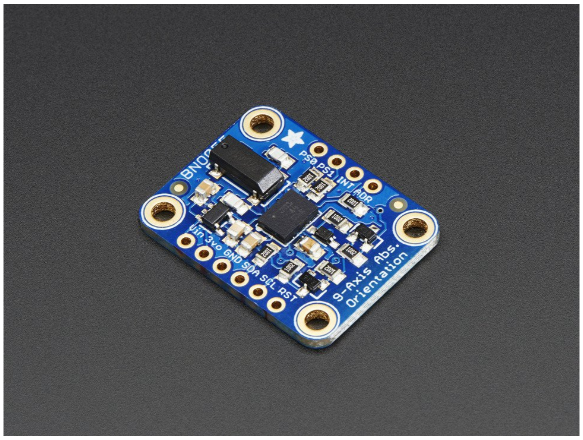


Figure 11: Bosch BNO055 IMU

3.4.4.2 Barometer Trade Study

A barometer will be used in addition to the accelerometer to measure barometric pressure and altitude. The BMP280 is the barometer flown on last year's ABS. The MPL3115A2 is being considered as an alternative option. Both options provide similar specifications for resolution, data rate, noise, and physical dimensions. These specifications are summarized in Table 17 and a trade study is constructed in Table 18.

Table 17: Comparison of Barometer Specifications

Sensor	Resolution (cm)	Noise level (m)	Rate (Hz)	Weight (g)	Size (mm)	Cost
BMP280	25	1	167	1.3	19x18	9.95
MPL3115A2	30	1	100	1.2	18x19	9.95

Table 18: Trade study of potential barometers

Barometer					
Options		BMP280		MPL3115A2	
Mandatory Requirements					
Measures 1 mile of altitude change		Yes		Yes	
Can interface w/ Arduino		Yes		Yes	
Wants (0-10)	**Weights**	**Value**	**Score**	**Value**	**Score**
Resolution	25%	7	1.75	6	1.5
Data Rate	20%	8	1.6	6	1.2
Low Noise	35%	5	1.75	5	1.75
Cost	5%	7	0.35	7	0.35
Weight	5%	8	0.4	9	0.45
Size	10%	8	0.8	8	0.8
Total Score		6.65		6.05	

Based on the results of the trade study table above, the BMP280 is the leading choice for a barometer, primarily due to the higher data rate and slightly higher resolution. Otherwise, the two sensors are very similar with the MPL3115A2 weighing slightly less. Therefore, the BMP280 is the sensor which tentatively will be used going forward, pending bench testing of both sensors to confirm they perform in line with manufacturer specifications. A picture of the BMP280 barometer is included below in Figure 12.

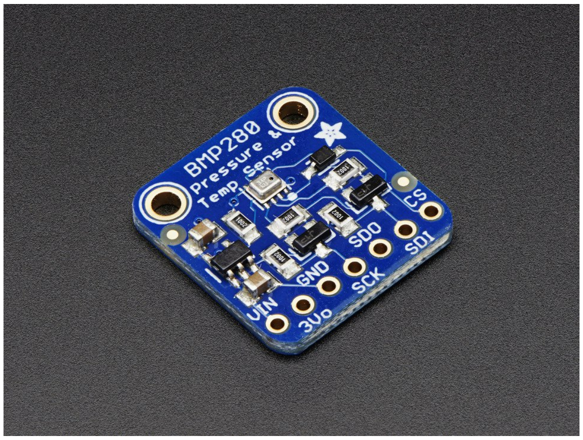


Figure 12: Bosch BMP280 Barometer

3.4.4.3 Microcontroller Selection

A large number of readily available microcontrollers were considered for the on-board processing of the Air Braking System. Since many of these low cost options provide sufficient processing memory and speed, the selection process has focused on inclusion of an on board micro-SD card reader and sufficient General Purpose Input/Output (GPIO) pins for current avionics design with room for expansion.

The primary controllers under consideration are the Arduino MKR ZERO and the Adafruit Feather M0 Adalogger. The Arduino MKR ZERO has a 32 bit SAMD21 Cortex low power ARM processor with 22 digital and 8 analog I/O pins. The Adafruit Feather M0 Adalogger has a 32 bit ATSAMD21G18 ARMo Cortex processor. Both the Arduino and Adafruit board run on 3.3V logic, 32 KB of RAM, 256 KB of Flash memory, a built in microSD card reader, and sufficient I/O pins for the Air Braking System.

The Arduino MKR ZERO has been a reliable choice in previous years and provides two more I/O pins than the Feather M0 allowing for expansion of the system. Additionally, our preliminary plan is to program the system using the Arduino IDE, giving the Arduino MKR ZERO the advantage of having native support without additional software libraries. Therefore, the MKR ZERO is the preliminary choice. A picture of the Arduino MKR ZERO is shown in Figure 13.

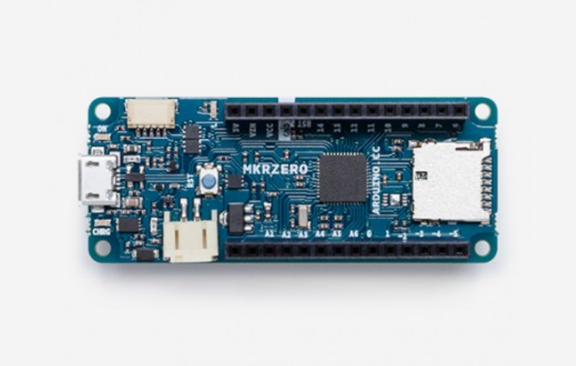


Figure 13: Arduino MKR ZERO

3.4.4.4 Servo Motor Selection

The servo motor that actuates the mechanical system is the Power HD 1235MG. The primary specifications considered were the maximum torque, the physical dimensions of the motor, and the price. The Power HD 1235MG provides a maximum stall torque of 560 oz-in which is greater than the 332 oz-in of max torque predicted by Matlab modeling of the system. In the unlikely event of a jam, the Power HD 1235MG has a high stall current of 9 Amps. Therefore, a 7.4V power supply shall be selected with a sufficient maximum current-C rating to provide a factor of safety >2 for the maximum current supplied. Table 19 below lists technical specifications for the Power HD 1235MG, and a picture of the motor is shown in Figure 14.

Table 19: Servo Motor Technical Specifications

Power HD 1235MG	
Servo Motor Type	DC Brushed
Gear style	Metal
Stall torque	560 oz-in
Speed	0.20sec/60° at 6V — 0.18sec/60° at 7.4V
Dimensions	59.5mm x 29.5mm x 55.0mm
Weight	170g
Operating Voltage	6 V - 7.4 V

Figure 14: PowerHD 1235MG Servo Motor

3.4.4.5 Battery Selection and Allocation

The selected battery voltage is 7.4 V to match the required specification for the servo motor. Primary factors considered are the capacity, size, weight, and cost. In previous years the ABS was powered by two batteries to supply power to two servo motors. With the reduction in number of motors to one, only one battery is utilized further reducing the weight of the system.

The first option considered is Turnigy nano-tech 6000mah 2S2P Hardcase LiPo battery. This battery supplies 7.4 V with a capacity of 6000 mAh and a discharge ratio of 65C. The advantages of this battery are is a high capacity leading to a longer run time and a high maximum current supply improving the safety of the system in case of current spikes. Disadvantages include the higher price and weight.

The second option considered is a Tenergy 7.4V 5200 mAh liPo battery with traxxas connector. This has advantages of high capacity and discharge rating, similar to the Turnigy nano-tech.

The third option is a Tenergy 7.4 V, 2200mAh LiPO Battery. This battery provides greater advantages through reduced weight and cost, while still providing sufficient voltage and current rating up to a maximum of 66 A. Due to the advantage of lowering the weight of the system considerably while still providing sufficient specifications, the Tenergy 7.4 V, 2200 mAh battery is the leading design choice. Table 20 below compares the specifications of the listed battery options. A picture of the selected Tenergy battery is shown below in Figure 15.

Table 20: Battery Technical Specifications

Battery Name	Capacity (mAh)	Voltage (V)	Discharge Rating (C)	Mass (g)	Dimensions (mm)	Price ($)
Turnigy nano-tech LiPo 2S2P Hardcase Pack	6000	7.4	65	313	138 x 46 x 25	33.94
Tenergy LiPo with traxxas connector	5200	7.4	60	293	139 x 47 x 23.9	56.95
Tenergy Replacement LiPO Battery for Syma X8C X8W X8G	2200	7.4	30	102.06	82 x 32 x 18	36.99

Figure 15: Tenergy 7.4 V, 2200mAh battery

To ensure the selected battery will provide sufficient run time, the current draw of the system is derived in Table 21. The most important consideration is the current draw of the Power HD 1235MG servo motor, which draws 15 mA while idle, and as the servo rotates the current increases from 900 mA with no load to 9.0 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 with a 2200 mAh battery the system can run approximately 9.6 hours while idle, and 14 minutes while stalled.

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

Table 21: Current Consumption of ABS

Device	Current Consumption (mA)
Power HD 1235MG	15 → at Idle Current (stopped)
	900 (at 7.4 V) → at Running current (no load)
	9000 (at 7.4 V) → at Stall current (locked)
BNO055	12.3
MPL3115A2	2
Arduino MKR ZERO	100
LEDS (4)	100
Total Idle Current	229.3
Total Maximum Current	9214.3

3.4.4.6 Printed Circuit Board Design

The printed circuit board is designed with a student license of the Eagle CAD 9.2.1 software. A two layer board was chosen for ease of routing considerations, and to save space in the overall footprint of the assembly and reduce the cost of the PCB. The PCB will be supplied by OSH Park with a cost of \$5/in^2.

The electrical trace widths, especially those connecting the battery to the motor, are optimized to ensure they can carry the high power required at this junction without overheating and damaging the PCB. Additionally, the Eagle program provides verification procedures to ensure the board design produced has width and layout tolerances acceptable for the requirements set by our chosen manufacturer.

The PCB is designed in such a way that minimizes external wiring off the PCB traces. The board has open through holes along its edges to interface between the sensors and microcontroller using libraries to interface with those components. The PCB divides power appropriately between the motor and relatively low-energy microcontroller through voltage regulation chips providing 3.3 V to microcontrollers and sensors.

The final additions to the PCB will aid in the user interface with the system. Multiple switches are used to power and arm the air brake prior to launch. These switches will be wired to the board out of necessity that they be placed in a location accessible when the system is inside the rocket body. Additionally, the visual feedback of multiple colored LEDs will be visible from the outside of the rocket through the hole in the ABS coupler which gives the barometer a pressure reading as confirmation that the system is functioning as expected.

A preliminary design of the PCB schematic is shown in Figure 16, and a board layout is shown in Figure 17.

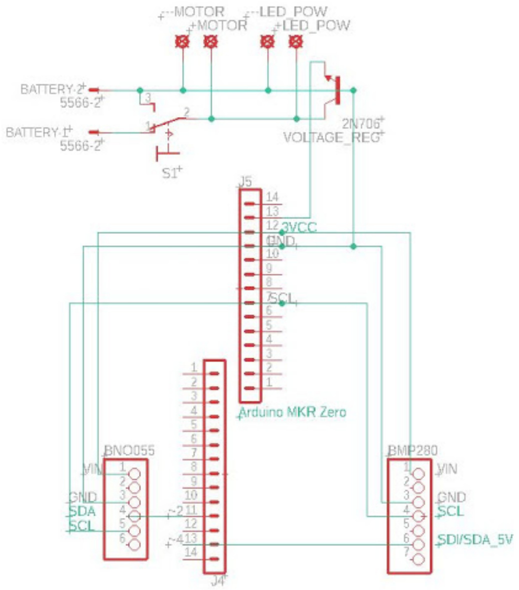


Figure 16: ABS PCB Schematic

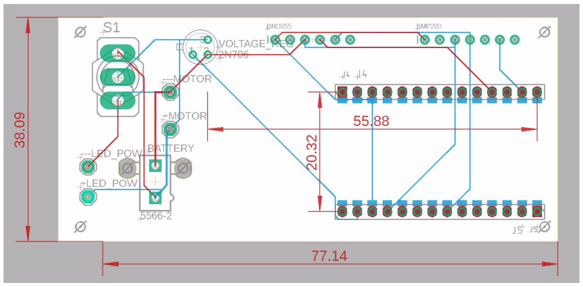


Figure 17: ABS PCB Layout

3.4.5 ABS Control System Design

3.4.5.1 Overview of ABS Control Structure

The ABS control code will first activate on the launchpad, giving visual confirmation via LED status lights that it is receiving sensor data from an accelerometer and barometer, and is connected to the SD card. Upon activating the arming switch, a third LED will give confirmation that the system is armed. Sensor data will then be continuously read into a Kalman filter, summarized below. The output of this filter will be used to determine when liftoff has occurred. Accelerometer and barometer data will then be read into the Kalman filter until the filtered data indicates burnout has occurred. After burnout, filtered sensor data will be fed into a proportional-integral-derivative (PID) controller to estimate an optimal drag tab extension. The rocket's velocity at its current altitude will be compared to the velocity at that altitude of a pre-calculated ideal flight; the difference between these two values constitutes an error value.

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. This process ends when sensor data indicates that the rocket has reached apogee, at which point the drag tabs will retract for the remainder of flight.

A flow chart of the preliminary ABS control structure is shown in Figure 18.

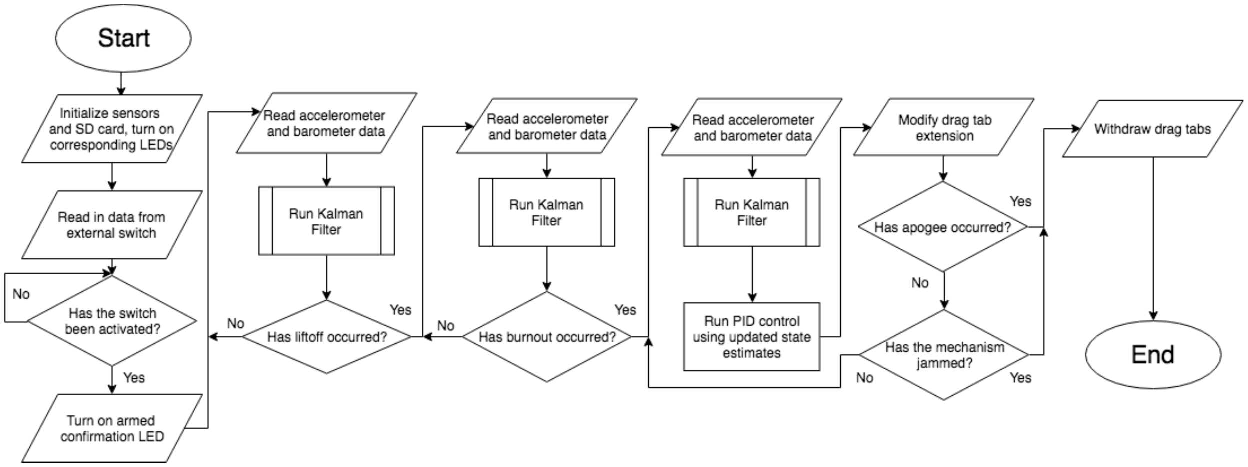


Figure 18: ABS Control Code Flow Chart

3.4.5.2 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. A flow chart depicting the Kalman filter application is shown in Figure 19.

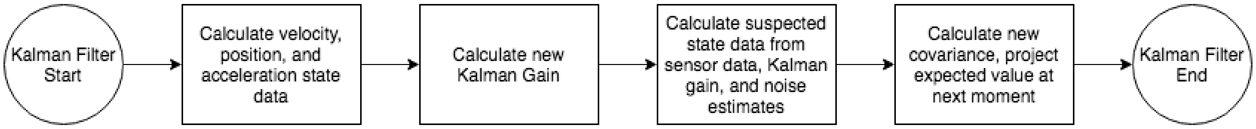


Figure 19: ABS Kalman Filter Flow Chart

Since the Kalman filter has not been utilized in previous years, a simulation of the filter was developed to test its performance on data from last year's test flights. The output of this filter on both accelerometer and barometer data can be seen in Figure 20 and Figure 21, respectively. These graphs suggest that the Kalman filter will be effective in tuning out noise spikes from both sensors, which was a major fault in the previous iteration of the ABS. Further simulation tests shall be performed before CDR, as well as a live test of the data filtering on the upcoming Subscale test flight which will provide refinement of the filter's parameters.

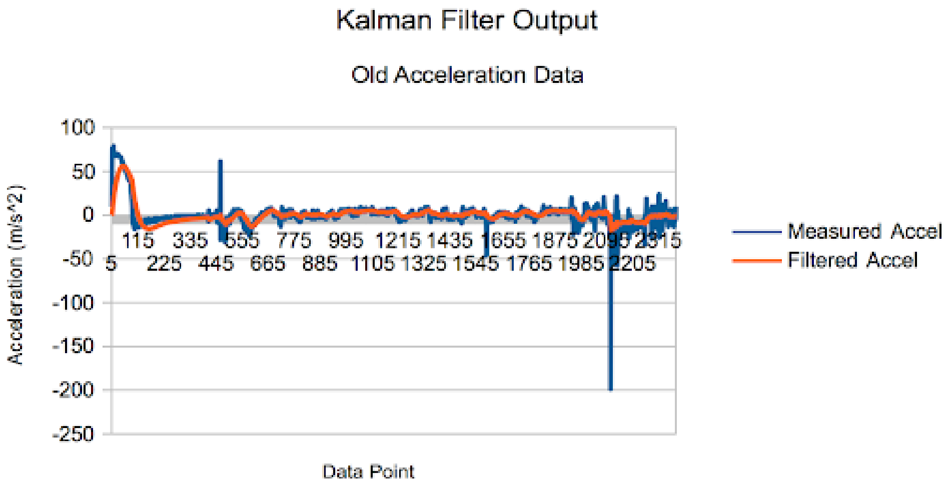


Figure 20: Kalman filtering of 2018 accelerometer data

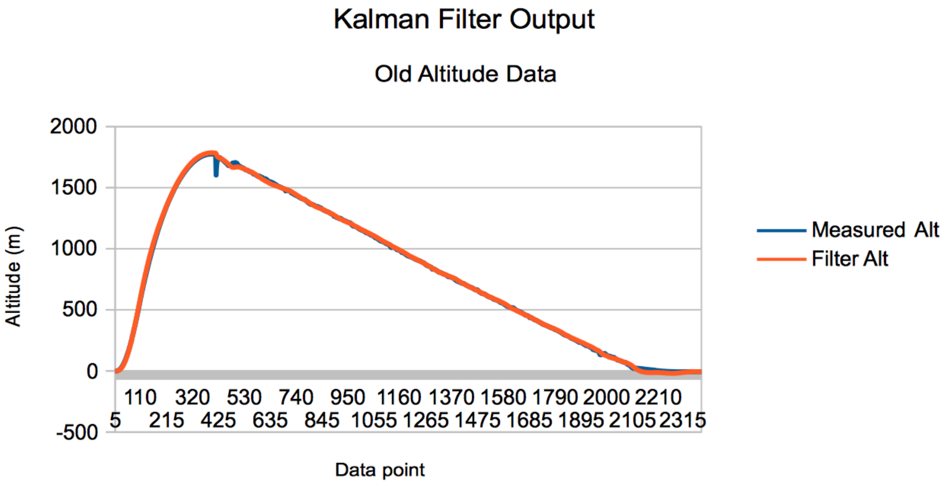


Figure 21: Kalman filtering of 2018 barometer data

3.4.6 ABS Integration Strategy

Two options were considered for the access point of the Air Braking System. One option considered was to design a hinged hatch along the side of the vehicle body for accessing and loading the ABS. The primary advantage of this strategy is the high ease of accessibility to the payload even after the rocket has been fully assembled. However, this disadvantage of this design is that it would require designing latching mechanisms to secure the hatch shut, complicate simulations, and reduce the structural integrity of the vehicle body. Hence this option was not selected.

The second option considered was to design a separation point in the rocket that provides accessibility to the ABS payload bay. The advantage of this design is that it is a simple approach and is easier to coordinate integration with vehicle the design as a result of separation points already being part of the design for the recovery system. This design will require an additional separation point in order to access the ABS. This separation point will secured using screws that will lock the Fin Can to the Body Tube during flight, but provide separation during assembly. At this time, this dedicated separation point provides ample accessibility and will be pursued.

Two options are under consideration for integrating the the ABS into the Fin Can of the rocket. The first option is to secure the ABS into the Fin Can of the rocket using threaded steel rods that will run through holes drilled in the cross sectional ABS bulkheads. These rods will then be secured by lock nuts to the fore bulkhead of the ABS. This option has been successfully utilized in previous years. A second design being considered is to integrate the ABS by designing the ABS with a slide and twist to lock mechanism similar to the one utilized by the Recovery system's CRAM. At this time the steel rods integration strategy is the leading design choice due to its simplicity and improved structural integrity along the whole length of the ABS.

3.4.7 ABS Sub-scale Flight Testing

Two verification tests will be performed on the subscale launch for the Air Braking System. The primary test will be to conduct a control flight of the subscale rocket without any Air Braking System, and then in a second launch attach a model of the fully extended drag tabs to the subscale rocket. This will be done to verify that the rocket maintains stability and decreases in flight apogee when the drag tabs are extended during flight as expected based on the design. The drag system that will be 3D printed and attached to the subscale launch vehicle is shown in Figure 22 below.

The second test will gather flight data via a prototype of the Air Braking System sensory avionics, collecting data with our leading selections for barometer and accelerometer. This will provide data on the raw performance of the sensors in terms of resolution and noise levels, and will provide data collection for adjusting parameters of the Kalman Data filter.

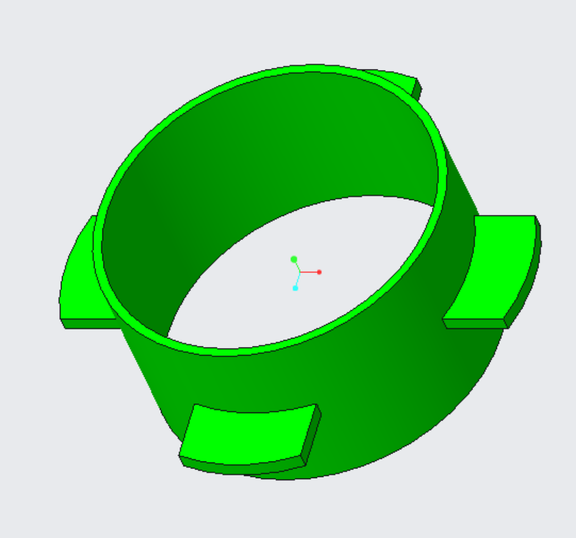


Figure 22: Subscale drag tab model

3.5 Recovery Subsystem

3.5.1 Overview

The vehicle will separate into two parts via a spring deployment mechanism. The payload section contains the nose cone, UAV bay, and transition section. The booster segment contains the parachute section and the fin can. Upon apogee, these two bays will separate and be recovered under the same parachute.

3.5.2 Mechanical Parachute Deployment System

The team has decided to pursue a mechanically driven recovery system as one of the avenues to eject the parachutes. This is driven by the system possessing a greater capability to endure ground testing, thus further ensuring its reliability during flight. Subsequent sections shall address the preliminary design of this system further.

3.5.2.1 Mechanical Parachute Deployment System

The Mechanical Parachute Deployment System uses the energy stored in a compressed spring to eject the parachute from the rocket at at apogee. The system consists of three main components. The foremost section is the CRAM, which houses the altimeters and the batteries that power the altimeters and servos. The next section is the servo bay, which houses the servos that release the spring at apogee as well as the latch mechanism, which retains the spring until apogee. The aftmost section of the deployment system is the spring assembly itself. The shock cord that connects the parachute to the rest of the rocket will pass through the entire assembly, going through the center of the spring, around the latch mechanism, and through the CRAM and mount to a structural bulkhead. Figure 23, below, outlines the current layout of the deployment system and labels the critical components.

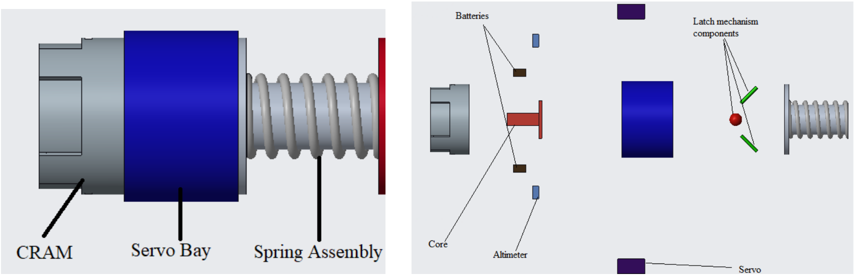


Figure 23: Deployment system as assembled (left) and exploded view (right)

3.5.2.2 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 CRAM assembly is independent of the deployment system and can be removed and repaired separately.

3.5.2.3 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 rocket body. Figure 24, below, is the current design of the CRAM body.

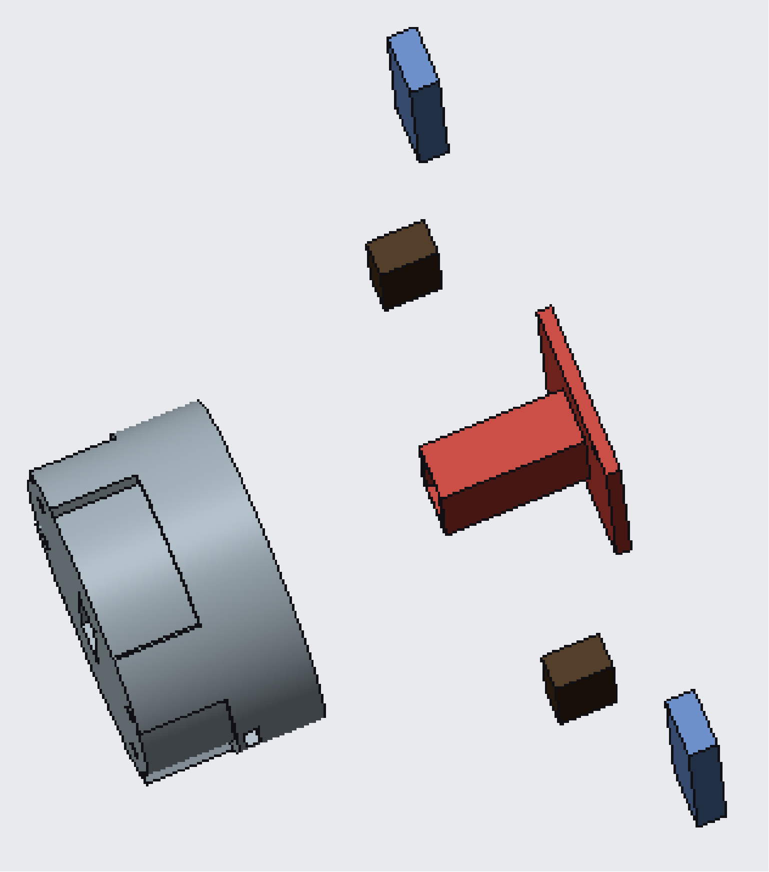


Figure 24: Deployment system as assembled (left) and exploded view (right)

The CRAM body consists of a cylinder with central cutout that allows the CRAM core, with the altimeters and batteries mounted to it, to slide easily into and out of the casing.

The slits cut into the side of the CRAM allow access to the switch that connects the battery to the altimeters. The 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. If a different type of deployment mechanism is decided upon, the bolt holes can be used to secure a bulkhead to the top of the CRAM. The bottom of the CRAM contains a large hole that will allow the shock cord connecting the top portion of the rocket to the parachute to connect to a structural bulkhead set into the rocket. Due to its geometric complexity, the CRAM body and core will be 3-D printed from ABS plastic. 3-D printing allows for the CRAM to be manufactured with high precision and reliability. 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 25 below, has protrusions that will mate with the cutouts of CRAM body. 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 rocket, through the protrusions in the mounting bulkhead, and into brass tapping inserts set into the CRAM. The protrusions in the mounting bulkhead provide a backing to prevent the screws from shearing the body tube should excessive forces be encountered, while the tapping inserts ensure that the screws will not strip out of the CRAM body. The combination of mounting bulkhead and external screws guarantees secure mounting while allowing the CRAM to be removed with relative ease.

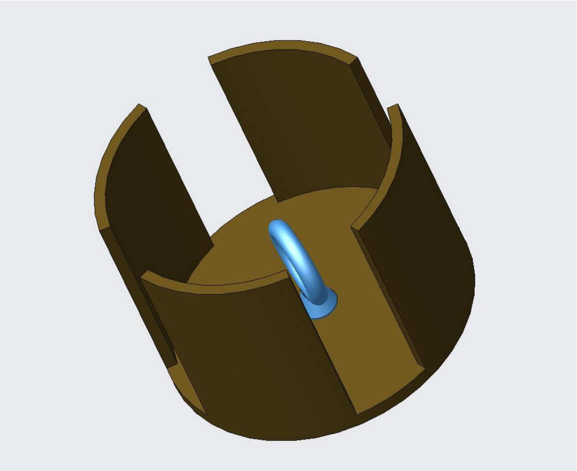


Figure 25: Design of mounting bulkheads

3.5.2.4 CRAM Core

The CRAM core is a removable sled that the altimeters and batteries are mounted to. The removeable sled design is one that allows easy access to the altimeters after the rocket is successfully recovered. Figure 26, below, is the current design of the CRAM core.

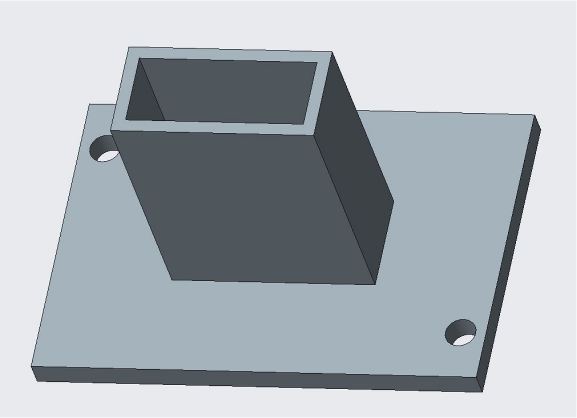


Figure 26: Design of CRAM core

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 core. The projections on the side of the core provide mounting locations for altimeters and batteries, while the holes in the protrusions allow for electrical connections to pass through to the servo bay. The CRAM core will be constructed of the same material as the CRAM body.

3.5.2.5 Shock Cords and Recovery Fittings

Shock cords will be used to connect the parachute to the separate portions of the rocket. The rear portion of the rocket will be connected through an eyebolt in the Air Braking System, while the top portion will be connected to an eyebolt in a structural bulkhead, with the shock cord routed through the recovery system. The shock cord will 9/16 flat nylon with a breaking strength of 2400 lbs. Nylon shock cord is used instead of kevlar because the nylon cord's extra width helps to prevent zippering of the body tube, while the slightly elastic nature of the cord reduces the impulse that the rocket receives during parachute opening.

Figure 27: Design of CRAM core

The shock cord will be connected to the eyebolts with ‘quick-links’, essentially carabiners that are capable of being locked in the closed position with a screw-over sheath. Quick-links are used to reduce assembly time during launch preparation, as the shock cords can be easily clipped and screwed in place on the recovery eyebolts instead of needing to be tied in place.

The eyebolts that the shock cords will connect to will be $\frac{5}{8}$-16, forged construction, 316 stainless steel eyebolts. 316 stainless steel is used due to its high yield strength and resistance to corrosion.

3.5.2.6 Spring

In previous years, an 8 gram black powder charge was required to reliably separate an airframe with a diameter of 5.5 inches and parachute compartment length of 24 inches. Based on empirical data, $1.5*10^{-4}$ grams of black powder is required to pressurize a 1 cubic inch space to 1 psi. From this, it was determined that an 8 gram ejection charge in a 5.5 inch diameter, 24 inch length parachute compartment will produce a pressure of 13.13 psi in the airframe, which corresponds to 257 lbs on the upper bulkhead of the parachute compartment. In order to replicate this with a mechanical system, the spring that separates the rocket must be capable of producing at least this much force, so no ejection springs with less than 300 lbs of maximum load were considered.

Another primary concern when selecting the ejection spring is the inner diameter of the coiled spring. One of the shock cords that connect the parachute to the separated rocket, as well as part of the latch mechanism that retains the must be capable of passing through the inner diameter, so springs with an inner diameter less than 2 inches will be not be suitable for use.

Given these considerations, a spring from The Spring Store, part number PC343-3031-5000-MW-4630-CG-N-IN, will be used as the main spring in our system. This spring meets both mandatory design considerations and is the lightest spring that was found to do so. Table 22, below, outlines some of the important properties of the spring.

Table 22: Spring Characteristics

Parameter	Value
Outer Diameter	3.031 in
Inner Diameter	2.345 in
Free Length	4.630 in
Compressed Length	2.956 in
Wire Diameter	0.343 in
Spring Constant	341.3 lbs/in
Maximum Load	571.3 lbs
Material	Music Wire
Weight	17.73 oz

3.5.2.7 Spring Support

The spring, which will be compressed during ascent to apogee, will be secured to a centering ring which will take most of the load of the compressed spring during flight. This centering ring will then be bolted to the servo bay, to prevent the spring from sliding out of the rocket after rocket separation. This centering ring will be manufactured from $\frac{1}{4}$ inch thick Garolite G10 fiberglass. Garolite G10 offers excellent strength and impact resistance, while maintaining relatively low density and reasonable cost. Attached to this centering ring will be a tube that will run up through the center of the spring. The purpose of this tube is two-fold: it helps to prevent the spring from buckling during compression, and keeps the latch mechanism and shock cord from catching on the coils of the spring. Since this tube will not bear any weight during flight, it can be made from light, cheap materials. Phenolic was chosen for the tube material as it is both inexpensive and lighter than comparable materials such as plywood.

An array of 4 cords will be used to attach the top of the spring to the latch mechanism. Multiple cords will be used instead of a single cord to provide redundancy in the case that one of the cords breaks in flight. The cords that will restrain the string will be $\frac{1}{8}$ inch Kevlar cord with a breaking strength of 2100 lbs, seven times the load that the spring will be under. This combination of exceptionally high tensile strength and redundant setup ensures that the spring will not unexpectedly decompress during assembly or flight.

Attached to the free end of the spring will be a mobile bulkhead that will slide along with the spring inside the body tube as the spring releases. The function of this bulkhead is to push the parachute out of the separated rocket body and prevent it from being tangled in the coils of the spring. This mobile bulkhead will have a hole in the center to allow the shock cords to pass through and will be made from plywood. Plywood is cheap, relatively light, and extremely easy to machine, making it perfect for components such as the mobile bulkhead.

To ensure that all of the spring's force goes into separating the rocket, instead of compressing the parachute, there must be some sort of rigid, yet mobile connection between the top of the spring and the bulkhead on the opposite side of the parachute compartment. This will be accomplished by taking an airframe coupler, or similar size of tube, cutting it into three pieces, and surrounding the parachute with this coupler. These pieces will be tethered to the mobile bulkhead that is attached to the spring. With this setup, the mobile bulkhead will push on the bottom of the tube, which will transfer the force of the spring onto the bulkhead on the opposite side of the parachute compartment. After the rocket is separated, the pieces will continue to leave the rocket before falling away from the parachute and remaining tethered to the rocket. In addition to transferring the force of the spring, the pieces of tube also serve to protect the parachute and Chute Releases as they exit the rocket. Phenolic airframe tubing was chosen as it provides an excellent combination of compressive strength and low weight.

3.5.2.8 Redundant Mechanical Latch Comparison and Selection

The energy in the compressed spring is released using a doubly redundant mechanism. Multiple designs for a latch of these specifications were considered and are outlined below. In each mechanism, a solid stopper object or a small mating latch is affixed to the free end of the shock cords holding the spring in compression. At apogee, said stopper is mechanically released, allowing the spring to decompress and cause separation of the payload and booster sections.

3.5.2.8.1 Rotating Bar Release

In the rotating bar release latch scheme, a cylindrical bar is independently turned in one direction by two servos using two freewheels when the rocket reaches apogee. The bar, shown in Figure 28, has material removed at its center. This removal gives the otherwise uniform bar two unique positions: the closed position, when the bar's center cross-section is at its widest, and the open position, when the cross-section is at its tallest and thinnest. In the closed position the mated latch is prohibited from separating from the bar, and the parachute does not release. In the open position the mated latch is able to slide free of the more vertical cross-section, and the parachute is ejected. Double redundancy is achieved by the two independent servos connected to the rotating bar by freewheels. If one servo were to stall the other servo would continue to rotate the bar, which would ratchet past the stalled servo.

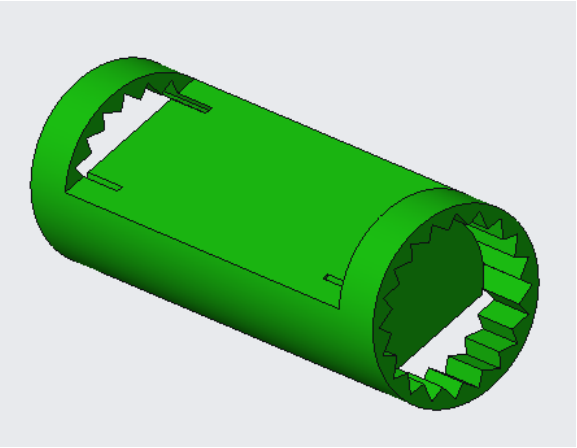


Figure 28: Rotating bar for latch mechanism

3.5.2.8.2 Plate Release

A metal stopper in the form of a small rectangular plate is permanently fixed to the free ends of the shock cords compressing the spring. The face of the stopper facing the spring has multiple bearings which reduce the friction between the stopper and the two metal plates holding it in place. These plates prohibit the stopper from moving toward the far end of the spring, thereby releasing its energy, when the mechanism is in a closed position. When closed, both plates are pressed together at the center of the body tube and above the stopper. When the latch is opened, the plates are retracted by two independent servos, the stopper escapes the plates, and the energy in the spring is released. The servos are independently operated and connect to their respective plate through a rack and pinion mechanism where the servo directly operates the pinion and rack gearing is mounted to or machined into the plate.

Double redundancy for this latch is achieved as follows.If one servo were to stall from the outset, the other plate would retract far enough to clear space for the stopper. The stopper, now only being secured by one side, would develop a net moment about its point of connection to the shock cords. Under these conditions the stopper would rotate free of the stalled plate and release the compressed spring.

3.5.2.8.3 Angled Plate Release

In this latch, a spherical stopper is attached to the shock cords under tension. Instead of flat surfaces, this stopper is held by two angled metal plates as shown in green in Figure

29, below. These plates are operated by independent servos via the same rack and pinion mechanism as in the Plate Release latch. However, they have symmetric lines of motion that are angled relative to the centerline of the rocket. The angle of plate motion and the spherical stopper size are such that when fully closed, the normal force of the stopper on the bars is perpendicular to the forks' lines of motion. This ensures that the force of the stopper on the forks does not contribute to the forks' extension or retraction before their actuation by the servos. Double redundancy is achieved in the same way as the Plate Release latch.

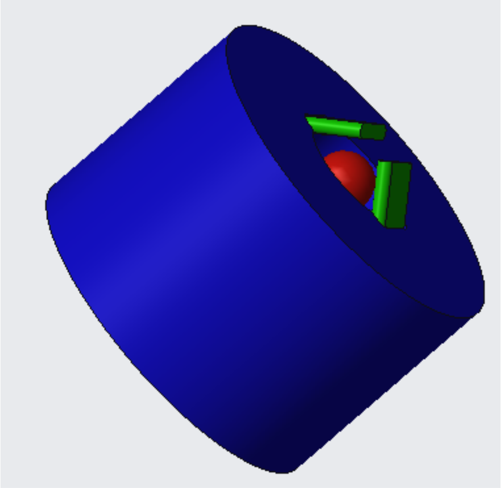


Figure 29: Angled Plate Release Latch Mechanism

3.5.2.8.4 Selection

Each latch mechanism has distinct advantages and disadvantages, which when compared, can allow for the selection of the most optimal latch.

The Rotating Bar latch allows for the use of multiple commercially available parts, enhancing its reliability. In addition, the nature of its redundancy is mechanical in nature, which can be supposed to be more realizable than redundancy of physical nature. However, the overall mechanism is more complicated, which leads to a variety of drawbacks including increased space and monetary consumption. Furthermore, due inherent space constraints, the freewheels necessary are too large if purchased, and nearly impossible to construct if machined.

The Plate Release latch is simpler, allowing reduced space consumption and a lower fabrication price. In addition, the simplicity allows for fewer moving parts and thus more reliable operation; however, the mechanism, save a rack and pinion set, would be fabricated by the team. Furthermore, the redundancy of this system relies on a proper understanding of the system physics, and is not explicitly built into the mechanism. Also, due to the size of servos, the stopper, and the necessarily large range of motion of the plates, fitting all components horizontally is challenging, while other configurations adds unnecessary complexity.

Finally, the Angled Plate Release latch allows for more efficient use of the more available vertical space, while carrying almost all of the same advantages and disadvantages as the Plate Release latch. An additional disadvantage of the angled lines of motion is the smaller resulting moment about the connection point if one servo/fork pair were to stall when compared to the Plate Release. Even so, the moment generated in the Angled Plate Release case should be more than sufficient to release the spring. Finally, the lack of rolling elements in the Fork Release Results in increased friction between the stopper and the elements holding it in place. However, this concern, too, is nullified by the fact that the large tensile force on the stopper will act to pull it free of the plates.

3.5.3 Black Powder Deployment Mechanism

An alternative to the mechanical deployment mechanism is the use of black powder within the recovery system, which has been used successfully in previous years. The black powder system relies on three PVC pipes filled with energetics rather than a spring mechanism. A diagram of this design can be seen in Figure 30 This black-powder system is triply redundant, with three isolated systems. Each of the three altimeters will be wired to a specific PVC pipe, and once the rocket reaches apogee, an electric signal will be sent to the black powder contained within the pipe, forcing the parachute outward. These three systems are time-delayed with respect to one another, so all three of the black powder charges do not deploy at once.

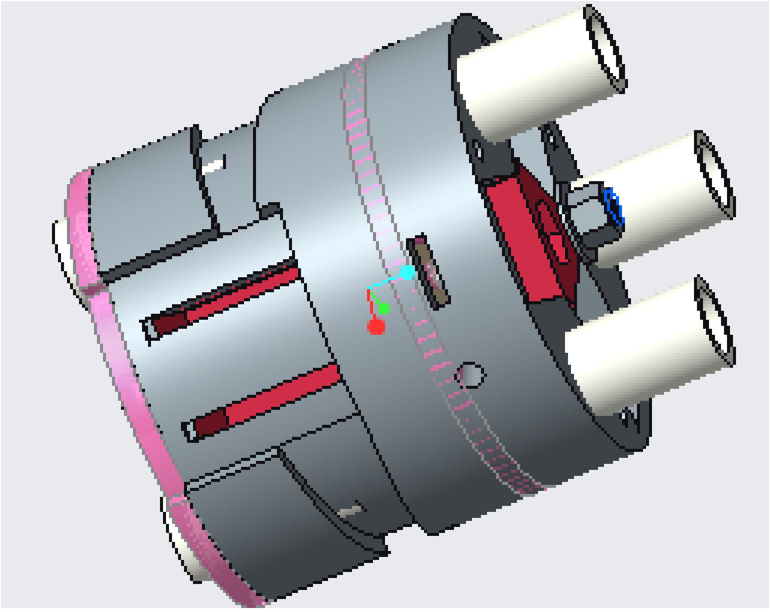


Figure 30: Black Powder Legacy System

The black powder deployment system would be verified with ground tests several times before test-launching the rocket in order to ensure that the can create the separation that is necessary for parachute deployment. Tests can also be conducted on individual altimeters to ensure that the proper signals are being sent at the right time.

3.5.4 Compressed CO_2 Separation Method

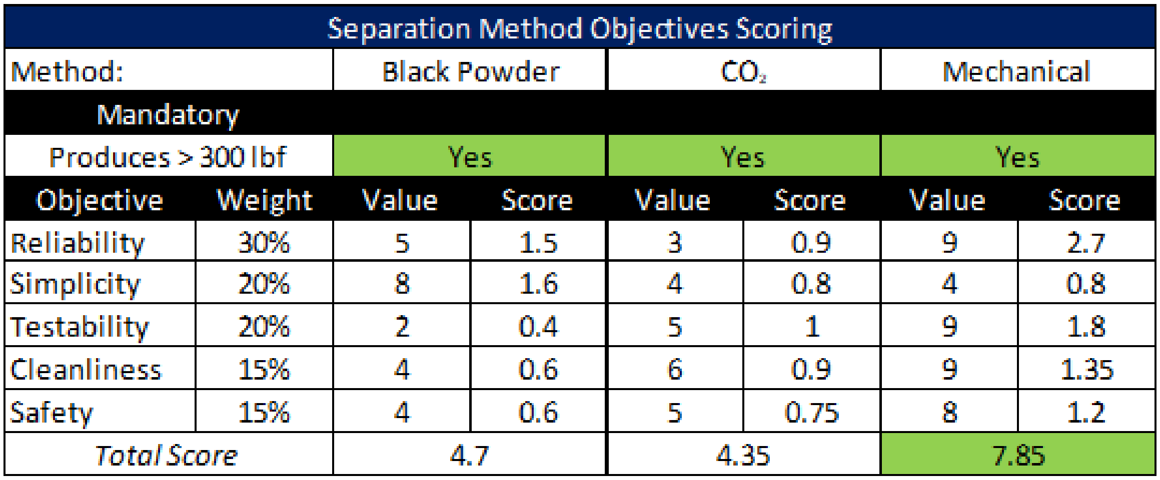
The CO_2 separation method would use a pair of independently redundant cold gas canisters to expel CO_2 into separation tubing. Because this system does not rely on charges to initiate gas expansion, it eliminates charge residue and the risk of fire. However, the compressed air canisters would require a large amount of storage space and add significant weight to the system.

3.5.5 Recovery Deployment System Trade Study

To effectively evaluate recovery system options, a Kepner-Tregoe trade study was performed in which the three potential recovery systems were evaluated: black powder separation (legacy method), compressed CO2 separation, and mechanical spring separation.

The vehicle bay separation method was determined using Kepner-Tregoe methodology and is shown in Table 23. Factors considered include cleanliness, simplicity, reliability, testability, and safety.

Table 23: Kepner Tregoe trade study table for recovery system design.



Separation Method Objectives Scoring							
Method:		Black Powder		CO_2		Mechanical	
Mandatory							
Produces > 300 lbf		Yes		Yes		Yes	
Objective	Weight	Value	Score	Value	Score	Value	Score
Reliability	30%	5	1.5	3	0.9	9	2.7
Simplicity	20%	8	1.6	4	0.8	4	0.8
Testability	20%	2	0.4	5	1	9	1.8
Cleanliness	15%	4	0.6	6	0.9	9	1.35
Safety	15%	4	0.6	5	0.75	8	1.2
Total Score		4.7		4.35		7.85	

The mechanical separation system was chosen for its reliability, testability, cleanliness and reusability, and safety. Moving forward, the recovery subsystem will be generated with this design in mind.

3.5.6 Chute Release

Because the of the design and weight constraints of the mechanical deployment system, dual deployment of separate parachutes is not feasible. In order to have dual deployment, the main chute will be tied up after ejection from the launch vehicle. There are a number of different ways in which the main parachute can be allowed to unfurl at a predetermined altitude. The options considered include the Jolly Logic Chute Release, and the Archetype Rocketry Cable Cutter.

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 set altitude which causes the parachute to unfurl. The chute release is shown in Figure 31.

Figure 31: Jolly Logic Chute Release

The Archetype Rocketry Cable Cutter functions by cutting a zip tie placed around the main chute. It is triggered by an e-match which receives a signal from recovery altimeters. A black powder or Pyrodex explosion causes a piston to cut the zip tie, releasing the main parachute. Figure 32 shows the cable cutter system.

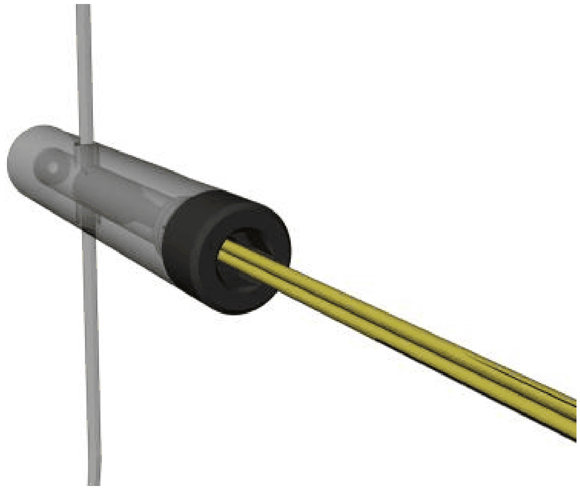


Figure 32: Archetype Rocketry Cable Cutter

A trade study was performed in order to determine the best way to release the main parachute at altitude. The results of this trade study are shown in table 24.

Table 24: Parachute release method trade study

Release Device					
Options		Jolly Logic Chute Release		Archetype Rocketry Cable Cutter	
Mandatory Requirements					
Contains main chute until activation		Yes		Yes	
Design Requirements	Weights	Value	Score	Value	Score
Reliability	50%	8	4	8	4
Safety	15%	10	1.5	7	1.5
Ease of Use	15%	10	1.5	8	1.2
Testability	15%	10	1.5	5	0.75
Cost	5%	4	0.2	9	0.45
Total Score		8.7		7.9	

The Jolly Logic Chute Release is more expensive, but it does not require the use of black powder and so is much safer, easier to use, and testable than the Archetype Rocketry Cable Cutter. For these reasons, the Jolly Logic Chute Release was chosen for use on the launch vehicle.

3.5.7 Altimeter Trade Study

Two altimeters were examined for possible use in the recovery system. The Eggtimer Altimeter, has a pressure sensor that works up to 30,000 feet and has two high-current inputs (65W) along with three outputs that can be used for a drogue and main chute. It works best for the mechanical system because it can produce a pulse width modulation signal used to modulate the servo motors. It can also be used in the black powder system if the mechanical system fails. It has constant samplings of altitude and velocity to prevent false triggering and premature deployment of the recovery system. Finally, the Eggtimer Altimeter collects data and provides the peak altitude after flight.

The second altimeter that might be used is the Raven 3 Altimeter. The advantage of this altimeter is that it has four high powered outputs compared to the three of the Eggtimer. The Raven 3 has the ability to collect data for the current and voltage output along with the barometric data with ±.3% accuracy. Each output of the altimeter can be used for one stage of the recovery process, including apogee deployment and main chute deployment. This altimeter also outputs the peak altitude after landing. The disadvantage of using the Raven 3 Altimeter it lacks many of the features the Eggtimer has, such as the easy constant samplings of velocity and altitude data along with the easy ability to modulate servo motors. For these reasons, the Eggtimer altimeters were chosen for the recovery system.

3.5.8 Recovery Staging

The launch vehicle separation will be staged so as to follow the drift and descent time requirements. The recovery details are described in Table 25.

Table 25: Recovery Staging

Stage	Action	Altitude	Description
1	1.1 Spring Release	4700ft AGL	The four nylon shock cords used to compress the spring are released by a servo motor and latch mechanism
1	1.2 Parachute Separation	4700ft AGL	The released spring pushes a moveable bulkhead to separate the rocket section for parachute deployment
1	1.3 Jolly Logic Chute Release	4700ft AGL	The Chute Release elastic is wrapped around the folded main parachute, preventing the main parachute from opening up during and after ejection
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 in Table 25 are shown in Figure 33.

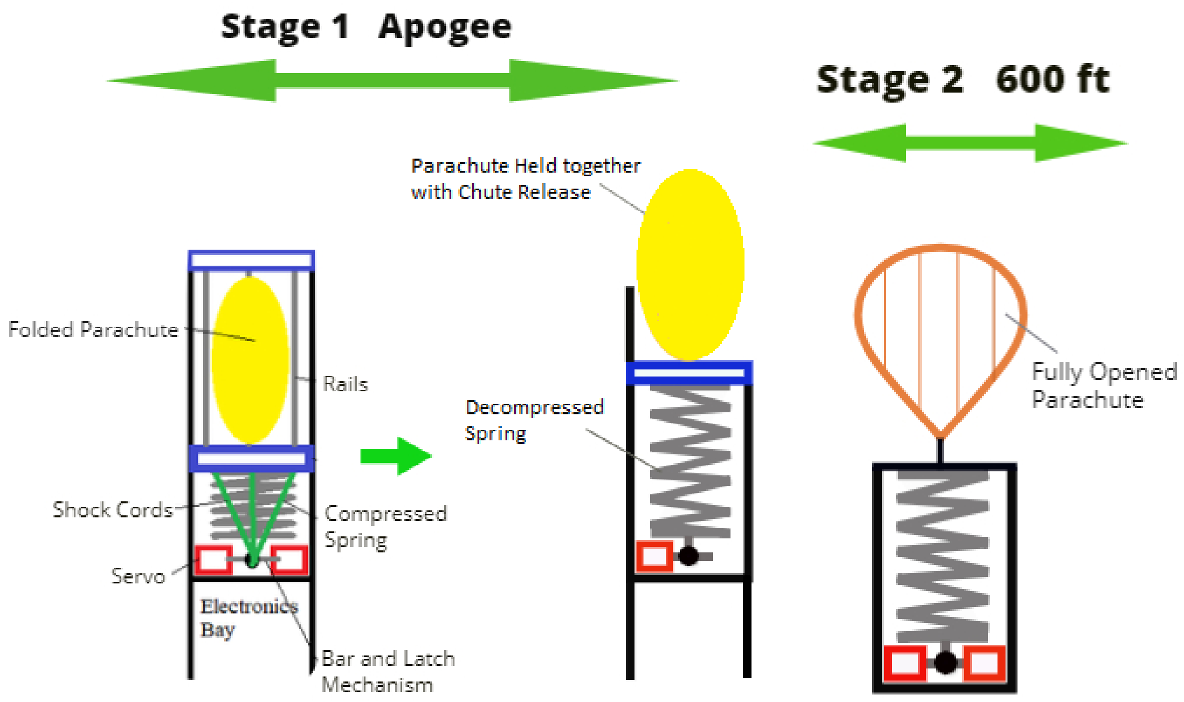


Figure 33: Main parachute ejection and chute release activation

3.5.9 Electronics

The main parachute ejection will be triggered by Eggtimer Model Rocket Flight Computer which takes barometric samples at 33Hz. The Eggtimers will send a pulse width modulation signal to two PowerHD-1235MG servo motors. Both the servos and the altimeters will be powered with Tenergy Li-ion 18650 7.4v batteries.

3.5.10 System Design

3.5.10.1 Parachute Sizing Requirements

The minimum nominal diameter of the main parachute was calculated based on the minimum kinetic energy requirement of 75ft-lb. Using a force balance found in equation 3 where m_v is the mass of the vehicle, g is acceleration due to gravity, C_D is the drag coefficient of the parachute, ρ is the air density at sea lever, the nominal diameter of the parachute D_0 can be found.

$$Drag = m_v * g = \frac{1}{8}\rho V^2 C_D D_0^2 \pi \tag{3}$$

Substituting the in the kinetic energy KE for the terminal velocity yields Equation 4 where m_s is the mass of the heaviest subsection of the rocket.

$$D_0 = \sqrt{\frac{4m_v m_s g}{\rho KE C_D \pi}} \tag{4}$$

Table 25, below, shows the weight of each individual section and minimum parachute diameter to meet the kinetic energy requirement.

Table 26: Weights of Vehicle Sections

Section	**Weight (oz)**	**Minimum Parachute Diameter (in)**
UAV and Recovery Bays	480	132
ABS and Fin Can	360	114

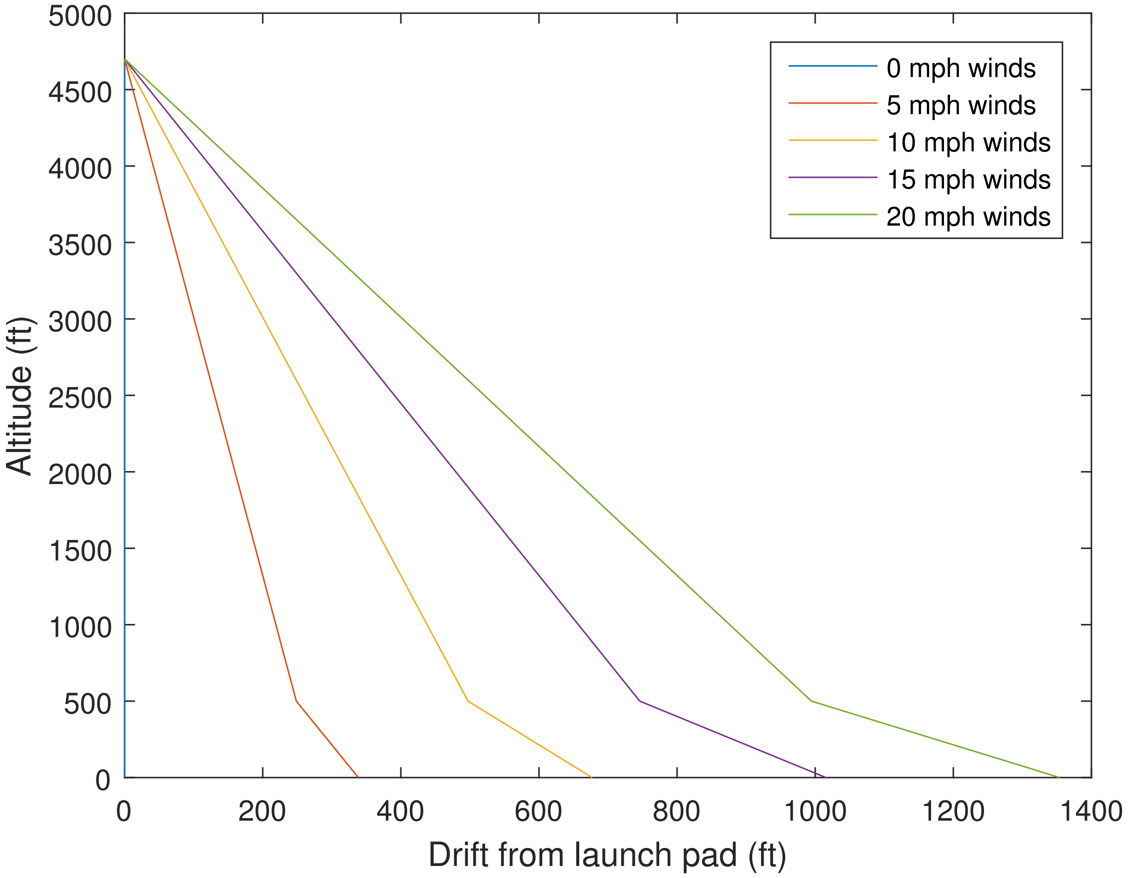
In order to meet this requirement, the Cert 3-Series XX Large parachute was chosen. The nominal diameter of the parachute is 12.82ft. From this, the terminal velocity and the descent time after main deployment were calculated based off of a main deployment altitude of 500 ft AGL. Table 27 shows the pertinent characteristics of the chosen parachute.

Table 27: Characteristics of the Cert 3-Series XX Large

Diameter (ft)	12.82
Terminal velocity (ft/s)	10.83
Weight (oz)	64
C_d	2.92

Based on this information, the drag due to the packed parachute held by the chute release could be calculated. Assuming a C_d value of 0.25, which is common for streamers, the terminal velocity of the launch vehicle under the streamer is 247.75ft/s. With these terminal velocities, the descent time was calculated to be approximately 80.1s, which is below the descent time requirement. Based on this information, the drift during various testing conditions could be calculated. The drift radius in various launch conditions is shown in Figure 34.

Figure 34: Drift Estimations



As shown, the predicted drift radius for any reasonable launch conditions is well below the maximum drift requirement of 2500ft.

3.5.11 Subscale Vehicle Recovery

The subscale launch of the rocket will include a more basic deployment of the parachute than the mechanical, or black powder system that will be included in the full scale rocket. The subscale rocket will use basic motor ejection that consists of a black powder charge on a delay. The eggtimer altimeter that will be used in the full scale launch will still be included in the subscale, but only in order to verify its functionality within the rocket, and to obtain altitude data. Only one parachute will be ejected from the rocket in the subscale in order to test chute release, and will be ejected at apogee. This parachute will be 36 inches in diameter, which will keep the terminal velocity under 22ft/s. Given a subscale weight of 44oz, the kinetic energy at landing will be less that 30ft-lbs, which is 40% of the full scale limit set by NASA. This was verified using equation 4.

3.5.11.1 Vehicle Integration

The recovery system will be placed between two permanent bulkheads epoxied to the launch vehicle. The epoxied bulkheads will be loading bearing during descent and will also keep the recovery system in place during flight. In the foremost section of the recovery system, the parachute shock cord will run through the CRAM and quick link to an eyebolt inside of the epoxied bulkhead. There will also be external screws which mount the CRAM inside of the launch vehicle to prevent movement during any point in flight. In the aftmost section of the rocket, a shock cord will run though a centering ring and quick link to an epoxied bulkhead on fore of the ABS.

3.6 Mission Performance Prediction

3.6.1 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. Table 28 below shows the results of the OpenRocket flight simulations for both motors under all conditions.

Table 28: Flight Simulations

Motor	Wind Speed (mph)	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s^2)	Ground Hit Velocity (ft/s)
Cesaroni L1395-BS	0	4884	581	218	8.76
	5	4872	636	218	7.87
	10	4848	635	218	7.45
	15	4789	634	218	8.71
	20	4708	633	218	8.4
Cesaroni L1115	0	4982	548	206	8.96
	5	4965	548	206	8.87
	10	4924	547	206	8.29
	15	4872	546	206	8.28
	20	4818	544	206	7.77
Aerotech 1120	0	4827	532	187	7.18
	5	4813	532	187	7.44
	10	4769	531	187	7.96
	15	4724	530	187	7.85
	20	4843	545	187	7.83

As the table shows, the Cesaroni L1120-BS motor produced a lower apogee than the L1115 and the L1395 at each of the specified wind conditions. Given the current target apogee of 4700 ft, the L1115 is a more feasible choice, as it will give ABS enough room to demonstrate effectiveness. The L1395 produced a slightly higher maximum acceleration (218 ft/s^2 compared to 206 and 187 ft/s^2), but at 6.8g, this acceleration is acceptable for a rocket of this size. The stability of the rocket is currently approximated between 2.71 and 2.83, which is above the 2.0 requirement, but still nearing over-stability.

3.6.2 Static Stability Margin

The stability for the launch vehicle is required to have a margin of at least 2 calipers. The vehicle must have a center of pressure aft of the center of gravity to prevent aerodynamic forces on the rocket from creating a moment. The unloaded vehicle has a stability margin of 4.11, and a table of the loaded stabilities with all three potential motors can be found below. The stability was calculated with CAD modeling and OpenRocket simulations. The stabilities can easily be altered should the center of gravity shift in the launch vehicle by adding ballast to sections of the vehicle. Table 29 lists the margins for each currently considered motor.

Table 29: Stability Margins

Motor	Static Stability
Cesaroni L1395	2.83
Cesaroni L1115	2.81
Aerotech L1120	2.77

3.7 Subscale Vehicle

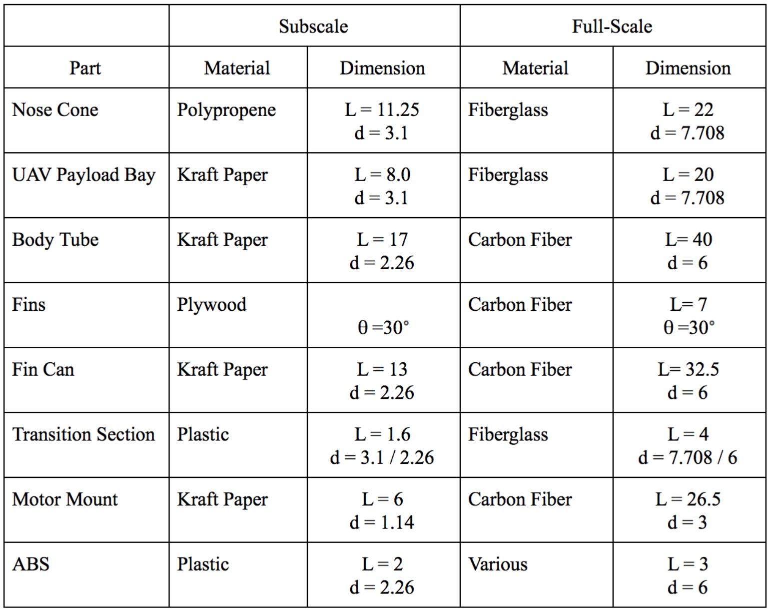
3.7.1 Comparison to Full Scale Vehicle

In order to test our design and get the desired stability and altitude values our subscale will have a scaling factor of 40%. Each individual piece will either be ordered or cut to be the necessary size. In Table 30, you can see the comparison of full-scale and subscale dimensions and materials; all dimensions are in inches. Materials on subscale were determined both considering price and functionality. On the other hand, materials for full-scale were determined considering payloads and it's compatibility with the design of the rocket as a whole. For example, while most sections of the rocket's subscale will be made out of kraft paper the full-scale body will be made out of carbon fiber. Another design consideration between the subscale and the full scale is the material of the bulkheads. In the full scale, all centering rings and bulkheads will be made out of fiberglass. For the subscale, plywood will be suitable for all load bearing surfaces.

As for motor choices the Cesaroni L1395-BS, Cesaroni L1115, and Aerotech L1120 Motor were considered for full-scale. For subscale the Aerotech G79-7W motor will be used to take the necessary stability and drag measurements. This has a projected apogee of 1481 ft without the ABS substitution, and 1036 ft. with the tabs inserted.

The air braking system (ABS) of the rocket will be simulated by a 3D printed, solid part. The part will consist of a cylinder with four solid flaps that fits in between the fin can and the body tube. In Table 30 below, you can see a CAD of the described part. This part is removable and will only be slid into the body tube to calculate drag values of ABS.

Table 30: Subscale to Full Scale Comparison



	Subscale		Full-Scale	
Part	Material	Dimension	Material	Dimension
Nose Cone	Polypropene	L = 11.25 d = 3.1	Fiberglass	L = 22 d = 7.708
UAV Payload Bay	Kraft Paper	L = 8.0 d = 3.1	Fiberglass	L = 20 d = 7.708
Body Tube	Kraft Paper	L = 17 d = 2.26	Carbon Fiber	L= 40 d = 6
Fins	Plywood	θ =30°	Carbon Fiber	L= 7 θ =30°
Fin Can	Kraft Paper	L = 13 d = 2.26	Carbon Fiber	L= 32.5 d = 6
Transition Section	Plastic	L = 1.6 d = 3.1 / 2.26	Fiberglass	L = 4 d = 7.708 / 6
Motor Mount	Kraft Paper	L = 6 d = 1.14	Carbon Fiber	L = 26.5 d = 3
ABS	Plastic	L = 2 d = 2.26	Various	L = 3 d = 6

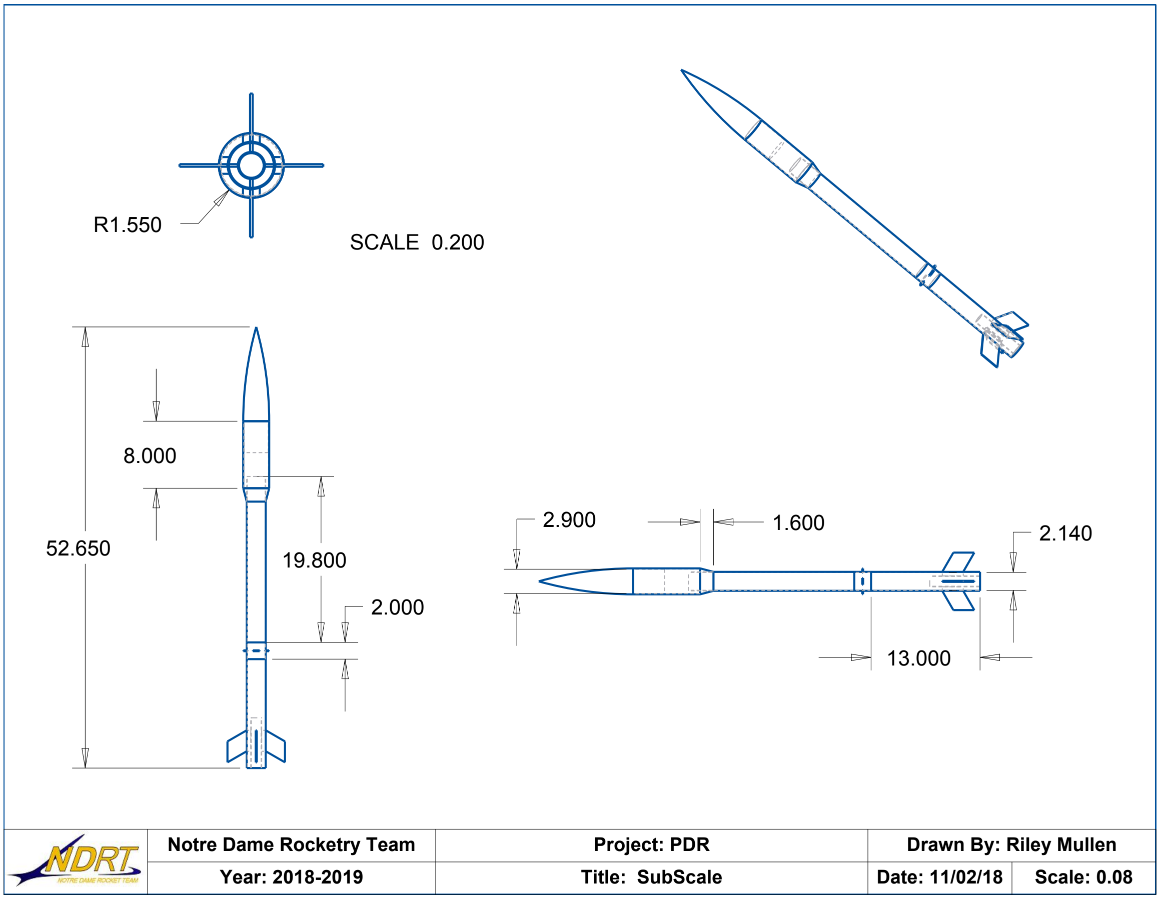


Figure 35: Subscale Vehicle Design

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 31 below.

Table 31: 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 32 below.

Table 32: 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 33, and the description of each risk level is listed in Table 34.

Table 33: 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 34: 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 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 sub-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.

4.3.1 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

4.4 Procedures

Prior to construction, 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.

4.4.1 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.

4.4.2 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.

4.5 Sub-Scale Rocket Plan

Safety plans specific to construction and launch of the sub-scale are either already implemented or currently being implemented.

4.5.1 Construction

Construction of the sub-scale rocket will be performed solely by members of the team who have achieved at least a level 1 safety certification from the University of Notre Dame through its Student Fabrication Lab. The certifications completed by each member will be recorded and kept up to date by the Safety Officer. All members of the team who have been identified to be integral to construction of the sub-scale have completed the necessary certifications to complete their roles in construction, this includes all officers of the team and senior members. All necessary PPE, tools, and tool guards for construction have been acquired and implemented. Additionally, the Safety Manual shall be published and released to the team prior to construction, which shall ensure that all necessary mitigations for any personnel hazards due to construction of the sub-scale rocket shall be properly implemented. An ORR will be conducted prior to commencement of sub-scale construction

4.5.2 Launch

Launch of the sub-scale rocket will be performed solely by experienced members of the team who have prior experience of launches. New members without this experience will not assist, and will attend as spectators to help them to learn what goes into a launch. All necessary PPE has been acquired for the sub-scale rocket launch, and the team has identified all hazards and failure modes posed by sub-scale launch has ensured that they pose as little threat as possible. The team will abide by the NAR Safety Code and the Launch Procedures outlined by Michiana Rocket. Additionally, the Safety Manual shall have been published and released to the team, which shall ensure that all necessary mitigations for any personnel hazards due to launch of the sub-scale rocket shall be properly implemented. An ORR will be conducted prior to the sub-scale rocket launch.

4.5.3 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 Technical Design: Payload

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

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.

5.2 System Level Trade Studies

The main subsystems of the payload experiment were evaluated through trade studies in order to quantify the design decisions at the Preliminary Design Review level. This section shows the studies undertaken for each subsystem. Figure 36 shows a flowchart of main subsystems for the payload experiment.

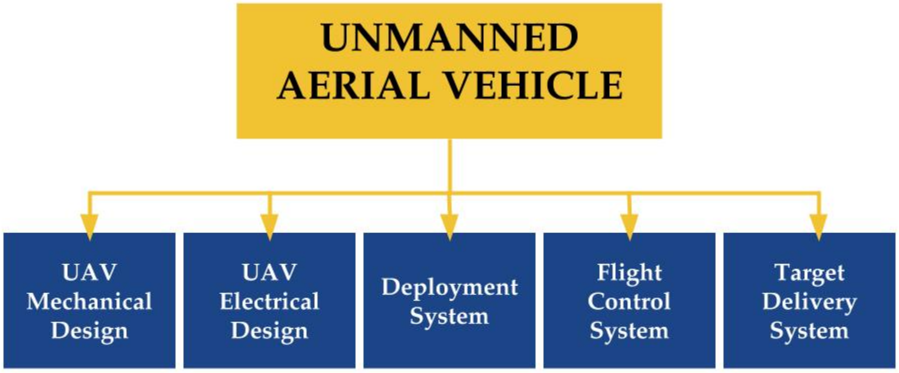
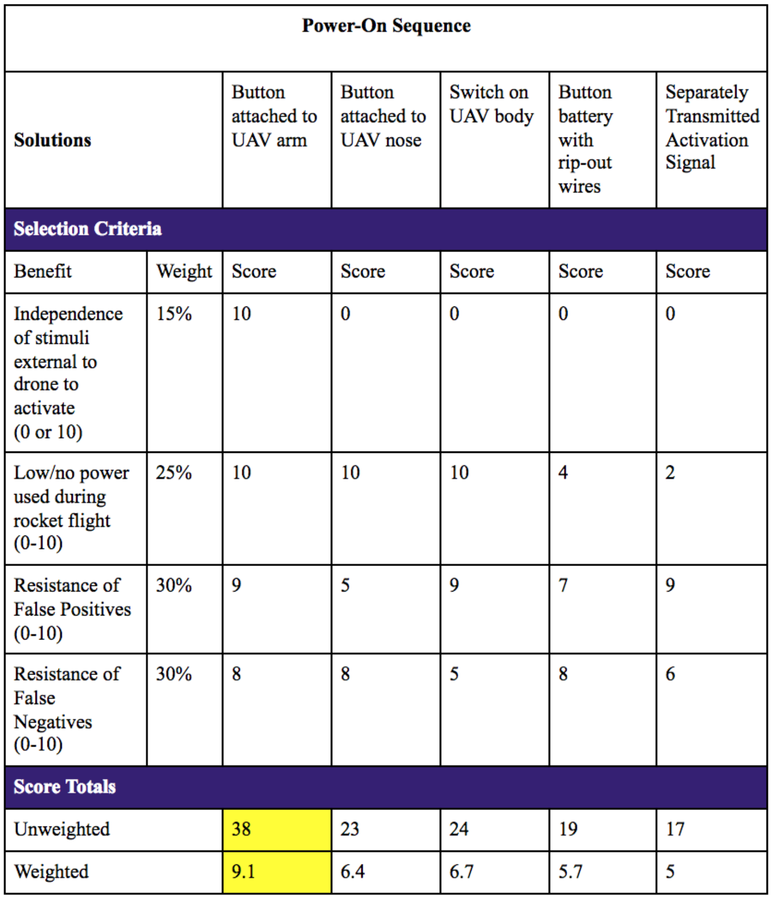


Figure 36: Subsystem breakdown of the payload experiment.

5.2.1 UAV Electrical Design

Table 35 shows a trade study of different ways to power on the UAV.

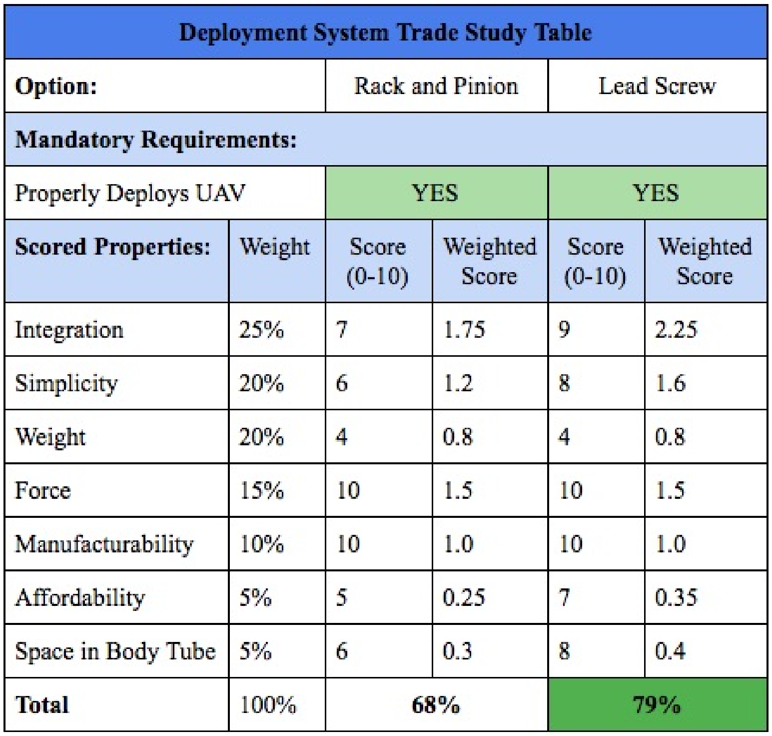


Power-On Sequence						
Solutions		Button attached to UAV arm	Button attached to UAV nose	Switch on UAV body	Button battery with rip-out wires	Separately Transmitted Activation Signal
Selection Criteria						
Benefit	Weight	Score	Score	Score	Score	Score
Independence of stimuli external to drone to activate (0 or 10)	15%	10	0	0	0	0
Low/no power used during rocket flight (0-10)	25%	10	10	10	4	2
Resistance of False Positives (0-10)	30%	9	5	9	7	9
Resistance of False Negatives (0-10)	30%	8	8	5	8	6
Score Totals						
Unweighted		38	23	24	19	17
Weighted		9.1	6.4	6.7	5.7	5

Table 35: Power-On Sequence trade study for the UAV electrical design.

5.2.2 Deployment System

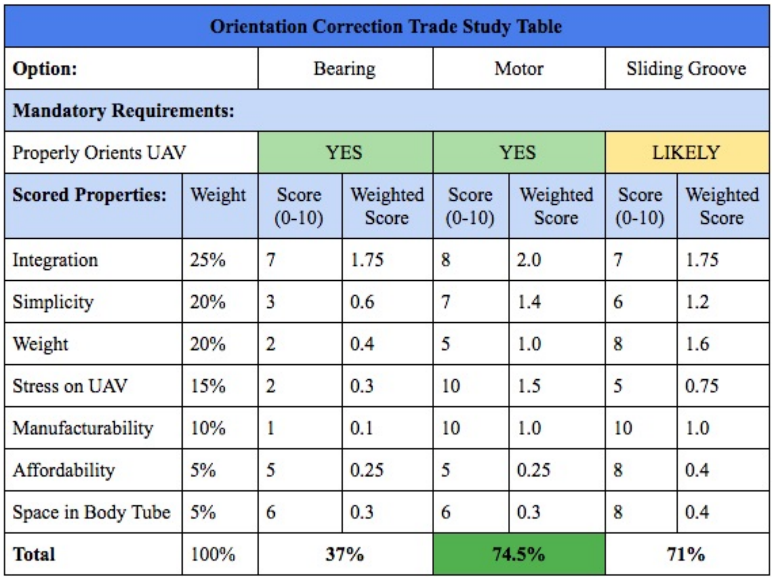
Table 36 shows a trade study of different deployment systems for the UAV.



Deployment System Trade Study Table					
Option:		Rack and Pinion		Lead Screw	
Mandatory Requirements:					
Properly Deploys UAV		YES		YES	
Scored Properties:	Weight	Score (0-10)	Weighted Score	Score (0-10)	Weighted Score
Integration	25%	7	1.75	9	2.25
Simplicity	20%	6	1.2	8	1.6
Weight	20%	4	0.8	4	0.8
Force	15%	10	1.5	10	1.5
Manufacturability	10%	10	1.0	10	1.0
Affordability	5%	5	0.25	7	0.35
Space in Body Tube	5%	6	0.3	8	0.4
Total	100%	**68%**		**79%**	

Table 36: Deployment method trade study for the linear motion of the UAV exiting the rocket.

Table 37 shows a trade study of different ways to correct the orientation of the UAV.

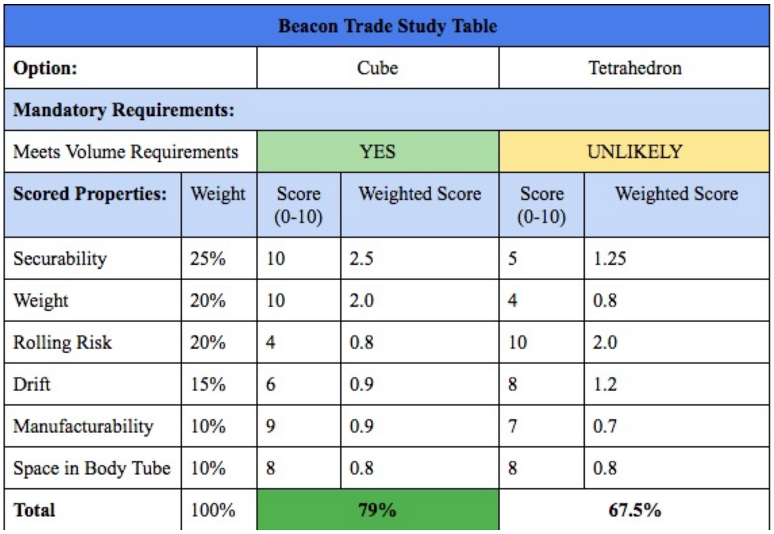


Orientation Correction Trade Study Table							
Option:		Bearing		Motor		Sliding Groove	
Mandatory Requirements:							
Properly Orients UAV		YES		YES		LIKELY	
Scored Properties:	Weight	Score (0-10)	Weighted Score	Score (0-10)	Weighted Score	Score (0-10)	Weighted Score
Integration	25%	7	1.75	8	2.0	7	1.75
Simplicity	20%	3	0.6	7	1.4	6	1.2
Weight	20%	2	0.4	5	1.0	8	1.6
Stress on UAV	15%	2	0.3	10	1.5	5	0.75
Manufacturability	10%	1	0.1	10	1.0	10	1.0
Affordability	5%	5	0.25	5	0.25	8	0.4
Space in Body Tube	5%	6	0.3	6	0.3	8	0.4
Total	100%	**37%**		**74.5%**		**71%**	

Table 37: Orientation method trade study to properly ensure the UAV can take off vertically.

5.2.3 Target Delivery System

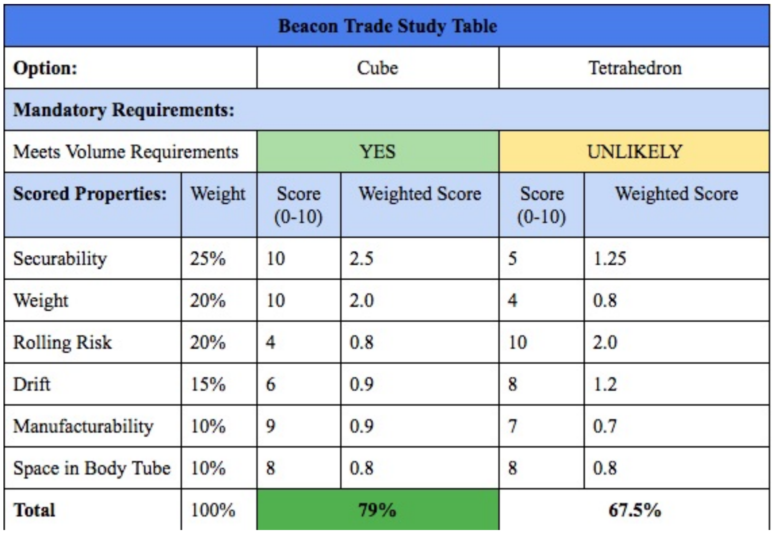
Table 38 shows a trade study of different shapes of beacon to deploy.



Beacon Trade Study Table					
Option:		Cube		Tetrahedron	
Mandatory Requirements:					
Meets Volume Requirements		YES		UNLIKELY	
Scored Properties:	Weight	Score (0-10)	Weighted Score	Score (0-10)	Weighted Score
Securability	25%	10	2.5	5	1.25
Weight	20%	10	2.0	4	0.8
Rolling Risk	20%	4	0.8	10	2.0
Drift	15%	6	0.9	8	1.2
Manufacturability	10%	9	0.9	7	0.7
Space in Body Tube	10%	8	0.8	8	0.8
Total	100%	**79%**		**67.5%**	

Table 38: Beacon body trade study to determine the best shape for beacon.

Table 39 shows another trade study of different shapes of beacon to deploy.



Beacon Trade Study Table					
Option:		Cube		Tetrahedron	
Mandatory Requirements:					
Meets Volume Requirements		YES		UNLIKELY	
Scored Properties:	Weight	Score (0-10)	Weighted Score	Score (0-10)	Weighted Score
Securability	25%	10	2.5	5	1.25
Weight	20%	10	2.0	4	0.8
Rolling Risk	20%	4	0.8	10	2.0
Drift	15%	6	0.9	8	1.2
Manufacturability	10%	9	0.9	7	0.7
Space in Body Tube	10%	8	0.8	8	0.8
Total	100%	**79%**		**67.5%**	

Table 39: Beacon deployment method trade study to compare mechanisms.

5.3 Payload Subsystems

In order to achieve mission success for the 2019 NASA Student Launch Competition, the payload has been organized into subsystems, as seen in Figure 37.

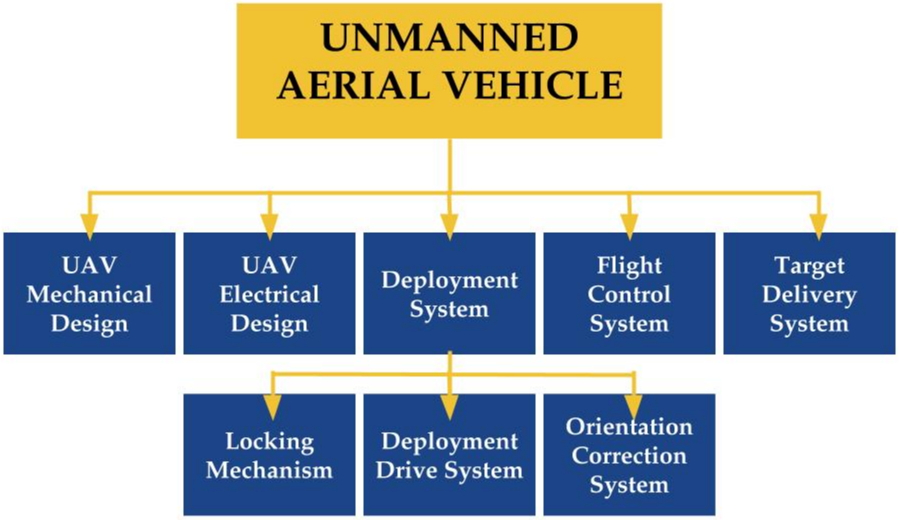


Figure 37: Further breakdown of the payload experiment subsystems.

5.3.1 UAV Mechanical Design

The 7” propellers, seen in Figure 38, are the smallest size propellers that can reasonably provide the lift necessary to support the weight of the drone as estimated at a thrust of about 250g per propeller or a combined thrust of 1000g, while propellers larger than 7” cannot fit as easily into the restricted space of the rocket’s payload bay.

Figure 38: Carbon fiber props for use at competition.

With propellers smaller than 7”, the UAV would not be able to generate sufficient lift because the motors would not be able to rotate fast enough. With propellers larger than 7”, the motors would remain well within their operating speed ranges but the UAV would need to be larger than the payload bay can fit easily. Larger propellers would allow for longer flight times compared to 7” propellers by reducing the power draw to generate a given thrust; however, larger propellers would also complicate the design of the UAV to fit inside the rocket. Thus, 7” propellers are the best choice for the UAV.

The UAV will have foldable arms so that it will have dimensions within the constraints of the inner diameter of the rocket. The UAV arms and folding mechanism of the UAV arms have been designed to maximize robustness and integrity while minimizing weight and volume. To be under the weight restriction, the UAV will be made out of polylactic acid (PLA) for preliminary designing purposes and will then be made out of carbon fiber once a final design has been adequately tested. The carbon fiber will not interfere with the electronics as long as the electronics remain on the exterior of the UAV.

Two designs were proposed for how the UAV would be placed inside the rocket. The first design the team proposed had both of the arms of the UAV lock into an H-position, Figure 39.

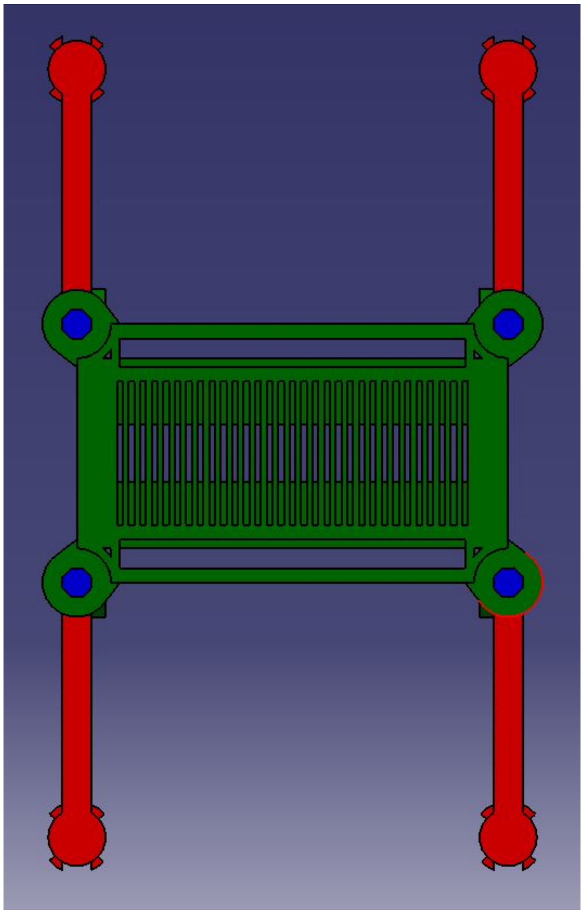


Figure 39: H-Formation of the UAV.

This would mean each arm would have to rotate only forty-five degrees when the arm would unfold. Additionally, having the arms in this folded configuration would reduce the overall width of the UAV in the folded configuration allowing for the design of the body to be widened if necessary. However, having both arms parallel would make the overall length of the UAV very long. The UAV must not be longer than twenty inches to fit inside the UAV payload bay of the rocket, and this design would nearly fill that entire space. The second design the team proposed had both pairs of arms fold towards the back end of the UAV as seen in Figure 40.

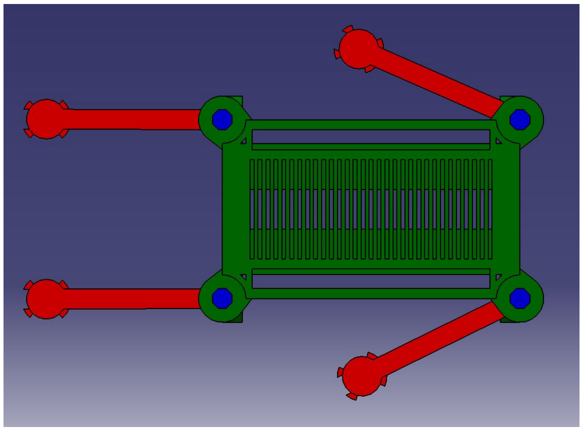


Figure 40: Folded formation of the UAV.

This would efficiently fold the UAV into a position that minimizes the space it takes up within the rocket. While it minimizes the volume occupied by the UAV, it increases the rotation necessary to fold in and out for two of the arms as the front arms will need to rotate almost 180 degrees while the back arms will rotate 45 degrees. This design would additionally minimize any width corrections needed for the body. However, with the selection of key electronic parts, mainly the Pixhawk 4 controller and the Turnigy nano-tech LiPo battery, very minimal adjustments to the width of the body would be necessary. For this reason and the reduction in volume, the team has decided to fold the arms of the UAV towards the front end of the UAV.

Two designs were proposed for the orientation of the UAV arms in their unfolded position. The first design proposed that the arms be oriented in an H formation as seen in Figure 39. This formation would make the rotation of each arm relatively equal during deployment. Primarily, this formation would be used if the battery was under the UAV thus allowing the props to rotate over the body, thus a shorter length arm could be used. However, this design would put the propeller motors in a rectangular position which would require modifications to the control software for the UAV. The second design proposed that the arms be oriented in a more common X formation seen if Figure 41.

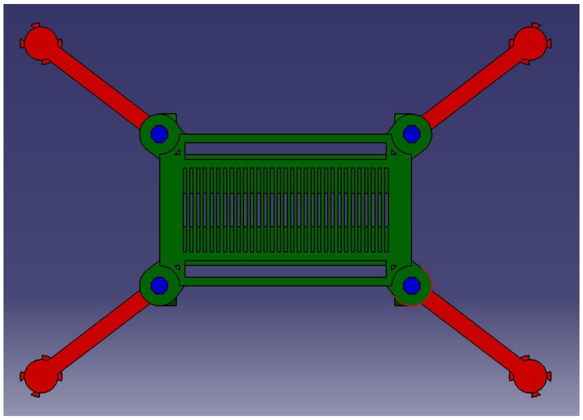


Figure 41: X formation of the UAV.

This formation would place the propeller motors in a square position which is supported by the UAV control software. Additionally, this would be the preferred orientation with the battery in the middle of the body as the arms would be coplanar with the battery. This design would require two arms to rotate more than the other two during deployment increasing the complexity of motion. Since the UAV control software is configured for square positioned motors and since the battery will be in the middle of the UAV, the team has decided to orient the arms of the UAV in an X.

Two designs were proposed for the deployment mechanism for unfolding the UAV Arms. The first proposed design uses four servo motors to unfold the arms and lock them in place. The rod of the servo motor would act as the pin for the arm and rotation of the servo motor would rotate the arm in the same amount. This would provide precise rotations of the arms and would rotate the arms smoothly with no large impulses. However, the addition of four servo motors would increase the the weight of the UAV and would require electricity to operate reducing the flight time of the UAV. The second design proposed uses torsion springs to create a mechanical deployment system. A helical torsion spring would be placed around the pin holding the UAV arm in place. One end of the helical spring would be locked into the UAV arm by placing it into an insert on the arm and the other end of the spring would similarly be locked into the UAV body. The arms would be rotated to their folding location, simultaneously rotating the torsion springs, and the rear arms would be locked into place by resting against a pair of rods protruding from the rear bulkhead. The front arms would be connected to the rear arms by twin belt-and-pulley systems, constraining the motion of the front arms to be proportional to the rear arms' motion. The sizes of the front sprockets to the rear sprockets would be decided by the ratio of the angle of rotation of the rear arms to the angle of rotation of the front arms. The UAV's landing struts would be inserted into holes in the deployment platform and held in place by cotter pins, securing the UAV in place and preventing the arms from rotating and moving the UAV on the platform.

As the platform travels along the lead screw away from the rear bulkhead, the rear arms would rotate to stay in contact with the bulkhead rods and the front arms would rotate in sync with the rear arms, constrained by the sprockets and chain. 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 the rear bulkhead and the arms reach their fully-deployed positions, where they would be held in place by a combination of mechanical stops integrated into the UAV body and a small amount of constant torque exerted by the torsion springs. The rear arms would lose contact with the bulkhead rods and the UAV, now clear of the rocket's body, would be ready for takeoff, and be locked into place by a bar in the housing that would block rotation of the arms. As the UAV is deployed from the rocket, the arms would be able to rotate as the bar is no longer restricting the motion of the arms. Upon deployment, the arms would be unlocked by the hairpin being removed from and would be free to rotate to their unfolded orientation due to the torque generated by the torsion springs. The arms would rotate until the stoppers integrated into the UAV body would stop rotation at forty-five degrees. To maintain this location, the spring would be slightly rotated when the arm was connected to the body to ensure a constant torque holding the arm in the desired orientation. This design would be more reliable and more robust since it is a mechanical system that requires only a signal to trigger the arms to unlock. Additionally, this system does not add weight to the UAV and does not reduce flight time. However, the arms would experience a greater impulse upon deployment, but this impulse would not be great enough to break the arms. Due to the simplicity and robustness of the mechanical deployment mechanism, the team has decided to use this method to unfold the UAV arms.

The following is the process for the arm unlocking process:

1. Rods fixed to the rear bulkhead hold the rear arms in place.
2. Pulleys and a belt connect the forward arms to the rear arms.
3. UAV platform travels along lead screw away from the rear bulkhead, and torsion springs push rear arms to stay in contact with rods. The belt and pulley system rotates the arms forward to match the rotation of the rear arms scaled by ratio of forward and rear pulley diameters.
4. UAV platform reaches end of lead screw, the rear arms reach end of rotation, they stop rotating, and they lose contact with rods. The forward arms reach the end of rotation, stop rotating, and lock into place.

Item 2 may be quantified with the following equation, Equation 5:

$$\frac{DiameterForwardPulley}{DiameterRearPulley} = \frac{AngleRearArmRotation}{AngleForwardArmRotation} \tag{5}$$

The team will be using a 2:1 ratio for the belt and pulley system.

Frame design, as seen in Figure 42, namely, the decision between placing the battery on the bottom versus placing the battery in the middle of the UAV was deliberated. The pros and cons of placing the battery on the bottom are the following:

1. Pro
   (a) A thinner body leads to a lower volume and less material, which makes the body lighter.
2. Cons
   (a) Full redesign of the Beacon Deployment System would be necessary.
   (b) The center of mass and center of gravity would be lower.
   (c) The battery would be more exposed when landing. There would be no PLA base to protect.

The pros and cons of placing the battery in the middle are the following:

1. Pro
   (a) A more central center of mass and center of gravity
   (b) The Beacon Deployment System would remain on the bottom of the UAV.
   (c) The battery would be better protected.
   (d) Design allows for more anchor points for electronics.
2. Cons
   (a) Thicker body would result in a heavier body.

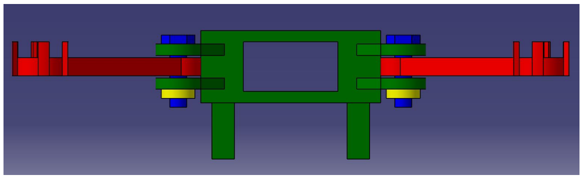


Figure 42: Frame design that allows for beacon delivery clearance with battery shelving.

5.3.2 UAV Electrical Design

When designing the unmanned aerial vehicle (UAV), perhaps the greatest limiting factors are the physical length of the UAV payload bay and vehicle design weight constraint of 80 oz. In order to fulfill both NASA requirement 4.4.5. and 4.4.8. regarding the successful delivery of the simulated navigational beacon to the Future Excursion Area (FEA), flight time is the most important design specification.

This represents a competing interest between the design of the drone and the rocket body. The rocket body sets a well-defined size and weight constraint that limits the ability to use a large, heavy battery which consequently limits the possible flight time. To converge on a design solution, the major focus for the UAV design iterations was a power consumption study at each stage of design. The UAV body was assumed to be large enough to fit each component. Therefore, as each component is considered weight and power consumption are valued the most.

The current size and weight allocation for the UAV housing is a payload with a weight of 80 oz. and a loaded length of 20 in. However, this weight constraint is for the drone and its deployment mechanism combined, so the drone was designed to weigh between 30-40 oz.

The final constraint that guided the design process was the cost of each component. The performance of each component was deemed more important than cost when finding candidates, but when selecting between components that both met the desired specifications, cost became a deciding factor.

For the selection of power components an iterative design process was used. The iteration started with the motor, followed by the props, the electronic speed controllers (ESCs), and the lithium polymer (LiPo) battery, as shown in Figure 43.

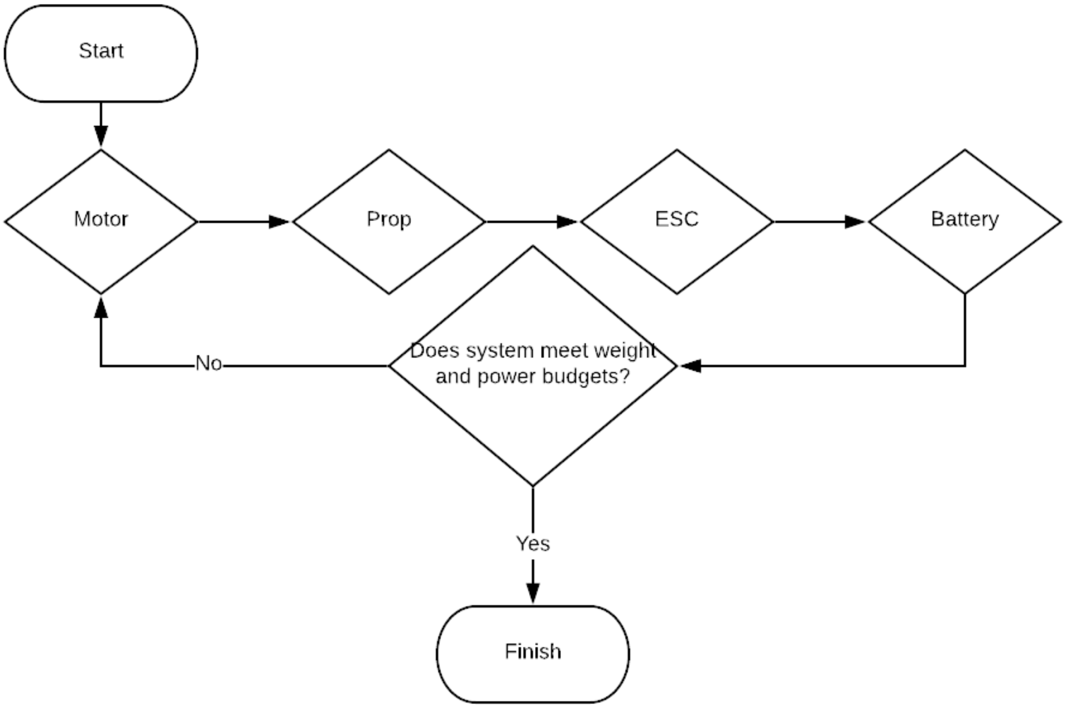


Figure 43: Iterative design process.

The process can further be broken down as the following.

1. Find a system of 4 motors with 30-40oz of thrust at 70% thrust (from T Motor site)

   In order to fly, the motors need to be capable of generating thrust equal to the drone's weight. However, the drone will not be able to get off the ground if the maximum thrust available is equal to weight, so the motors need a little bit of clearance to increase altitude. Therefore, a system of motors capable of generating 30-40 ounces of thrust at 70% throttle was specified.

   (a) Find props based on motor specs

   Once a motor of sufficient thrust with some given values of current and voltage was selected, the next step was to select props. Motor specifications provide information on performance (thrust and current draw) with respect to different propellers. That information was used to determine the length and pitch of the props. The overall length of the payload bay of 20" was used as the final constraint to guide prop selection.

   (b) Find an ESC

With a motor and prop dimensions in hand, the power requirement and current draw of the motors was determined. This dictated the rating required for the ESC.

2. Find a battery based on voltage requirement

   Finally, once the power components were chosen, the battery could be selected. Considerations for the battery were voltage necessary to drive motors, capacity for maximizing flight time, C rating for maximum current draw, and overall physical weight and size. When determining the max current draw, an estimate of on-board controller needs was added to the motor current.

   Once a system was chosen, its performance was considered against the constraints imposed by the requirements of other systems. If some aspect of the system exceeded limits or failed to meet the specifications, the process was repeated to correct that factor. For example, a larger battery was chosen to generate longer flight time, and shorter props were chosen to better fit inside the rocket.

The three motors considered were all products from T-Motor, a trusted and reputable Radio Controlled (RC) motor company. These were the MN1806, MN2212, and Antigravity 4004. First-Person View (FPV) motors were also looked at because they offer a very high thrust to weight ratio, however the current draw is too high for the system and would require a battery that would have been outside the weight allowance. The Antigravity motor was considered because it provides the most thrust per Watt, however it was not chosen because the total thrust provided was more than what was needed, even on the lowest end. Comparing the MN1806 to the MN2212, the MN1806 fit the 30-40 oz thrust range, and it also outperformed the MN2212 in thrust per watt while weighing 45g less per motor. For this reason, the team moved forward with the MN1806 KV1400 motor from T-Motor.

The options for props were narrowed down greatly by the specifications for the selected motor. The motor chosen provides data for props between 5 and 9 inches. The prop ultimately selected was the Multirotor Carbon Fiber T-style Propeller 7x2.4. This was chosen because of its length, thrust capability, and required battery size. It is a two-blade prop that is short enough to fit into the payload bay when implemented into the body design. Also considered were longer props and four-blade props. Their advantage was greater thrust at a given voltage. However, they were too large to fit in the payload bay and had to be discounted. When comparing the 7 inch option to the other size options, the 7 inch prop was the only prop size that provided enough thrust.

The ESC ultimately selected was the Lumenier 18A 32bit Silk ESC optoisolator (OPTO)

(2-4s). This was selected primarily based on its amperage rating, corresponding to the required amperage rating of the selected motor.

The battery ultimately selected was the Turnigy nano-tech 4500mAh 3S. This provided enough power for the selected ESC's and motors for the desired flight time (around 9-14 minutes). This was an upgrade in terms of capacity from a 3000mAh battery once it became clear that longer flight time was needed.

The system architecture of the payload consists of the Central Processing Unit (CPU), the flight controller, the ground station, the hand-held transmitter, and a camera.

Since several team members have utilized Raspberry Pi's in previous projects, the team chose this platform for the UAV's onboard CPU. The following are two models the team primarily researched:

1. Raspberry Pi 0

   Pi 0 streams information to the ground station where the target detection algorithm is processed; subsequently these coordinates are transmitted back to the Pi 0 and sent to the flight controller.

2. Raspberry Pi 3 Model B (Raspberry Pi 3B)

   Onboard Pi 3B, Figure 44, performs all target detection processing and sends coordinates to the flight controller. This solution protects from communication loss with the ground station. The team selected this CPU for the UAV due to the reduced complexity in wireless communication.

Figure 44: Central Processing Unit of the UAV.

The team selected the Pixhawk line of flight controllers based on brand reputation and the prior experience of team members. Within this line, the following models were considered:

1. Pixhawk Mini

   The team considered utilizing the Pixhawk Mini as a small and lightweight solution, but this model was discontinued by the manufacturer.

2. Pixhawk Falcon

   The Pixhawk Falcon was rebranding of Pixhawk mini, providing a lightweight flight controller with a small form factor and low power consumption. One of the main drawbacks of this option is its lack of connection ports.

3. Pixhawk 4

   The Pixhawk 4, Figure 45, is faster, has onboard heating for cold weather testing, and has more connection ports, including a servo rail that is useful for power splitting. Despite having several more features, this option is not significantly larger or heavier than the Pixhawk Falcon. Thus, the team selected this model to use for the UAV.

Figure 45: Pixhawk 4 flight controller.

For the ground station, the team will be utilizing two separate laptops for increased viewing screen real estate. One will be receiving video stream from telemetry with the Raspberry Pi 3B, and the other will be utilized to observe real time UAV coordinates.

The main metrics for the transmitter were compatibility with the Pixhawk and the cost. The Spektrum Dx6e was initially chosen because it is more economical compared to other Spektrum transmitters. Also considered was the Taranis Qx7, because of its price point. However the transmitter does not transmit using the Digital Spectrum Modulation (DSM/DSMX) communication protocol and would require additional adapters and converters that add cost and weight to the UAV. In the end, the FrSky Taranis X9D Plus 2.4 GHz Advanced Continuous Channel Shifting Technology (ACCST) Radio was chosen because the team's faculty specialist in drones donated the handheld transmitter for the team's use. The Taranis has full telemetry capability, three separate programmable fail-safe modes, and a JR style Radio Frequency (RF) module slot.

As the Raspberry Pi 3B was selected as the CPU for the UAV, the team decided to primarily research the cameras designed specifically for this device. Options included:

1. Pi Camera Module V2

   This model, Figure 46 is standard camera module that integrated with Raspberry Pi CPUs. It provides 8 megapixels of resolution and can take high resolution videos as well as still photographs. The team would use this device to stream constant video to the Raspberry Pi 3B, which can then be used either for target detection or manual flight. Thus, the team selected this model.

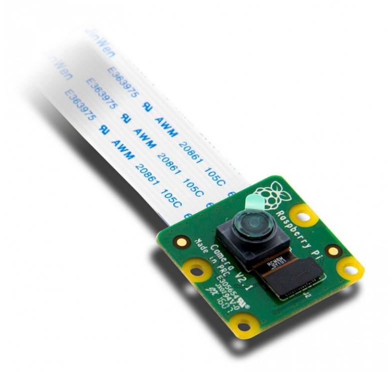


Figure 46: Pi Camera Module V2 that interfaces with the Raspberry Pi 3B.

2. Pi Noir Camera V2 This camera is identical to the Pi Camera Module V2, except it lacks an infrared filter, which provides the ability to see in the dark. However, the lack of this filter makes vision in daylight somewhat more difficult. Since the UAV would ideally be operating in the brighter conditions of Alabama, this feature would be detrimental to overall targeting functionality.

The UAV system will be 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 switch to manual flight control is possible. The UAV will fly a pre-programmed flight plan upon deployment from the drone. During flight, the on-board CPU, a Raspberry Pi 3 Model B, will process data from the on-board camera using a search algorithm to detect the target. Once the target has been detected, the on-board 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.

An overview of the Communication System architecture is visible in Figure 47.

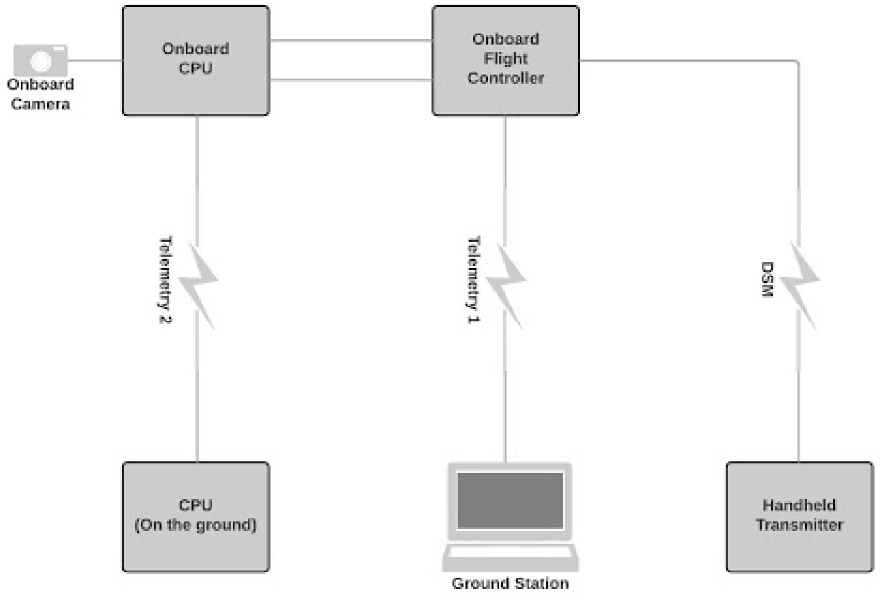


Figure 47: Communication system architecture.

To meet the UAV standby mode criterion during rocket flight, the team first drafted desired criteria for the feature. First, the power on sequence should be resistant to false positives. In this case, the drone should not be powered on until the deployment sequence is initiated. Second, the drone should not be susceptible to false negatives; when deployed, full power should always be activated. Third, the standby mode should not consume power from the UAV battery, as this will reduce overall flight time once deployed. Lastly, the team desired the power on sequence to be activated independently, eliminating the need of an external stimulus. With these criteria in mind, the team considered the following solutions:

1. Button-On-Arm

   The Button-on-Arm system includes two mechanical buttons and two contacts, one per arm. The first button will be inserted between the power distribution board (PDB) 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.

2. Button-On-Nose

   One option is to have a normally-closed button connected to the front of the UAV (which is facing the bottom of the rocket). This button will be pressed down by a contact during launch and landing. When the UAV deployment mechanism moves the UAV, the button will release, which will enable power on the UAV. This option allows for minimal parts and complexity on the UAV and deployment mechanism. Additional benefits are that no power will be consumed prior to the power on sequence and no external signal is required to enable full power. The major drawback of this design is that sequence initiation is dependent on stable positioning of the drone in the rocket, which will have to withstand extreme forces.

3. Switch-On-Body

   A switch on the side of the UAV's body along with an arm attached to the side of the rocket body was considered. The two will be aligned such that the switch will turn as it hits the arm while the UAV passes by. At its initial state, the switch will keep be open to prevent power flow. As the UAV exits the rocket, the switch will hit the arm and be closed, enabling power flow. This option allows the UAV to power on without any external signals or wires. However, it requires precise positioning of the UAV in order for the switch to hit the arm, which could be disrupted during the rocket's launch and landing.

4. Button Cell Battery With Rip-Out Wires

   This option includes a normally-closed relay, a small button cell battery, and wires. The relay will be placed between the LiPo battery and the flight controller. The button cell battery will connect to the relay via wires and mounted to the interior housing of the rocket. Wires connecting the battery cell to the relay will be female bullet connectors; male bullet connectors will be on the relay itself. While the button cell is connected, the relay will be open and the UAV will not be powered on. Upon deployment sequence, the UAV will move away from the button cell and eventually the tension force on the wires will cause the bullet connectors to unplug. At this point, the relay will close and the UAV will power on. The main benefits of this power-on method are that the button cell is lightweight and eliminates the need for an external signal to power on the UAV. Potential flaws to this method are that the wires could potentially be unplugged mid-flight, and the button cell may run out of power and cause the UAV to be powered on.

5. Separate Transmitted, Ground Station Signal With Low-Power Standby Mode

   After the Question-and-Answer session with NASA, a standby mode is sufficient for the UAV payload to qualify as being powered off. The team considered setting the UAV into a low-power mode during flight, and, upon deployment, a signal would be sent from the ground station to activate full functionality on the UAV. Only the Raspberry Pi 3 would be powered on while in standby mode. The activation signal would be sent to the Raspberry Pi 3, which would then close relays to enable high power flow for the other systems. The main benefits of this system are that no additional components would be required for implementation, and the manually delivered signal would grant control of power on timing. One disadvantage of this activation method is decreased flight time for the UAV due to the Raspberry Pi consuming battery power during the rocket's flight. A second drawback is the potential of poor telemetry between the payload and the ground station, which would prevent UAV activation.

6. Chosen Design

   After considering the options as detailed in the trade studies in Table 35, the team decided to implement the Button-on-Arm power-on system. This option accounted for many of the disadvantages found in other options. For example, as long as the button is pressed, no power can be supplied to the UAV, so the UAV cannot power-on prematurally. Additionally, once the arms are unfolded, there is minimal chance that the system does not turn on because nothing else can compress the button. Last, this design does not depend on a component of the rocket body to interface with the UAV and turn it on. This decreases possibility of error by consolidating the system onto the UAV alone. The system is wholly dependent on its ability to unfold correctly and presents a near-binary scenario: if the arms are unfolded, the system is on. If the arms are folded, the system is off. The main downside to this design is its resiliency to vibration. There is a chance that in-flight vibration will jostle the contact and allow the system to power on. However, by placing the buttons closer to the elbow of the arms, the separation between the arm and body as a function of arm angle can be minimized. Thus, the Button-on-Arm power-on system has shown to be the optimal solution.

5.3.3 Deployment System

Proper deployment ensures the safe locking of the payload while housed inside the launch vehicle, the correct orientation of the payload upon recovery, and the unobstructed exit of the payload from the launch vehicle under the supervision of the Remote Deployment Officer.

5.3.3.1 Deployment Drive System

Successful deployment of the unmanned aerial vehicle is one of the most pivotal steps in the completion of Payload Experiment Requirement 4.4.1.: "Teams will design a custom UAV that will deploy from the internal structure of the launch vehicle." A rack and pinion and a leadscrew were the two main deployment systems considered. The rack and pinion would consist of a circular gear and linear rack with gear teeth. The rotation of the gear would cause the linear motion of the rack. The leadscrew consists of a threaded rod and motor that is propelled by the rotation of the rod. A trade study, as shown in Table 36, was used to determine which deployment system was preferable. The most important property for the system was the ability for it to be integrated into the payload bay of the rocket. It would be necessary for the system to be easily incorporated into the general rocket design in order to maximize its probability of success. The leadscrew was given the better score for integration due to it being more compatible with the need to orient the payload. The leadscrew was also graded to be simpler than the rack and pinion because it allowed for axial orientation and deployment. The rack and pinion and lead screw both received a low to mid score for the weight due to the material variety for both the leadscrew and rack and pinion. While metal was considered for both, nylon was chosen due to its sufficient strength and lightweight. Both systems provide the force required to deploy the UAV and are easy to manufacture. Affordability and space in the body tube were weighted the least because adequate funding has already been acquired and there is a decent amount of space allotted for the payload. The leadscrew was scored to be more economical and provide the most efficient use of the body tube. All of these factors lead to the conclusion that the leadscrew was the preferable system.

A stepper motor, a Nema 14 Step Motor, with a leadscrew will be attached to the bulkhead closest to the transition section of the rocket. This is the bulkhead that is free to rotate, but not translate. Therefore, the leadscrew will rotate with the entire housing and UAV assembly during orientation correction. The leadscrew will then run through a threaded nut on the second bulkhead, which is attached to the platform, and into the nose cone of the rocket. The UAV platform will be connected directly to to the leadscrew nut. When the step motor is turned on, the nut on both the UAV platform and the bulkhead will move the system linearly toward the fore of the rocket. The movement of the front bulkhead will provide continued support for the lead screw and metal rods. Two types of motors were initially considered: gear motor and step motor. The two main factors regarding the motor selection are torque and control system. Gear motors produce a higher torque compared to step motors with similar volume, but the step motor is preferred in this deployment stage because it produces a high torque that is acceptable and a simpler control system. The torque needed for the lead screw was found via the following equation, Equation 6.

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

In this equation, T is the torque needed, F is the external force, W is the mass of the load, μ is the friction coefficient on the sliding surface, g is acceleration due to gravity, and P is the ball screw lead.

Metal round rods will be securely fastened to the first bulkhead by epoxy and metal, machined supports and will run through the sides of the platform to provide a counter-moment on the platform. This will ensure that the nut translates linearly on the leadscrew and does not rotate. The top bulkhead will not only be attached to the platform, but it will also be attached to the nose cone. Thus, the leadscrew will simultaneously drive the UAV out of the rocket and push off the nose cone. The step motor will rotate until the UAV has cleared the end of the body tube, which will allow for its unobstructed takeoff. The deployment system can be seen in Figure 48.

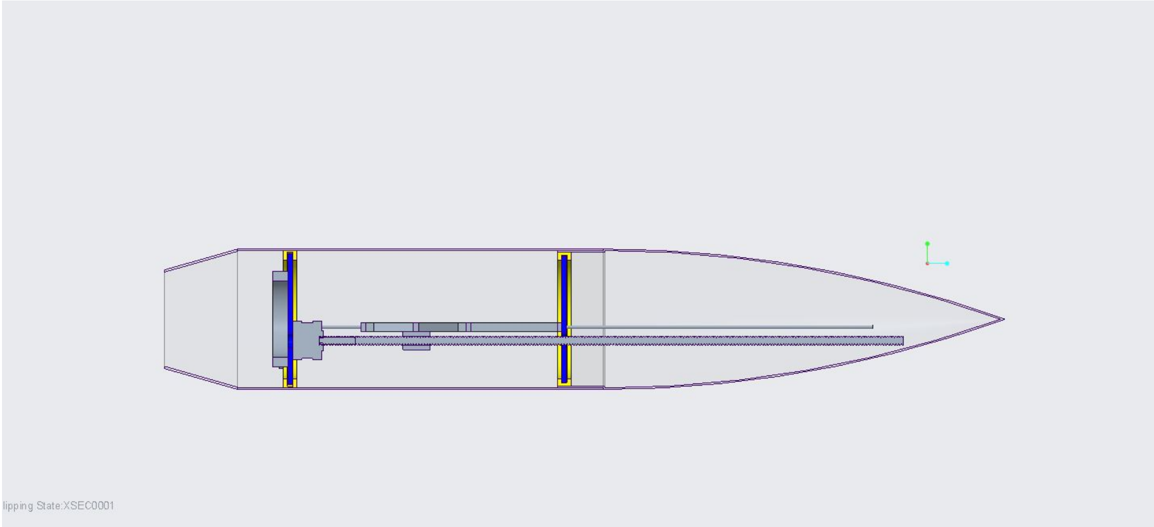


Figure 48: A cross section of the the deployment system.

5.3.3.2 Orientation Correction System

The orientation correction system is quite possibly one of the most critical elements to proper UAV deployment. As the rocket falls to the ground, and the recovery system is deployed, there is no way to determine the orientation in which it will land. Furthermore, the UAV is designed to take off vertically, and cannot successfully take off unless this orientation condition is met. For these reasons, a system must be in place to ensure that the UAV is prepared for a vertical takeoff, regardless of the alignment in which it lands.

Three different methods were initially considered for orientation correction: a bearing system, a motor and accelerometer system, and a sliding track system. Through trade studies and further analysis, it has been determined that the best overall system for orientation correction is a stepper motor and accelerometer system. The accelerometer will be turned on before flight, and will collect data on the orientation of the UAV platform. After landing, the stepper motor will use accelerometer data to turn the UAV platform to orient it vertically. The stepper motor will interface with a bulkhead via a gear-like connection, which will be constrained by two concentric tracks. The tracks will serve to prevent the bulkhead from translating, but will allow it to rotate. This bulkhead will be directly attached to the UAV platform. This configuration can be seen in Figure 49. The bulkhead and track will both be manufactured out of 3/8" MDS-filled cast nylon to minimize friction during rotation but maintain strength and durability. The stepper motor, when locked, will prevent the UAV and its housing from moving. This is essential for in-flight motion. Conversely, the motor will spin the UAV and its housing once the rocket has landed. The motor will be fixed to the inside of the body tube using RocketPoxy glue.

In order to correct the orientation, a motor is required to rotate the UAV platform. Two different types of motors were initially considered: stepper motor and servo motor. Stepper motors have higher holding torque than servo motors at speed lower than 1000 RPMs (citation needed). Because the orientation correction stage does not require high rotation speed, stepper motors are preferred. Additionally, stepper motors are less in weight and in complexity, and are more affordable than servo motors. Although stepper motors use an open-loop control system, the feedback and accuracy of the step motors could be regained via the accelerometer. The accelerometer the team has chosen, the L3GD20H Triple-Axis Gyro Breakout Board, will sense the various turns the payload bay will experience throughout recovery, has built-in high and low pass sensing, and has the ability to interface well with multiple microcontrollers.

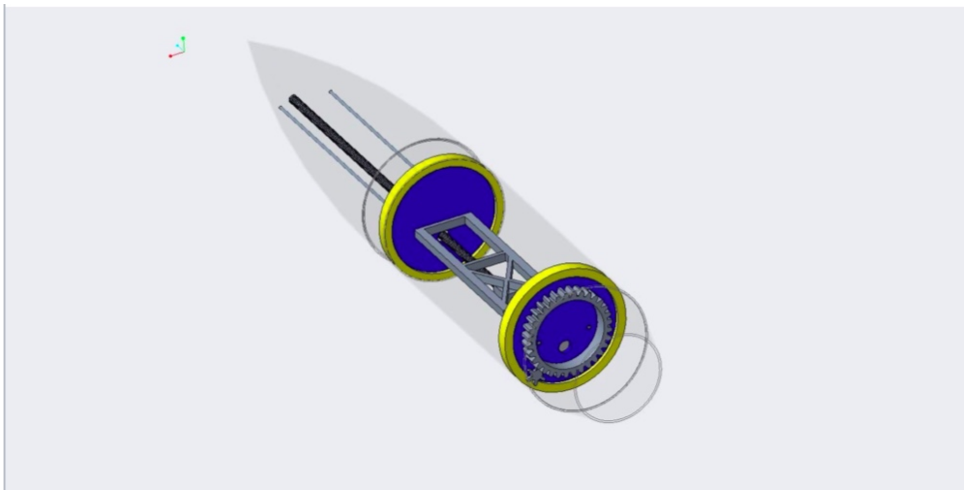


Figure 49: The deployment system with orientation correction viewed from behind.

5.3.3.3 Locking Mechanism

The locking mechanism will serve to fix any motion of the UAV during flight. UAV motion during flight can affect the stability and flight performance of the rocket. By properly locking the UAV, motion during flight will be restricted. The locking mechanism of the UAV must remain engaged during flight, however, the UAV must also be free to take off from the platform once rocket flight and deployment have ended. It is also advantageous for the locking mechanism to be as simple as possible, in order to reduce weight and increase robustness.

The decided locking mechanism design is a mechanical system using flanges and hairpin cotter pins. The UAV struts will be seated in flanges, which are to be fastened to the platform. The flanges will permanently restrict motion of the UAV in the horizontal plane. Through holes will be drilled in the flanges and UAV struts, where hairpin cotter pins can be inserted. During flight, the pins will restrict UAV motion in the vertical direction. Thus, the UAV will be fully constrained by the flange-pin system. In order to remove the cotter pins, strings will be attached between the fixed bulkhead near the transition section and the pins themselves. When the lead screw motion drives the platform out of the rocket, the strings will tighten, thus pulling the pins out of the flange and UAV legs. The UAV will then be free to move in the vertical direction for takeoff. The assembly is shown below in Figure 50.

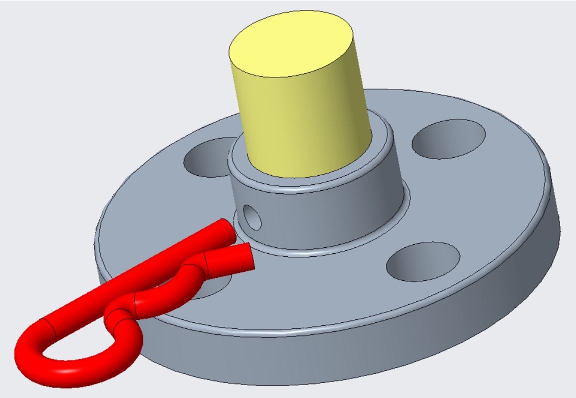


Figure 50: An orthogonal view of the flange, hairpin cotter pin, and UAV strut configuration.

5.3.4 Flight Control System

For a quadcopter UAV, there is a large variety of propeller types that can be chosen. The two main considerations for propeller selection are the diameter and the pitch of the propeller. Figure 51 shows these two important features of the propeller.

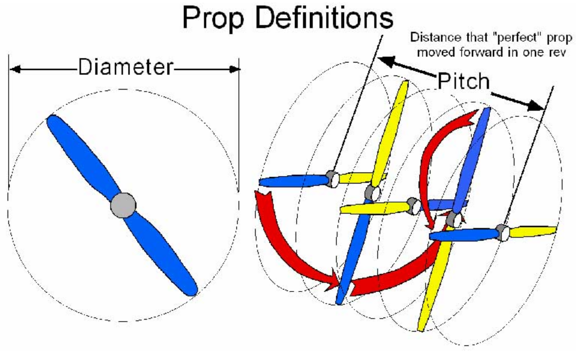


Figure 51: The diameter and pitch of a propeller.

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 solid medium in one revolution. The aircraft's motor and battery specifications influence the diameter and pitch of the propellers. For the UAV, four identical propellers will be used. The propellers used will be seven inches in diameter with a pitch of 2.4 inches, and are made out of carbon fiber. They will each be attached to a brushless electric motor. Under this configuration, each motor can provide 252 grams of thrust. Using a 3s battery with 4,500mAh 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 largely based on the recommendation of the battery manufacturer. They were also chosen to ensure that the UAV would fit into the body of the rocket during the rocket's flight.

The UAV will be flown using the “X configuration,” seen in Figure 52, in order to maximize control.

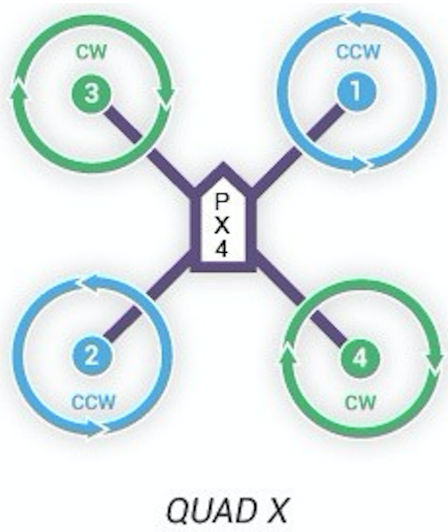


Figure 52: The “X configuration” allows for increased rotational acceleration.

The other main quadcopter configuration is the “+ configuration,” seen in Figure 53, which leaves the drone with less stability in the roll axis when moving forward, pitching.

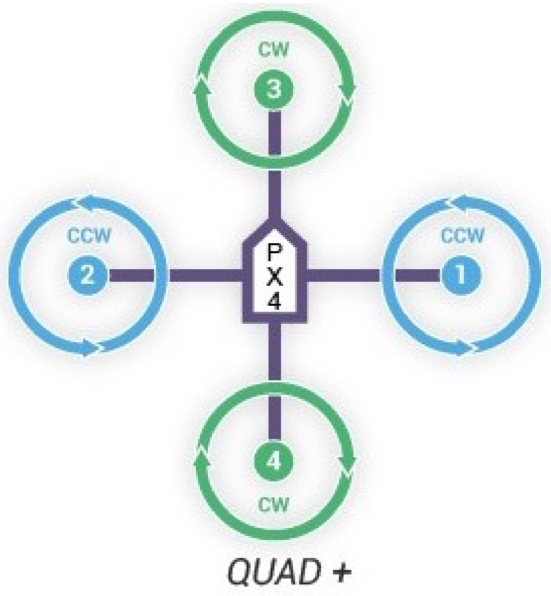


Figure 53: The “+ configuration” of a UAV.

The X configuration also has two propellers contributing to the pitch and roll movements with perpendicular moment arms of about 0.71 times the length of the arm. This results in about 42% more rotational acceleration in the “X configuration” than the “+ configuration” because there are two propellers each with a moment arm of 0.71 times the length of the arm compared to one propeller with a moment arm of the length of the arm.

For steady flight, the four propellers would be spinning around 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. 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.

The drone will be controlled by software that uses DroneKit-Python to autonomously control the movement of the drone when flying to the Future Excursion Area to drop off the beacon. While manual flight can be more flexible, it is completely reliant on the drone operator having a line of sight to the drone. This can lead to difficulties if the drone flies behind an obstacle such as a tree. Manual flight also severely limits the range of the drone since at a distance it is difficult for the human operator to keep track of the orientation and location of the drone. These shortcomings can be partially mitigated with the use of live-streamed video from the drone to the human controller. The software will use the GPS coordinates of the closest Future Excursion Area to initially set waypoints, sets of coordinates that identify a specific point in physical space, for the drone. Then, other means of target detection, such as a video stream analysis with Open Source Computer Vision Library (OpenCV), will fine tune the exact location of the target to reduce error and successfully deliver the simulated navigational beacon.

The drone can be controlled with this program in one of two ways:

1. Setting a target position to make the drone travel to a specific location.
2. Setting velocity components to move the drone a certain direction.

It is beneficial to set a target position when the end position is known, but it is better to set velocity components when many movement changes are expected. According to Rule 9 of the High Power Rocket Safety Code of the National Association of Rocketry, the rocket will not be launched if wind speeds exceed 20 miles per hour. However, wind speeds above 10 miles per hour will cause difficulty for the drone if just given a waypoint. Setting velocity components will give the drone operator more flexibility to handle sub-optimal conditions. In order for the program to calculate the position of the drone relative to the position of the desired location, frame conversion functions will be used. Since the locations of the Future Excursion Areas will be determined before the launch of the rocket, the drone will be controlled by setting a target position.

The program will find the closest Future Excursion Area and then and set a waypoint towards that target. In testing of other drones, it has been found that the drone will end up within 3 meters of the given target. The drone will then search the area around the waypoint for the Future Excursion Area using the onboard camera and image recognition. Once found, the drone will reduce its altitude and release the beacon. The human operator can take control of the program at any point by hitting a switch on the controller. This helps ensure safety and reliability.

For manual flight, a pilot will fly the drone with a handheld transmitter. A generic scheme of a handheld used for drone flight is shown below in Figure 54. It will have 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.

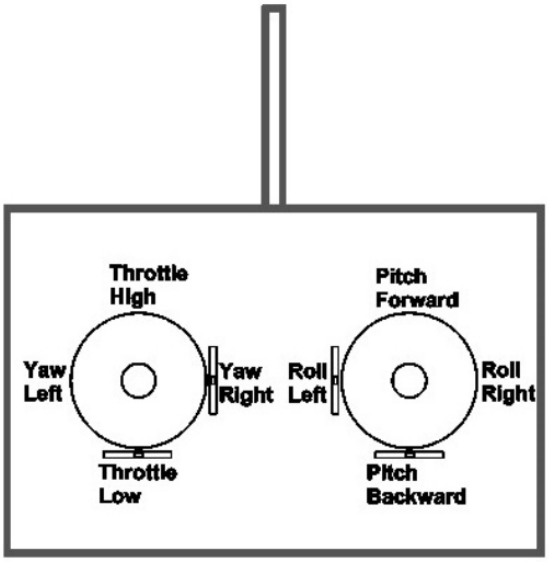


Figure 54: A simplified model of a manual flight controller.

Pictured on this model are the two joysticks used to control the flight of the drone. The position of the text around the joystick corresponds to the movement of the drone when the joystick is moved in that direction. Not pictured in Figure 54 are the various toggles that control other operations of the drone. Along with the joysticks on the handheld, there are a few other toggles that control other operations of the drone, as seen in Figure 55.

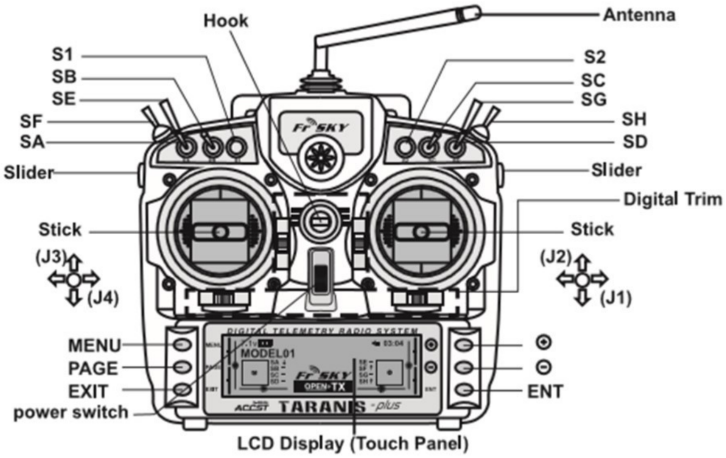


Figure 55: FrSky uses frequency-hopping ACCST technology across the entire 2.4GHz band for excellent range.

For the FrSky Taranis X9D Plus 2.4GHz ACCST Radio used in this mission, 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.

5.3.5 Target Delivery System

The payload experiment shall fulfill Deployable Unmanned Aerial Vehicle/Beacon Delivery Requirement 4.4.5. and 4.4.8. in regard to the successful delivery of the simulated navigational beacon. The team goal is to remain as autonomous as possible when it comes to delivering the beacon. A data-driven approach and a hand-crafted feature have been considered. The beacon delivery system uses a double redundancy in order to help ensure a successful deliver.

5.3.5.1 Target Detection

One of the biggest problems the UAV will face is navigating to the target and piloting into an acceptable position to drop the beacon. While the GPS coordinates of each beacon are given, the GPS on the UAV will only be accurate to within around 7 meters. Because of this and the fact that the target is only 10 feet by 10 feet, GPS coordinates alone will not be enough to reliably allow the UAV to deploy the beacon on the target.

In order to more accurately determine the position of the target once within range, a computer vision system will be used. The goal of this system is to accurately identify the position of a target given an input video feed. Video will be captured from a Raspberry Pi camera and analyzed by the Pi onboard the UAV, with approximately one frame per second transmitted back to the ground station for monitoring. Two computer vision approaches were considered: data-driven features, which would use a convolutional neural network to analyze the data and return a likely target outline; and hand-crafted features, which would involve examining things like color, texture, or geometry to predict the boundary.

In order to determine which method to use for detecting the Future Excursion Area (FEA), the team will perform a series of tests. The team will construct its own 10x10 FEA based on the color of the sample provided. Then, using the Raspberry Pi camera that will later be placed onboard the UAV, the team will record several flights above the FEA placed in different weather conditions, lighting conditions, and against different backgrounds. The team will then analyze this footage in order to determine the color space that allowed the system to most consistently and accurately detect the FEA.

One option considered is the use of data-driven features to locate the target. Specifically, this would mean constructing a convolutional neural network and training it on video taken of the sample FEA. This process is seen in Figure 56.

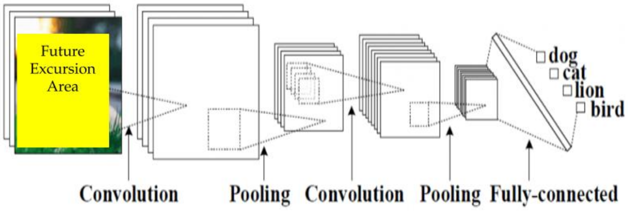


Figure 56: A convolutional neural network.

Doing this would allow the computer to determine what features in the input images are important for locating the target. It could figure out what matters and what is irrelevant with much more ease than a human, especially given its non-linearity. As long as the training data is representative of most or all possible target configurations and lighting conditions, the model should be very flexible and able to identify the target with high accuracy in any situation accounted for by the training data.

There are some drawbacks of a data-driven approach. Some crucial element of identifying the target at the launch site could be completely different in South Bend, such as the difference between the color of the earth and the color of the target. It would be impossible to fully take such differences into account unless training footage was taken at the launch site and the system was tested there, which is unfeasible. Training the model would also take a substantial amount of time, up to a week depending on the specific architecture chosen. This would limit the ease of diagnosing and correcting any errors. In general, convolutional neural networks are very computationally expensive, and the Raspberry Pi may limit the framerate of the analysis to 1-2 frames per second (FPS). This could hinder the drone's ability to adjust its position in real time and center itself on the target.

Another option is to create a hand-crafted feature that will be able to analyze a video stream of the ground below the UAV during its flight to find an object that is within some specified color space range. The team would write a Python script using the OpenCV library that would then run on the Raspberry Pi onboard the UAV and analyze the footage from the Pi camera. The Pi will also repeatedly stream a frame to ground control at specified intervals. This will allow the team to track whether or not the target detection system is behaving properly, and assist in helping the team to manually direct and correct the flight path in the case that the target is not correctly identified.

In order to determine the color space to use for detection of the FEA, as well any additional features to use the footage along with color identification, the team will use the footage collected during the test flights. The team will then analyze the performance of each color space and detection feature with respect to its consistency and accuracy of detecting the FEA.

Prior to testing, the color space that the team expects to use is hue, saturation, value (HSV). This color space can be expected to be more accurate than red, green, blue (RGB) because it is based off of hue, so the color detection should perform better in the case of varying color intensity. Along with color recognition, the team is going to test the use of both geometric and texture features in different combinations to help identify the target. They will also be important for edge detection, since the bounding box of the FEA will need to be accurately identified in order for the UAV to calculate its center point. In addition, the team shall perform testing to identify the height above the FEA at which the drone will stop using computer vision to correct its flight during its descent once it is too close to the target to view the bounding box of the FEA.

While using this hand-crafted feature will provide a robust solution, it does also come with some drawbacks. The biggest drawback is that using a computer vision system is very computationally expensive at run-time, as individual analysis needs to be done on the frames being streamed. This drawback is slightly mitigated by the fact that this solution will be able to analyze 20-30 frames per second.

After testing is performed, the team will analyze the results and decide which method to use for target detection based on the weighted criteria in Table 40 below.

Table 40: Weighted criteria for the Target Detection System.

Benefit	Weight
Accuracy (0-10)	35%
Precision (0-10)	35%
Running Speed (0-10)	30%

In terms of computing speed, hand-crafted features have a definite advantage. Convolutional neural networks are computationally expensive and will likely only be able to process one or two frames per second. With a hand-crafted model, fewer computations will likely be required, so it could run closer to fifteen frames per second. This is important because it will allow the UAV to make more precise changes to its position in order to properly position itself over the target and drop the beacon. Additionally, depending on the amount of other scripts running on the Pi, a limited computation may be the only viable option.

When it comes to actual performance, determining which model will outperform the other is difficult without implementing both and comparing the results. Data-driven features have the advantage of being able to figure out what characteristics of the input image are most important to a degree of accuracy beyond what a human could accomplish. The problem is that if the training data is misrepresentative of testing area, the model could fail completely. Hand-crafted features will likely have a lower accuracy than a convolutional neural network. However, if engineered properly, they could still provide a reasonable level of accuracy. Also, if the tests run are simpler, such as measuring the color, they will be less likely to be thrown off by changes in the environment, and could be more reliable as a result.

Going on current information, hand-crafted features seem like they will be favorable. However, the team will collect data and implement both models, using the above table to determine which model is superior. If it turns out that convolutional neural networks are significantly more accurate, that could justify the increased computational load. However, if hand-crafted features perform better or aren't significantly worse, then it would be hard to justify the increased cost of running a convolutional net. The team's approach going forward will be to collect a large amount of training data in a variety of weather conditions and lighting and manually label the position of the target. This will give something to train the data-driven model on and craft engineered features to fit. Additionally, some of this data can be set aside to evaluate model performance and help determine the accuracy and precision of both. After measuring run time for each, a decision can then be made about which model is better using the above table.

5.3.5.2 Beacon Deployment

The team has created two preliminary designs for the navigational beacon which is to be deployed by the UAV, both of which attempt to maximize the ability of the UAV to deploy the beacon onto the Future Excursion Area. The first of these, as seen in Figure 57, is reminiscent of a singular road spike, in the shape of a tetrahedron. It would be constructed by bending two metal rods and welding them at their centers, with the NDRT acronym painted on the sides.

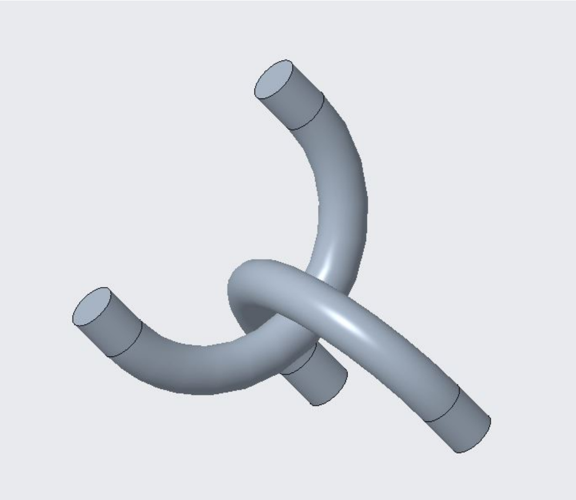


Figure 57: Tetrahedron shaped beacon design.

This design would minimize the chances of rolling post-touchdown of the beacon with the target, but would be of significant weight due to its metallic properties, potentially hindering the UAV and its ability to fly. Additionally, with this design, the 2019 Student Launch Handbook volume requirement could be difficult to achieve.

The second design, as seen in Figure 58, is a cube with the Notre Dame Rocketry Team (NDRT) acronym on each side.

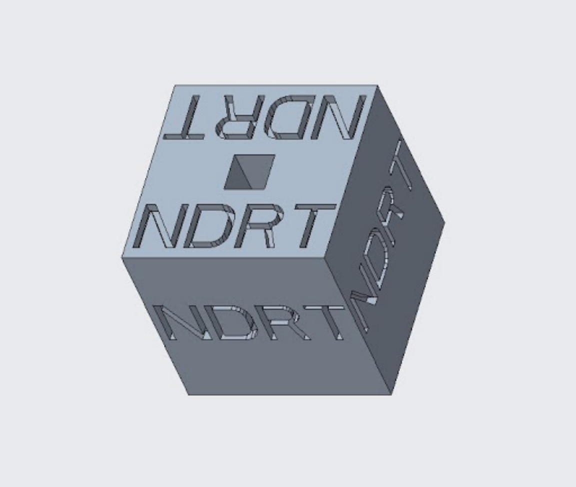


Figure 58: Cubic beacon design with NDRT acronyms.

This design would be 3D printed and would therefore be lightweight and simple to fabricate. Additionally, it would be secured to the UAV by a square rod placed through a matching hole in the middle of the cube. However, this design holds a risk of rolling post-touchdown with the target, due to its weight and shape. Additionally, this design, due to its light weight, could drift during free fall due to strong winds. Currently, NDRT is leaning toward the cubic beacon, as it seems to offer the most design benefits. The team will run extensive tests with each beacon design to determine which of the two is appropriate for the drone, specifically testing the behavior of the beacon post-impact and the affect weight of the beacon has on the flight time, as well as the ease-of-deployment from the UAV.

The team has designed two preliminary beacon deployment methods for the UAV. The first design can be seen in Figure 59, Figure 60, Figure 61, and Figure 62.

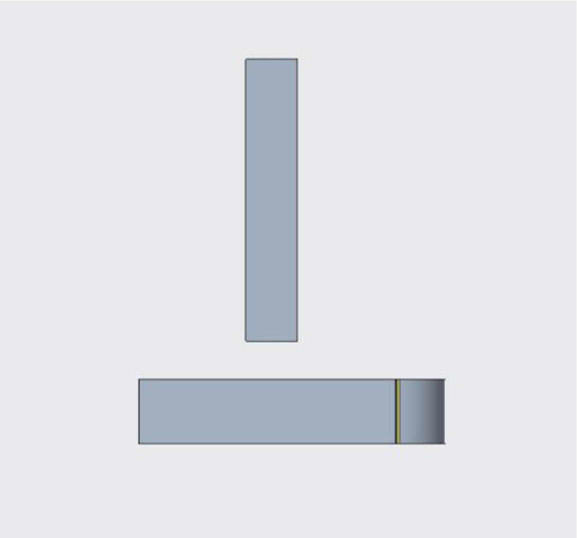


Figure 59: Side view of the first beacon deployment design.

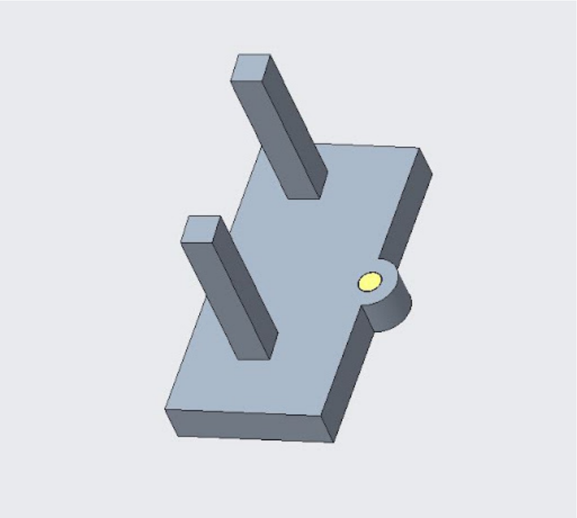


Figure 60: Phase I of the first beacon deployment design.

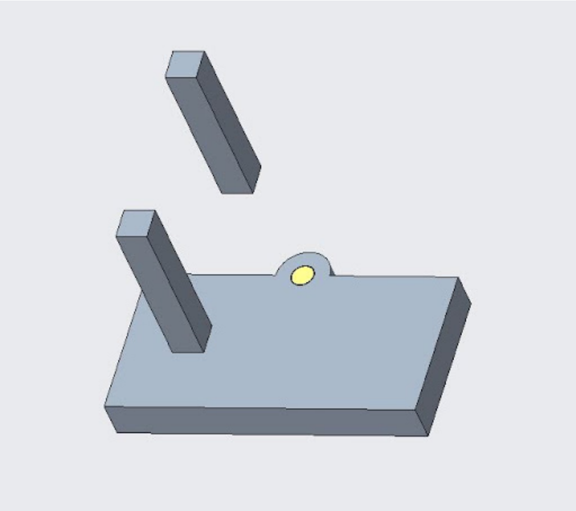


Figure 61: Phase II of the first deployment system.

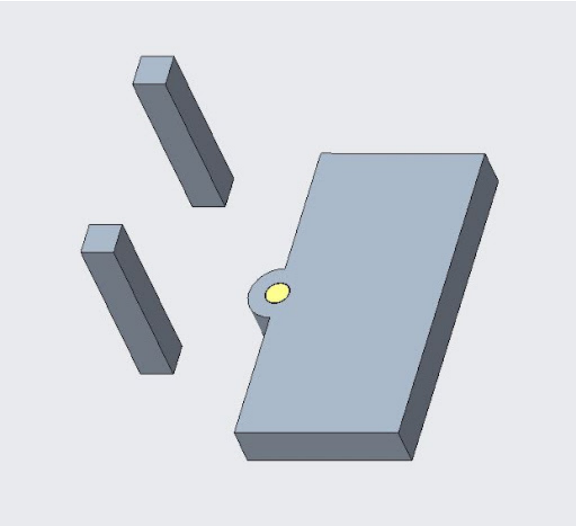


Figure 62: Phase III of the first deployment design.

This design works specifically with the second design for the beacon (Figure 58). Two beacons are attached, one to each square rod, as depicted above, 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, this 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. (A servo motor is prefered 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.) 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 enough, the friction between the beacon and the platform is negligible. For a secondary deployment, in case of failure the first time around, 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. Benefits to using this deployment system are 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 primary try. With this system, however, only the second beacon design could be utilized effectively.

The second beacon deployment design can be seen in Figure 63.

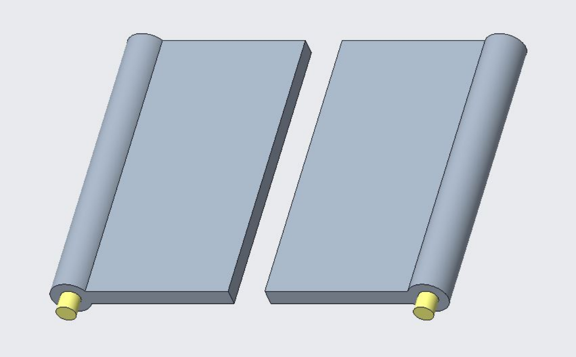


Figure 63: Second beacon deployment design.

This system can work for both navigational beacon designs. The beacon sits on the bay doors, which are closed during the flight of the drone. Upon receiving the deployment signal, two servo motors, colored yellow in the figure, activate and hinge the bay doors open. The navigational beacon then falls out of the UAV and onto the FEA due to gravity. Benefits to using this system are, as stated previously, that both beacon designs can be utilized. This system, however, requires the use of two servo motors, which could drain battery power from the UAV and add weight. Additionally, this system does not account for holding the beacon firmly in place during flight, which could compromise the stability of the UAV. Finally, this system would not allow for the deployment of more than one beacon at separate times. Both of these systems will be tested by the team to determine which provides the highest chances of successful, but the current choice is the first beacon deployment design.

The height from which the navigational beacon is to be deployed will also be tested. The considerations for beacon deployment are as follows:

1. The beacon will be dropped from a certain height.
2. The beacon will be placed upon the target by the UAV.

Benefits to placing the beacon directly on the target are the minimization of drift that could occur during free fall, as well as the offer of more control of the beacon's placement on the FEA.

Benefits to deploying the beacon in free fall include not requiring a programmed landing to facilitate placing the beacon. NDRT has also considered the attachment of a parachute on the navigational beacon, but this could cause significant difficulties with increased drift and drag on the beacon and is therefore an unlikely choice.

6 Project Plan

6.1 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.

6.1.0.1 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 an internal assessment 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 motor assembly and ejection charge 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 Notre Dame Rocketry Team shall hold weekly meetings to address project milestones and assign weekly tasks to members. 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:		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
	1.4.1. Students actively engaged in the project throughout the entire year.								
	1.4.2. One mentor (see requirement 1.13).								
	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	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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 and use the platforms as a means to spread awareness of the team at the University and in the South Bend community.	X		
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 team lead submits them to the SL Management Team.		X	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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 major and minor sections of each report prior to writing the main text. This outline shall then 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		
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		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.12	All teams will be requiReqtRed 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 recoveReqtRed (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		

General 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
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		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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	
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	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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		
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 rehearsed and timed at test launches.			X

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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		

General 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	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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		
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 vessels.	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		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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	
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	

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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	
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

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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

General 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	

General 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

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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	
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

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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
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

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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
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

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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		
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		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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 10on 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	
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
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

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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 ReqtReducing landing kinetic energy to below 75ftlb	x		
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 wiReqtRed independently from payloads and shall share zero connections or signals with payload electronics.		x	

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.5	All recovery electronics will be poweReqtRed 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 ReqtRedundant, 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 tetheReqtRed vehicle or any independent section to a ground receiver.		x	x		All parts of the rocket shall be tetheReqtRed 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 untetheReqtRed to the launch vehicle, will contain an active electronic tracking device.		x			The launch vehicle shall consist of two tetheReqtRed 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

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
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
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

6.1.0.2 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 ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
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						
		Allocation			300						
		Margin			0						

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		The ABS shall be active in payload demonstration flights. The payload shall demonstate a reduction in the control flight apoee of the rocket. Recorded apogee and flight data stored on the ABS microSD card shall indicate predicted performance of the system.	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 for simulated flight data. The system shall demonstrate predictable response and reliability of the mechanism.	2.24.1	Forward canards are prohibited to prevent attitude control of the rocket. The drag tabs must be verified to all deploy simultaneously to prevent inducing instability through moment imbalances from the additional drag force.	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 ABS shall exhibit autonomous control over the full range of actuation during flight.			X		A single servo motor, once powered on, shall provide continous control of the mechanism to dictate the actuation of the tabs. The servo shall make decisions autonomously based on data from avionics.	N/A	Continuous and autonomous control is necessary in order to fully 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-3	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.			
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 the power and arming switches available near the barometer pressure hole in the vehicle body. The LED indicators shall be inspected during integration to be both visible and change depending on simulated data being fed to the system.	N/A	The power and arming of all systems in the vehicle must be accessible externally to reduce risk of false triggers. Additionally, the ability to visually confirm the status of the control system through color 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 will record accelerometer and barometer data and pass it through a Kalman filter to reduce noise and calculate altitude and velocity within the given tolerances.	N/A	Accurate measurements are necessary to reliably control the apogee of the vehicle.		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
RC3.3-1	The launch vehicle shall descend under a parachute with a surface area greater than $7.57 ft^2$.		X			The parachute shall be chosen so that it has at least $7.57 ft^2$ 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	

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

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

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 and Deployment Drive System that shall allow for the complete clearance of the UAV for flight to the FEA			X		The team shall demonstrate the functionallity 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 power on the UAV. The system shall be change the state of the UAV from fully powered off to powerd on through operation of the deployment mechanism.	4.4.2	The UAV must be able to be powered on during deployment. Setting this as the type of system to achieve this eliminates potential variation in the design.		X	

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
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		The team shall constrain the UAV in all directions during flight to ensure that it remains immobile. The team will test the mechanism's durability in order to verify that it can withstand the loads and forces experienced during flight and upon 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	
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 software that uses DroneKit-Python.			X		The team shall demonstrate the operational functionallity 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		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

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
PL4.4.7.-1	The team shall use DroneKit-Python and the GPS coordinates of the FEA to set target positions. The software shall use the GPS coordinates of the closest Future Excursion Area to initially set waypoints for the drone.			X		The team shall generate input data for a simulated FEA location and verify the UAV will create a flight path around 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	
PL4.4.9.-1	The team shall design two 3D printed beacons for redundancy in a successful delivery to the FEA. The University of Notre Dame and a Notre Dame Rocketry Team logo shall be printed on both beacons.		X			The team shall print two custom objects to represent a navigational beacon and shall verify that the Notre Dame logo is clearly visible.	4.4.9	The clear identification of the beacon being Notre Dame's is critical to mission success and will be verified by a requirement.		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 encapsulates the battery on all sides.	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		

6.2 Project Budget

The Notre Dame Rocketry Team has budgeted $16,200 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 is charitable donations by the NDRT corporate sponsors. This year's sponsors include The Boeing Company and TimkenSteel, with a potential donation from Pratt & Whitney. A breakdowns of the funds secured at this point in time is given in Table 48.

Table 48: 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
TOTAL	$ **16,893.00**

The current sourced funds total $16,893 and are sufficient for covering the costs of this year's project. Going forward, the team hopes to continue building on its primary revenue stream and increase fundraising to support Research and Development costs for the program. After considering historic spending for the project and initial materials sourcing, a projected budget was established and funds were allocated to each of the major program categories. The budgeted amounts are given in Table 49 along with the current amounts expended for the project.

Table 49: Notre Dame Rocketry Team Funding Sources

Allocation	Amount
Vehicle Design	$ 5,000
Recovery Subsystem	$ 1,500
UAV Payload	$ 2,200
Air Braking System	$ 1,200
Rocket Subtotal	$ **9,900**
Educational Engagement	$ 300
Competition Travel	$ 5,500
Miscellaneous	$ 500
TOTAL	$ **16,200**

The largest expenditures for the team are the overall launch vehicle construction and traveling to competition. This budget allows for a margin of $ 693 for cost overrun as well as funding for future research and development.

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 50.

Table 50: Itemized Budget

Recovery System Components	Vendor	Description	Qty	Price per Unit	Total Cost
Parachute	Performance Hobbies	Parachute	1	239.00	239.00
Altimeters	Eggtimer	Altimeters	2	35.00	70.00
Garolite Plates	McMaster Carr	Used for Bulkheads	2	36.75	73.50
3D Printing	Notre Dame	ABS Plastic	1	120.00	120.00
PC343-3031-5000-MW-4630-CG-N-IN	The Spring Store	Spring	1	98.52	98.52
Steel Plates	McMaster Carr	Steel Plates	1	14.41	14.41
Steel Sphere (latch)	McMaster Carr	Steel Sphere	1	6.65	6.65
Shock Cords	Us Cargo Control	100ft of Shock cords	1	108.99	108.99
Chute Release	Jolly Logic	Chute Release	2	129.95	259.90
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	42.90	85.80
Eye Bolts	McMaster Carr	Eyebolts for bulkheads	2	5.13	10.26
5/16 In Threaded Link 1760lb Capacity Packaged	Del Cidt	Quick Links	4	2.60	10.40
BACOENG 3 Gallon Vacuum Chamber Kit	BACOENG 3	Vacuum Chamber	1	200.00	200.00
#29128 - 36" Nylon Parachute	Apogee Rockets	Drogue Parachute	1	21.80	21.80
		TOTAL COST			1374.20
		Budget Allocation			1500.00
		Margin			125.80
Vehicle Components	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	9.6
Subscale Motor	Aerotech		1	29.99	29.99
Subscale Tabs	3D Print		1	30	30
Subscale Fin Plywood	LOC Precision		1	5	5
Subscale Transition	3D Print		1	20	20

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
Fiberglass Nose Cone	MadCowRocketry		1	168.95	168.95
Carbon Fiber Body Tube (6")			1	539	539
Fiberglass Body Tube (7.51")			1	300	300
Carbon Fiber Sheet (1/8")		Fins	1	200	200
JBWeld	JBWeld		2	29.99	59.98
Fiberglass Motor Centering Rings			3	10	30
Fiberglass Bulkheads			3	9	27
Motor	Cesaroni / Aerotech		3	290	870
Transition Section	Custom Order		1	200	200
Screw Pack	Home Depot		1	10	10
Machining			1	300	300
Miscellaneous			1	500	500
		TOTAL COST			3521.68
		Allocation			5000
		Margin			1478.32
Air Braking System Components	Vendor	Description	Qty	Price Per Unit	Total Cost
Adafruit ADXL345	Excess Inventory	Triple Axis Accelerometer	1	0	0
Adafruit BMP280	Excess Inventory	Barometer	1	0	0
Arduino MKR ZERO	Excess Inventory	Microcontroller	1	0	0
Adafruit BNO055	Adafruit	Accelerometer & Orientation IMU	1	35.5	35.5
Adafruit LIS3DH	Adafruit	Triple Axis Accelerometer	1	5.5	5.5

Sparkfun MPL3115A2	Sparkfun	Altitude Pressure Breakout Board	1	22.81	22.81
Adafruit LED Sequins Multicolor Pack of 5	Adafruit	LED	2	4.5	9
Breakaway 0.1” 2x20pin Strip Dual Male Header	Adafruit	Header Pins for Sensors	3	1.5	4.5
Small PCB Test Points (100 pack)	Adafruit	PCB Test Points	1	10.5	10.5
Small Alligator Clip to Male Jumper Wire Bundle 6 Pieces	Adafruit	Alligator Clip Leads	1	4.5	4.5
Power HD 1235MG Servo Motor	Pololu	Servo Motor. Note: One additional unused in inventory.	1	59.95	59.95
PCB	OSH Park	Printed Circuit Board	3	25	75
Tenergy 30C 7.4V 2200 mAh	Tenergy	Battery	2	12	24
Tenergy TLP 2000 Universal Charger	Excess Inventory	Battery Charper for Li-Ion or LiPo batteries	1	0	0
Switch	Excess Inventory	Toggle Switch	2	0	0
5 V voltage regulator	Adafruit	voltage regulator	2	1.25	2.5
HDPE 0.25”x12”x12” Sheet	Interstate Plastics	High Density Polyethylene	2	19.91	39.82
Delrin Sheet 0.5”x12”x12”	Interstate Plastics	Delrin	1	95.87	95.87
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
Drive Shaft	Custom Machined	Shaft connecting motor and mechanism	1	15	15
Tie Rods	Custom Machined	Provide connection between cross piece and tabs	4	10	40

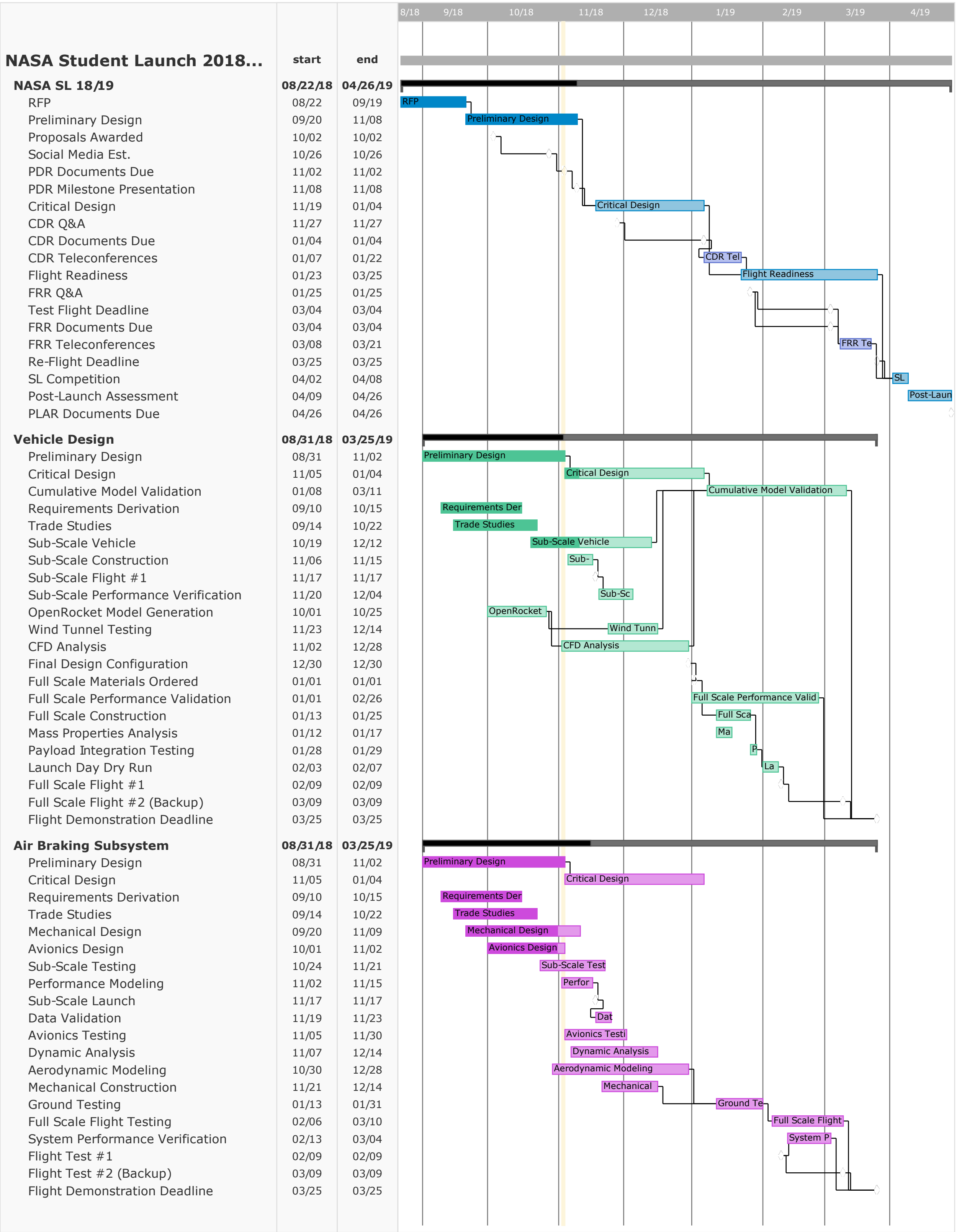
8 GB microSD Card	Samsung	SD card for datalogging	1	20	20
10-32x1.5” Nylon Screw	McMaster-Carr	Screws for mounting the motor	4	1.4	5.6
3D Printed Battery Case	Custom Machined	Case for battery	1	20	20
		TOTAL COST			512.03
		Allocation			1200
		Margin			687.97
UAV Payload Components	Vendor	Description	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	59.98
Multirotor Carbon Fiber T-Style Propeller 7x2.4 Black (CW/CCW) (2pcs)	Hobbyking	Carbon Fiber Prop	4	4.75	19
Lumenier 18A 32bit Silk ESC OPTO (2-4s)	GetFPV	Electronic Speed Controller	6	9.99	59.94
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	2.49
T-Motor MN1806 KV1400	T-MOTOR	Motor	6	25.9	155.4
Turnigy nano-tech 4500mAh 3S 35 70C Lipo Pack w/XT-90	Hobbyking	Battery	2	40.25	80.5
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	90

500mW Transceiver Telemetry Radio Set V3 915 MHZ	Holybro	500mW Telemetry Set 915MHz			NaN
Raspberry Pi Camera Board v2 - 8 Megapixels	Adafruit Industries	Raspberry Pi Camera	1	29.95	29.95
1254N11 MXL .255" Timing Belt Pulley (10 Tooth) Polycarbonate	McMaster Carr	Pulley	2	6.66	13.32
1254N18 MXL Series Lightweight Timing Belt Pulley (20 Tooth) Polycarbonate	McMaster Carr	Pulley	2	7.23	14.46
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 Motor Step Motor 1.8deg Bipolar 12V 0.4A	STEPPER-ONLINE	Stepper Motor for Linear, Translation Motion (Deployment)	2	18.9	37.8
Nema 17 Stepper Motor, DROK 40mm High Torque Bipolar DC Step Motor Kit	DROK	Stepper Motor for Rotational Motion (Deployment)	2	17.99	35.98
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	Accelerometer for Orientation Correction	2	12.5	25

Microcontroller for Deployment System	Adafruit	Microcontroller to Connect Accelerometer to Stepper	1	22	22
Metal Supports for Aluminum Rods	Lowes	Placed on Back Bulkhead to Help Stabilize Deployment	2	7.75	15.5
		TOTAL COST			1386.12
		Allocation			2200
		Margin			813.88
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
		Allocation			300
		Margin			0

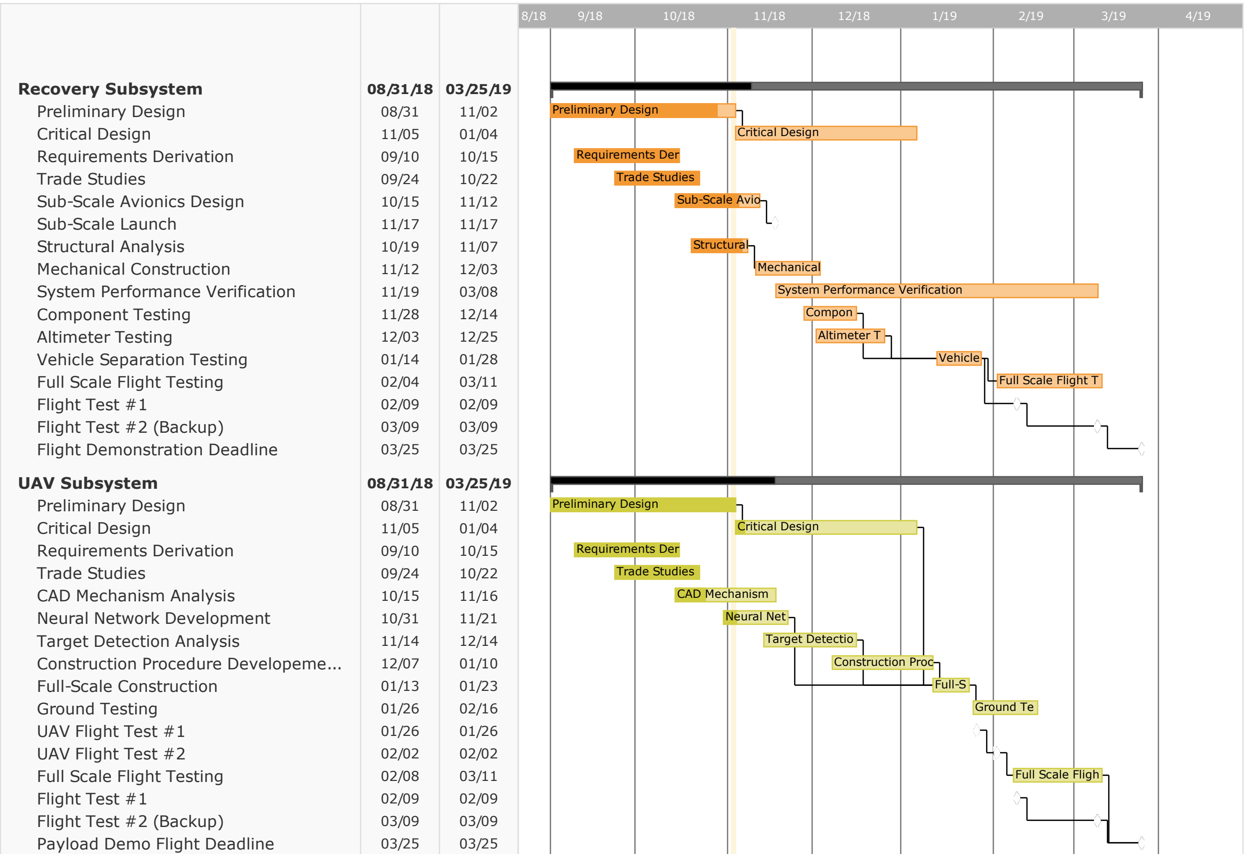
6.3 Project Timeline

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 64 and 65.



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	01/04
CDR Q&A	11/27	11/27
CDR Documents Due	01/04	01/04
CDR Teleconferences	01/07	01/22
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	11/17	11/17
Sub-Scale Performance Verification	11/20	12/04
OpenRocket Model Generation	10/01	10/25
Wind Tunnel Testing	11/23	12/14
CFD Analysis	11/02	12/28
Final Design Configuration	12/30	12/30
Full Scale Materials Ordered	01/01	01/01
Full Scale Performance Validation	01/01	02/26
Full Scale Construction	01/13	01/25
Mass Properties Analysis	01/12	01/17
Payload Integration Testing	01/28	01/29
Launch Day Dry Run	02/03	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	01/04
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	11/17	11/17
Data Validation	11/19	11/23
Avionics Testing	11/05	11/30
Dynamic Analysis	11/07	12/14
Aerodynamic Modeling	10/30	12/28
Mechanical Construction	11/21	12/14
Ground Testing	01/13	01/31
Full Scale Flight Testing	02/06	03/10
System Performance Verification	02/13	03/04
Flight Test #1	02/09	02/09
Flight Test #2 (Backup)	03/09	03/09
Flight Demonstration Deadline	03/25	03/25

Figure 64: Project Gantt chart, part I



Recovery Subsystem	**08/31/18**	**03/25/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/04
Requirements Derivation	09/10	10/15
Trade Studies	09/24	10/22
Sub-Scale Avionics Design	10/15	11/12
Sub-Scale Launch	11/17	11/17
Structural Analysis	10/19	11/07
Mechanical Construction	11/12	12/03
System Performance Verification	11/19	03/08
Component Testing	11/28	12/14
Altimeter Testing	12/03	12/25
Vehicle Separation Testing	01/14	01/28
Full Scale Flight Testing	02/04	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	01/04
Requirements Derivation	09/10	10/15
Trade Studies	09/24	10/22
CAD Mechanism Analysis	10/15	11/16
Neural Network Development	10/31	11/21
Target Detection Analysis	11/14	12/14
Construction Procedure Developeme...	12/07	01/10
Full-Scale Construction	01/13	01/23
Ground Testing	01/26	02/16
UAV Flight Test #1	01/26	01/26
UAV Flight Test #2	02/02	02/02
Full Scale Flight Testing	02/08	03/11
Flight Test #1	02/09	02/09
Flight Test #2 (Backup)	03/09	03/09
Payload Demo Flight Deadline	03/25	03/25

Figure 65: Project Gantt chart, part II

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 and ABS	Unbalanced forces on rocket; insufficient securing during flight	Induced spin or tilt on rocket flight; failure to hit precise apogee	3B	1. The UAV and ABS squads will ensure that their respective system functions properly through construction, testing, and launch 2. On launch days, the UAV and ABS checklists will be carried out 3. UAV and ABS 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 4. ABS will verify a ¿90% success rate for remaining secure during flight 5. ABS will verify a ¿95% chance of no structural failure of their system, especially relating to the drag tabs or the load-bearing rods 6. 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 will be available and required for any team member working with adhesives such as epoxy.	1. Procedures for using epoxy will be created and adhered to by all team members 2. Procedures for using gloves will be created and adhered to	2A
Contact with the spinning bit of a portable drill	Improper use of a portable drill	Cuts 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 will be 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

A.2.2 Testing Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by projectile from unplanned spring decompression during recovery testing	Latch mechanism or retainment cords that hold spring break during recovery system ground testing	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 will be designed and constructed to be capable of holding substantially more load than will be experienced during nominal recovery operation 3. An array of spring retainment cords will be used such that one broken cord will not compromise the retainment of the spring 4. The spring retainment cords will be 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 will be created and strictly adhered to 2. Analysis will be done on the latch mechanism to confirm that the mechanism is capable of taking greater than the expected loads prior to recovery system testing 3. The current recovery design calls for cordage with a tensile strength of 2100 lbs, 7 times the load at which the spring will be compressed	3A
Personnel hit by projectile from broken spring during recovery testing	Buckling of the spring during compression causing greater-than-designed stress in the spring	Potential for serious injury to nearby personnel	3B	1. The selected spring will have a low slenderness ratio to decrease the likelihood of buckling during compression 2. A tube will run through the center of the spring, preventing it from buckling	1. The current design calls for a spring with a length:diameter ratio of approximately 5:3, well within the range in which compression springs typically do not buckle 2. A tube or rod through the center of a spring is a proven method of preventing the spring from bucking during compression	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 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

A.2.3 Launch Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket flight path is not vertical	Angled launch rail; unstable rocket	Physical damage to personnel, bystanders, or property	4B	1. The rocket launch rail and stand will be set up correctly 2. The rocket will be designed with a static stability of between 2 and 2.8	1. The correct launch rail and stand configuration will be approved by the necessary officials 2. The center of gravity of the rocket will be measured and compared to the center of pressure after assembly, but before launch. If the stability of the rocket does not meet requirements, the rocket will not launch 3. The rocket will have no systems with the capability to spin or tilt the path of the rocket	4B
Rocket explodes on pad	Faulty or cracked motor	Projectiles cause physical damage to personnel, bystanders, or property; potential to affect large crowd if in close proximity to rocket	4B	1. Minimum distance tables will be enforced 2. Team mentor, David Brunsting, will the only one to handle and insert motor 3. The motor will be inspected before insertion	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 4. The rocket will launch only if the team mentor was the individual who inserted and secured the motor in the rocket	4B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket undergoes uncontrolled descent	Failure of recovery system to deploy	Physical damage to personnel, bystanders, or property; damage to rocket body or systems	3C	1. Recovery system will be robust	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	3C
Rocket motor lights off prematurely	Faulty ignitor, launch button pressed prematurely	Chemical or thermal burns to individuals close to the motor	3B	1. Comply fully with the commands of the Range Safety Officer and the team mentor	1. The Range Safety Officer feels that every command has been carried out successfully and in the spirit of the command 2. The Team mentor feels that every command has been carried out successfully and in the spirit of the command	3B

A.2.4 Recovery Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by projectile from unplanned spring decompression during testing	Latch mechanism or retainment cords break during recovery system ground testing	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 will be designed and constructed to be capable of holding substantially more load than will be experienced during nominal recovery operation 3. An array of spring retainment cords will be used such that one broken cord will not compromise the retainment of the spring 4. The spring retainment cords will be selected such they will be capable of holding substantially more load than would be experienced during normal operation	1. Procedures for ground testing and launch operation of the recovery system will be created and strictly adhered 2. Analysis will be done on the latch mechanism to confirm that the mechanism is capable of taking greater than the expected loads prior to recovery system testing 3. The current recovery design calls for cordage with a tensile strength of 2100 lbs, 7 times the load at which the spring will be compressed	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by projectile from broken spring	Buckling of the spring during compression causing greater-than-designed stress in the spring	Potential for serious injury to nearby personnel	3B	1. The selected spring will have a low slenderness ratio to decrease the likelihood of buckling during compression 2. A tube will run through the center of the spring, preventing it from buckling	1. The current design calls for a spring with a length:diameter ratio of approximately 5:3, well within the range in which compression springs typically do not buckle 2. A tube or rod through the center of a spring is a proven method of preventing the spring from bucking during compression	3A
Personnel hit by projectile from unplanned spring decompression during launch operation	Servo releases the latch mechanism during assembly	Potential for serious injury to nearby personnel	3B	1. 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 2. External safety pin(s) 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 launch operation of the recovery system will be created and strictly adhered to	3A
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 spring will be selected such that it is 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 tests of all recovery electronics, as well as full system ground testing, will be done to ensure that the recovery system is in fully working order prior to launch 3. The current design calls for a spring that is capable of producing 571 lbs of force, greater than the 300 lbs of force that was calculated to be necessary for separation	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 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 will be 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	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

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 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
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

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	1. Procedures and checklists for rocket handling will be created and adhered to	4A
Fin can malfunctions	Improper construction or insufficient strength of the fin can	Rocket can become aerodynamically unstable, and shear, possible total mission failure	4B	1. 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	1. The Team Mentor will ensure proper installation of motor and motor mount	1. 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	1. Procedures and checklists for parachute folding will be created and adhered to	4A
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

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
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. Instillation impedes function of Air Braking System	Possible loss of Air Braking System, resulting in partial mission failure	3B	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	1. Verify the installation of the Air Braking system is complete, and it is functional before the flight	2A
Rocket Loses 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	1. 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. Rocket is likely destroyed on impact with the ground	3A	1. 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. 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 either be completely new or freshly charged 4. The spring will be selected such that it is 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 will be created and strictly adhered to 4. Procedures for checking and replacing batteries prior to launch will be created and strictly adhered to 5. The current design calls for a spring that is capable of producing 571 lbs of force, much greater than the 300 lbs of force that was calculated to be required for rocket separation	3A
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 will be created and strictly adhered to 3. Procedures for folding the parachute prior to launch will be 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	1. The parachute will be chosen such that the rocket will descend at a safe speed.	1. Calculations will be done to ensure that the largest section of the rocket does not exceed 75 ft-lbs of kinetic energy while descending under the fully open parachute	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Parachute separates from the rest of the rocket during descent	Broken shock cord or eyebolt	Rocket descends at high speed and likely severely damaged on impact with the ground	4B	1. Shock cords will be 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 will be selected such that they are capable of holding more load than would be experienced in a normal flight	1. Calculations will be done to ensure that the shock cords will be capable of handling more than the loads they will experience during descent 2. The current design does not contain any sharp edges or other threats to the shock cord that needs to be covered 3. Calculations will be done to ensure that the eyebolts and other hardware will be capable of handling more than the loads they will experience during descent	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 descent of the rocket will be staged to reduce the descent time, and therefore the drift distance	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	2B
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 will be constructed such that it can take significantly higher loads than it will experience in flight 2. Restraining cords will be 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	1. Load analysis will be done on the latch mechanism prior to construction to confirm that it will be capable of sustaining the required loads 2. The entire parachute deployment system will be ground tested prior to flight to confirm that the system is in full working order 3. The current design calls for restraining cords with a breaking strength of 2100 lbs, 7 times the force that the spring will exert	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	4C	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	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	3A
Incorrect or missing sensor data	Malfunction in sensor sampling, improper component install, poor data filter code performance	The system is fooled into 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
Undesired micro-controller 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	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	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

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	Wires will be soldered to ensure stronger connections.	Soldered wires have a significantly decreased chance of disconnecting.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
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.	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.	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.	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	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	4A
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 not lined up properly during assembly	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 will be created and 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	Stands will be constructed to rest the rocket on during transport and assembly	Procedures and checklists for rocket assembly will be created and adhered to.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
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 will be created and followed during launch operations.	4A
Parachute folded improperly during rocket assembly	Recovery personnel do not understand how to fold a parachute for proper deployment.	Parachute could become stuck in rocket during descent.	4B	1. Recovery personnel must have practiced folding a the main parachute at least once before launch. 2. Recovery personnel must follow defined procedures for folding a parachute	Specific, consistent procedures for folding the parachute will be created and 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 spring decompression, recovery subsystem assembly, and recovery integration will be created and adhered to before any test flights of the vehicle.	3A
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	Ignitors 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 ignitors. He is Level 2 HPR certified through Tripoli Rocket Association.	4A

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 2. Rocket improperly loaded onto launch pad	Rocket will not reach target apogee	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 set up 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.	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 are not inserted; screws are not inserted	Rocket subsections separate during descent	4B	Perform inspecting of rocket before launch	1. Either the Safety Officer or one of the leads will inspect the rocket for both shear pins and screw locks 2. A pre-launch inspection checklist will be created and checked off before flight	4A
Shear Pins	1. Shear pins are not inserted 2. Incorrect number of shear pins used	Rocket unintentionally separates during flight	4B	Inspection of the rocket will be done before the rocket is on the launch pad.	Rocket assembly procedures and checklists will be created to ensure that the appropriate number of shear pins are used prior to launch	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Screw Locks	Screws are not installed during assembly	Rocket subsections separate during descent	4B	Full inspection of the rocket will be done before the rocket goes to the launch pad to ensure that it is properly assembled	Rocket assembly procedures and checklists will be created and adhered to.	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 will be created and adhered to.	4A
Centering Ring failure during flight	Centering rings are improperly epoxied or misaligned	Motor creates moment on the rocket; rocket trajectory is altered	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 centering rings will be created and strictly adhered to.	4A
Bulkhead failure during flight	1. Bulkheads improperly lined up during 2. Bulkheads improperly epoxied during construction	Rocket payloads or subsystems could separate from the airframe during flight	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 will be created and strictly adhered to during construction.	4A
Couplers fail to keep rocket together in flight	1. Couplers are not the proper length 2. Couplers are improperly epoxied	Rocket shears during the motor burn, causing severe damage to the airframe	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 will be created and 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 low 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

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
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 high winds or gusts	At least one member of safety team will check local forecast for predicted launch day winds.	2C
Trees, moist ground, manmade 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 high winds 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 high cloud cover	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	At least one member of safety team will check local forecast for predicted launch day humidity.	2B
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	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
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.	3A
Groundwater contamination	Leakage, improper disposal of batteries	TChemicals 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.	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

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
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 lab will possess appropriate 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
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.
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 from a 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 the rocket 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 high power 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.
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.