2015

MIT RocketTeam

Preliminary Design Review

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1. Executive Summary

1.1 Team Overview

The MIT Rocket Team (hereafter, "the Team") is a well-established student group focused on rocket-related projects. The organization's mission is to proliferate the knowledge of sciences related to rocketry, to foster the development of skills and techniques related to the field, and to provide a hands-on, project oriented outlet for application of theory learned in the classroom setting.

1.2 Competition Details and Goals

The Team has committed to competing in the 2016 International Rocket Engineering Competition (IREC), hosted by the Experimental Sounding Rocket Association (ESRA) in Green River, Utah. This Preliminary Design Review (PDR) is dedicated to an assessment of the team's current proposed rocket for the 2016 IREC.

The competition is divided into two categories (Basic and Advanced); the Team will be competing in the Basic category. This requires the delivery of a minimum 10lbs payload to a target altitude of 10,000ft above ground level. The competition is scored based on rocket performance (altitude, full recovery), payload, poster presentation, deliverables to ESRA, readiness, safety and operations, and the amount and quality of student-built hardware. The Advanced category requires the delivery of a minimum 10lbs payload to a chosen target apogee between 10,000ft and 23,000ft above ground level. In addition to this, all major launch vehicle and payload systems, including the body tubing, nose cone, parachute, and motor must be student designed and built.

Given our Team's first place performance in the Basic Category last year, we will strive towards building the methods to enable our team to compete in the Advanced category of IREC in the summer of 2017. In addition, we plan to improve areas that were suboptimal during last year's competition, especially the rocket integration time and the execution of live telemetry from the rocket. These goals are subdivided into our baseline, target, and stretch goals.

1.3 Vehicle Concept of Operations

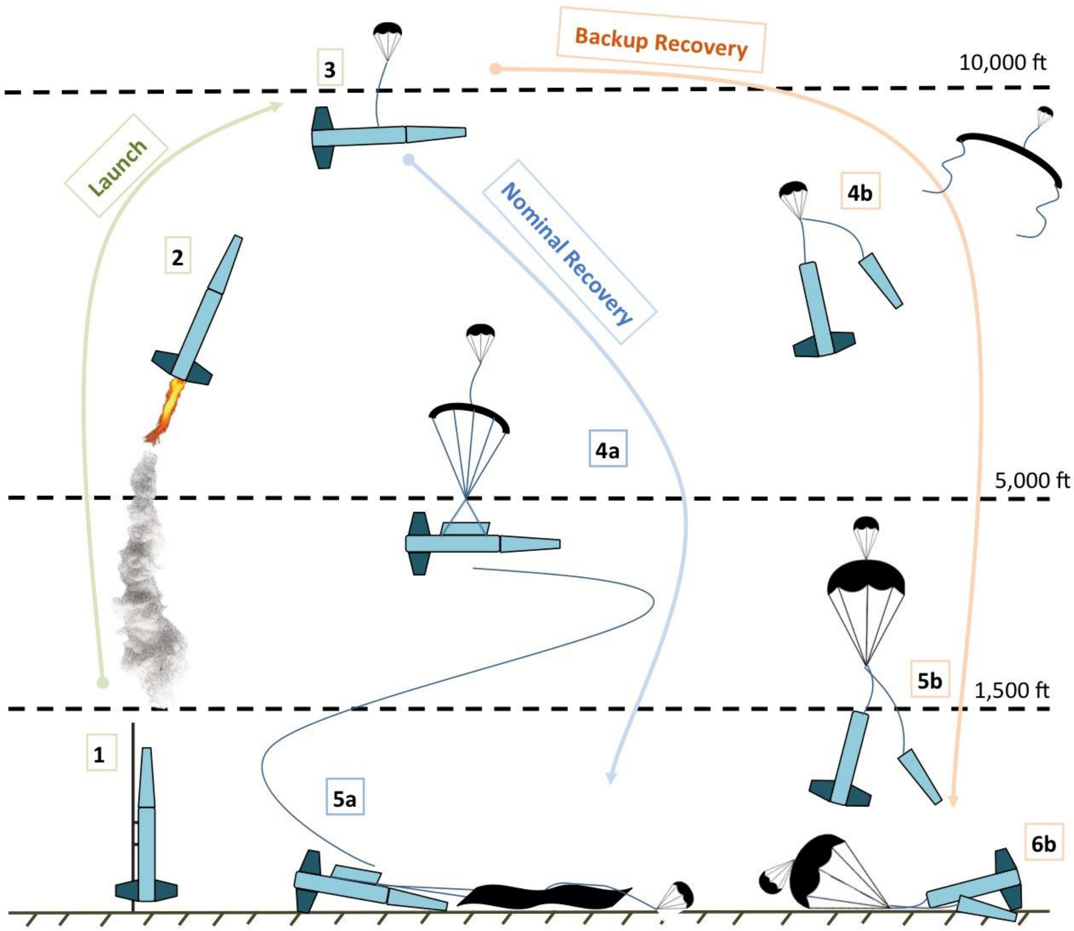

Figure 1: Concept of Operations

A commercial off-the-shelf (COTS) solid rocket motor is the primary propulsion system. We are also developing a custom solid propulsion motor, which, upon completion of specified tests and certifications for safety and reliability, may be flown in place of the COTS motor.

Nominal recovery would feature deployment of a parafoil at 5000ft AGL, which would be autonomously actuated to guide the entire rocket to a target location. Backup recovery is triggered in the event of parafoil deployment anomalies, and operates much like the dual deployment scheme commonly used in our 2015 rocket.

The Team hopes that this project will provide experience to team members in the areas of parafoil-based recovery, autonomous control, and design of solid propulsion systems.

1.4 Goals and Scope of Preliminary Design Review

The goal of this design review is to present the current state of the vehicle design, and plans to move forward into a fully detailed design in January. While the Critical Design Review will present rigorous analyses of all subsystems, the goal of this report is to present and assess the assumptions made and concepts generated up until this point.

1.5 Organization

Per the Team Constitution, the Exec Board is comprised of a President, Vice-President, Treasurer, Publicity Chair, and Social Chair.

For this project, 5 subteams have been formed, each with its own team lead: Avionics, Payload, Propulsion, Recovery, and Structures. Each team is tasked with certain deliverables essential to the fulfillment of the goals of the team, and the requirements of the competition. These deliverables and applicable subteam requirements, as well as their relation to system-level requirements, are detailed in later sections.

General team members are free to work for whichever subteam they desire, and may work for multiple subteams. They are also encouraged to participate in small-scale Estes model rocket projects and NAR certification rocket projects. Currently, we have around 35 regularly attending members on the Team.

2. Systems Engineering Overview

2.1 Requirements and Goals

The Team has outlined goals based on last year's performance and our plans to compete in the Advanced category next year. The combined requirements document is shown in Appendix A, and includes Basic Category Requirements in addition to these internal requirements outlined below. The requirements are numbered by subteam, and their corresponding IREC requirement or team goal is referenced. Each subteam is responsible for complying with their designated requirements, as well as the overall Team requirements. Subteam requirements are documented in their respective subteam sections.

The following are the Team's goals for this year's competition:

Table 1: Team goals

#	Baseline Requirements (B)	Target Goals (T)	Stretch Goals (S)
1	The Team shall ensure all members follow the safety plan to prevent injury during operations.	Team should integrate the rocket in 10 minutes.	Rocket should achieve live telemetry.
2	Rocket shall follow all IREC requirements.	Parafoil should deploy successfully.	Payload should land the rocket in target area.
3	Rocket shall gather and recover altitude data.	All sensor data should be gathered and recovered.	Flight data analysis infrastructure should lead to quick conclusion about results.
4	Rocket shall have one successful test launch prior to the	Rocket should have two	Rocket should reach

	competition.	successful test launches.	within 100ft of the target altitude.
5	Rocket shall reach within 1000ft of target altitude.	Payload should attempt to control the rocket's descent path and reveal this in the data.	Rocket should fly using custom propulsion.
6	The Team shall integrate as much flight-ready student-built hardware into the competition rocket as possible.		

2.2 Timeline

The following is a timeline of the planned events for the Team over the course of the year. To date, we have completed some of the first iterations of the system design, and we are poised to continue iterating the design during the winter, working towards the Critical Design Review and flight testing.

Table 2: Fall Semester Gantt Chart

Task	9/5/2015	9/12	9/19	9/26	10/3	10/10	10/17	10/24	10/31	11/7	11/14	11/21	11/28	12/5	12/12
Requirements Development															
System Design															
Motor Selection															
Custom Propulsion Formulations															
Custom Propulsion Testing															
Custom Propulsion Production Deadline															
Payload Drop Tests															
Recovery Deployment Tests															
Avionics Telemetry Tests															
PDR															
CDR															
Rocket Build															
Flight Test #1															
Flight Test #2															
Flight Test #3															
Flight Test #4															
Preparation for IREC															
IREC															

Table 3: IAP/Spring Semester Gantt Chart

Task	1/2/2016	1/9	1/16	1/23	1/30	2/6	2/13	2/20	2/27	3/6	3/13	3/20	3/27	4/3	4/10	4/17	4/24	5/1	5/8	5/15	5/22	5/29	6/5	6/12
Requirements development																								
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Flight Test #4																								
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2.3 Safety Plan

Given the dangerous nature of many of the rocket's components, including energetic, toxic, and electrical hazards, as well as general safety concerns such as the use of power tools, the Team implements strict regulations to ensure the safety of its members. These regulations are documented in a safety plan, which is reviewed by the MIT AeroAstro Facilities Committee. The team also elects the Safety Officer, who is responsible for ensuring team member compliance with the safety plan. The safety plan and Safety Officer focus on day-to-day lab activities.

In addition to the safety practices available in the safety plan, members are required to complete safety trainings to access certain labs and tools. In order to access MIT's main aerospace lab, the Gelb Lab, members are required to complete an MIT AeroAstro online safety course. Additionally, in order to access the AeroAstro Machine Shop, members are required to complete four hours of Machine Shop training on lathe and mill.

3. Payload & Recovery

Due to the nature of the Team's payload and recovery scheme, the Payload and Recovery subteams are closely related, and grouped together for organizational and logistic reasons. Please refer to sections 3.5 and 3.5.2 for more details.

3.1 Overview of Requirements

The Recovery and Payload subteams began the design process by outlining internal and IREC requirements (Table 4) to ensure that the design met both sets of requirements.

Table 4: Internal and IREC requirements

Internal Requirement	IREC Requirement	Description
3.1	2.1	Payload shall weigh more than 10lbs.
3.2	2.3	Payload shall be capable of being weighed independently of all other rocket components. The payload package will be completely removable from the rest of the rocket, allowing it to be weighed separately.
3.3	4.1	All rocket components (excluding consumables such as ejection charges) shall be recovered in reflyable condition. In other words, after recovering the rocket, it can be reintegrated and launched without repairing or replacing non-consumable system components.
3.4	4.1.1	The recovery system shall follow dual-event CONOPS. Nominally, this will include a pilot chute deployed at apogee, and a parafoil deployed at 5,000ft above ground level (AGL). In the event of an anomaly, a drogue chute will be deployed at apogee or before 1,500ft AGL, and a back-up main parachute will be deployed at 1,500ft AGL.
3.4.1	4.1.1.1	The initial deployment event shall occur at apogee and stabilize vehicle attitude. In the nominal recovery CONOPS, a pilot chute is deployed at apogee to initially stabilize the rocket's altitude and assist in deploying the parafoil from a hatch in the side of the rocket.
3.4.2	4.1.1.2	The second deployment event shall occur at an altitude no higher than 1,500ft AGL, reducing descent velocity to less than 30ft/s. In the nominal recovery CONOPS, a parafoil is deployed at

		5,000ft AGL. This altitude will give the system adequate altitude for the parafoil to guide the rocket to the desired landing location. While the 5,000ft deployment altitude is above the specified 1,500ft altitude, the backup main parachute is set to deploy at 1,500ft AGL in the event of an anomaly. ESRA officials have been informed of the Team's intent to deploy the parafoil above the specified altitude of 1,500ft.
3.5	4.2	The recovery system shall incorporate redundant recovery system electronics, each with a separate power supply. The primary recovery electronics system will be a student designed-and built flight computer with all of the functionality of a COTS flight computer and altimeter, plus the capability to guide, navigate, and control the rocket to the desired landing location. In the event of an anomaly, the system is equipped with a backup COTS flight computer. Both the student-designed and COTS flight computers will control deployment of the backup recovery system (drogue and main), making the COTS system redundant.
3.6	4.6	The system shall carry a radio beacon or similar transmitter aboard each independently recovered body. The rocket will be recovered as one body, and will be equipped with both a GPS transmitter and a radio beacon. The rocket will also be equipped with visual and audio locating aides, such as "screamers" and colored smoke charges (upon separation of the rocket).
3.7	2.2	Launch vehicles entered shall be able to recover themselves independent of active or passive payload function. While the payload sensor suite holds no recovery capabilities, the parafoil system and backup recovery system are not considered payload by ESRA.
3.8	4.7	The recovery system shall be successfully tested by ground or flight testing. The recovery system, payload, and entire rocket system will be ground tested and flight tested at least twice before the final IREC competition in June 2016.

3.2 Design Process

3.2.1 Goals

At the start of the fall 2015 semester, the Team began discussing payload ideas, and was excited to design and fly a glide-back recovery system with an autonomously actuated parafoil. Thus, from the start, the recovery subsystem encompassed the design and deployment of a parafoil, as well as the backup recovery system. When the official IREC 2015 rules were released, the team walked through the rules, outlined them, and developed a complimentary set of recovery-specific rules to guide the design process. These requirements are outlined in Section 3.1 above.

After conceiving the general idea for the payload/recovery system and outlining the requirements for the system, the Payload and Recovery subteams began brainstorming ideas for packing and deploying the parafoil and related systems.

We began by discussing whether to recover the entire rocket or just a portion of the rocket. We developed a pro/con list of each and decided to recover the entire rocket via parafoil (Table 5).

Table 5: Recovering Whole Rocket v. Section of Rocket Trade Study

Recover Whole Rocket with Parafoil		Recovery Portion of Rocket with Parafoil	
Pros	**Cons**	**Pros**	**Cons**
Faster, simpler, safer ground recovery operations (only recovering one object)	Parafoil failure possibly results in loss of the entire rocket	Parafoil failure possibly results in the loss of only a section of the rocket	Longer, more complex ground operations (recovering two separate objects)
Requires only one redundant recovery system, which greatly decreases the weight and complexity of the recovery system	Requires a larger parafoil to support the weight of the entire rocket	Requires a smaller parafoil to support just one section of the rocket	Requires the development of two separate recovery systems (booster and payload), which increases weight and complexity
Fewer failure modes with just one recovery system	Requires more complicated dynamics modeling	Simpler dynamics modeling	More failure modes with two recovery systems
Provides the team with more opportunities to learn and develop knowledge			

After closer inspection of the requirements, the Team decided to include a pilot chute with the primary parafoil system. The pilot chute acts as a small drogue and serves several purposes:

(1) Delaying parafoil deployment so the rocket does not drift out of a reasonable range
(2) Slowing the rocket down to lower shock loads when the parafoil deploys
(3) Orienting the rocket in a specific attitude to increase the reliability of the parafoil deployment

The team also noted that, though actuating the parafoil to a target area would significantly simplify the recovery process if successful, failure to control the forward movement of the parafoil could lead to the rocket drifting several kilometers downwind. The parafoil could experience failures that also lead to the loss of the whole rocket. Thus, to minimize this risk and to meet ESRA recovery safety standards, the team decided to include a backup recovery system. From the requirements, this system would include both a drogue and a main parachute. For simplicity, reliability, safety, and familiarity with the system, the team decided that the backup recovery system would be single separation, dual deployment, with a Tender Descender ™.

In order to collect our thoughts and narrow down ideas to choose the best, most effective design, the Recovery team created an informal design document that outlined the various ideas, along with trade studies of each. The design document informed our final decision. The rocket layout and deployment scheme was determined by in-depth discussions on logistics, ease of deployment and integration, and controllability. These conversations included a discussion of failure modes and the risks of different schemes. Please refer to Section 3.5 Key Technical Issues and Risks for details on these discussions. The final proposed design is described in the following sections.

3.2.2 Parafoil packing and deployment

Typically parafoils are used in conjunction with objects that have a rather small aspect ratio. Examples include military supply pallets (typically cubic) and skydivers. In contrast, our rocket has a large aspect ratio as well as fins.

The team discussed two possible orientations for parafoil deployment: nose deployment (Figure 2) and hatch deployment out of the side of the rocket (Figure 3 and Figure 4).

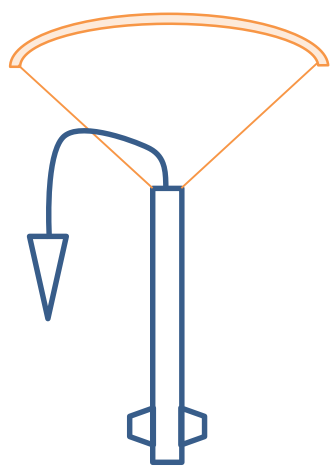


Figure 2: Nose Cone Deployment

For nose deployment, the parafoil would deploy out of the nose cone of the rocket, like a conventional parachute system. Nose deployment would offer the simplest design and would resemble recovery designs the team had built in the past. However, by deploying the parafoil from the nose, the backup system would need to be deployed from a hatch, as the control lines from the parafoil to the servos would prevent anything else from deploying from the nose. This was deemed unacceptable, because hatch deployment has not been sufficiently tested for backup purposes

Nose deployment would also result in the rocket hanging vertically under the parafoil. This orientation would offer a very low moment of inertia about the control lines, which would make the system harder to control and steer. Furthermore, the large fins on the bottom of the rocket could easily cause the rocket to spin in the wind. Twisting the rocket under the parafoil could make the system difficult to control and guide or tangle the control lines, resulting in failure of the system.

In light of the above reasons, the team chose to deploy the parafoil from a side hatch. Hatch deployment will allow the control lines to be centered over the center of gravity of the rocket and for the rocket to fly down in a horizontal orientation, with the axis of the rocket parallel to the horizon. This increases the moment of inertia about the control lines, leading to a system that is easier to control and has more stable dynamics. The hatch deployment also allows the parafoil to be deployed in a manner similar to that used by parachutists and jumpers, making available to the team a large body of relevant knowledge from parachutists. Furthermore, deploying the parafoil out of a hatch allows the team more flexibility in positioning the parafoil bay with respect to the location of the backup recovery system bay and avionics bay.

Figure 3: Side-first: Parafoil Oriented Parallel to the Axis of the Rocket

Figure 4: Nose-first: Parafoil Oriented Perpendicular to the Axis of the Rocket

The parafoil could be deployed out of the hatch such that the parafoil is parallel to the axis of the rocket (Figure 3) or such that the parafoil is perpendicular to the axis of the rocket (Figure 4). The side-first orientation was considered first, but since the rocket is highly asymmetrical in this orientation (in both aerodynamics and mass distribution), this orientation would be particularly difficult to steer. Therefore, we decided on the nose-first orientation (Figure 4), which is mostly symmetrical and has a large moment of inertia along the axis of the rocket.

It was also decided to pack the parafoil in a deployment bag. This will increase the consistency of packing the parafoil between test launches and the competition launch, decrease integration time, increase the reliability of the deployment system, and reduce the risk of the Parafoil snagging or burning during deployment.

3.2.3 Parafoil hatch

The side hatch will add design complications, which the team carefully considered before deciding on the hatch. Structurally, the hatch would weaken the tube that serves as the parafoil bay. To mitigate this, the team decided to add reinforcing plates to the inside of the tube, along the edges of the hatch. This both increases the structural integrity of the tube, and minimizes the risk of the parafoil snagging on the edge of the tube during deployment. The team also decided that retaining the hatch and keeping it secured to the body of the rocket was critical for safety and compliance reasons. Thus, the team decided to keep the hatch connected physically to the body of the rocket. The hatch will be constructed of fiberglass, like the rest of the body tubes, so it could pose a hazard if it were deployed and left to free fall. If the hatch remained connected to a parachute line, instead of the body of the rocket itself, it could create a risk of tangling, snagging or cutting the parachutes or parachute lines. Also, once the system was deployed, the hatch connected to the parachute lines would interfere with the dynamics of the system, and would likely have adverse effects on the inflation and performance of the parafoil. The team deliberated on several methods of retaining the hatch on the body of the rocket. As a result, it was quickly decided that the hatch would need to be connected via a hinge. This was the simplest and most sound method of attaching the hatch to the rocket. The team then discussed how to open the hatch. Proposed ideas included actuation with motors, pressurization of the bay via pyrotechnics or expanding gas, tension from the pilot chute line, or frangible bolts. The team discussed each idea and addressed the merits of each with respect to weight, volume, complexity, reliability, and familiarity with the team.

It was decided that the best design was to mount the hatch to the body of the rocket with a spring loaded hinge, set to hold the hatch open once deployed. The spring-loading will prevent the hatch from flapping unpredictably during recovery, thus reducing the risk of it snagging or cutting the parafoil and parafoil lines. The hatch will be held shut until the appropriate time by severable nylon bolts. The bolts will either be custom-created frangible bolts (Figure 5), severed by a pyrotechnically propelled cutting device, or with a Thermal Knife Driver (TKD). The custom frangible bolt technology has already been successfully tested in a variety of configurations, and will continue to be tested to improve the technology and ensure reliability. A custom TKD solution is being designed, and off-the-shelf solutions are also available. A careful design of the hatch and bolt assembly, in combination with packing the parafoil lines in a specific orientation, will minimize the loads placed on the hatch between the pilot chute deployment and the parafoil deployment.

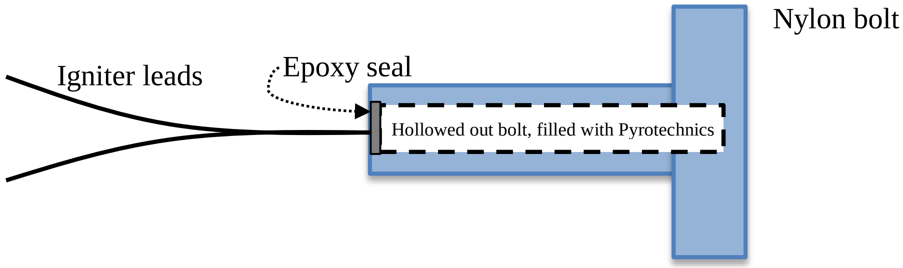


Figure 5: Frangible Bolt

3.2.4 Pilot Chute

The pilot chute is significantly smaller than any other chute on the rocket. This gave the team a large amount of flexibility in how to pack and deploy the pilot chute. Several ideas included deploying the pilot chute via piston (actuated with pyrotechnics, pneumatics, or expanding gas), pyrotechnic pressurization of the pilot chute bay, or mortar deployment. Again, the team discussed the complexity, weight, volume, reliability, and familiarity of each design, and decided to deploy the pilot chute via mortar (Figure 6). The team has a large body of information regarding mortar deployment, and mortar deployment offers a small weight and volume, with minimal complexity. The mortar system also features a small opening in the rocket, such that the hole does not require a special hatch or covering. A mortar system has already been successfully ground tested, and will continue to be ground tested to find the appropriate diameter mortar and amount of pyrotechnics to deploy the pilot chute reliably and safely.

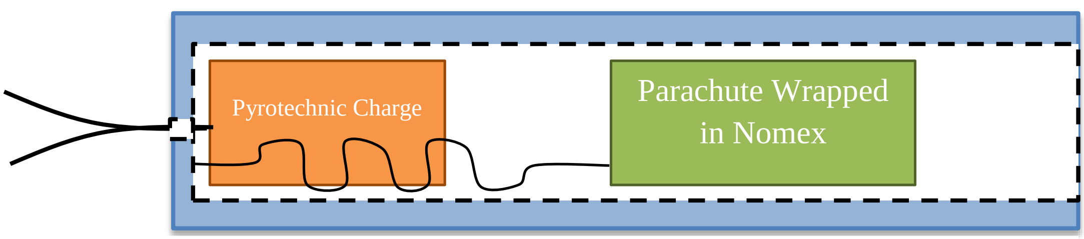


Figure 6: Pilot Chute Mortar Prototype

3.2.5 Parafoil Actuation

3.2.5.1 Prototyping

To better understand flight under a parafoil, the team constructed several iterations of remote-controlled parafoil gliders, each using servos with long lever arms to actuate the control lines. After testing a glider by dropping from 200ft from a quadcopter, it was determined that servos could indeed steer the flight of the parafoil, in terms of providing enough torque on the parafoil lines.

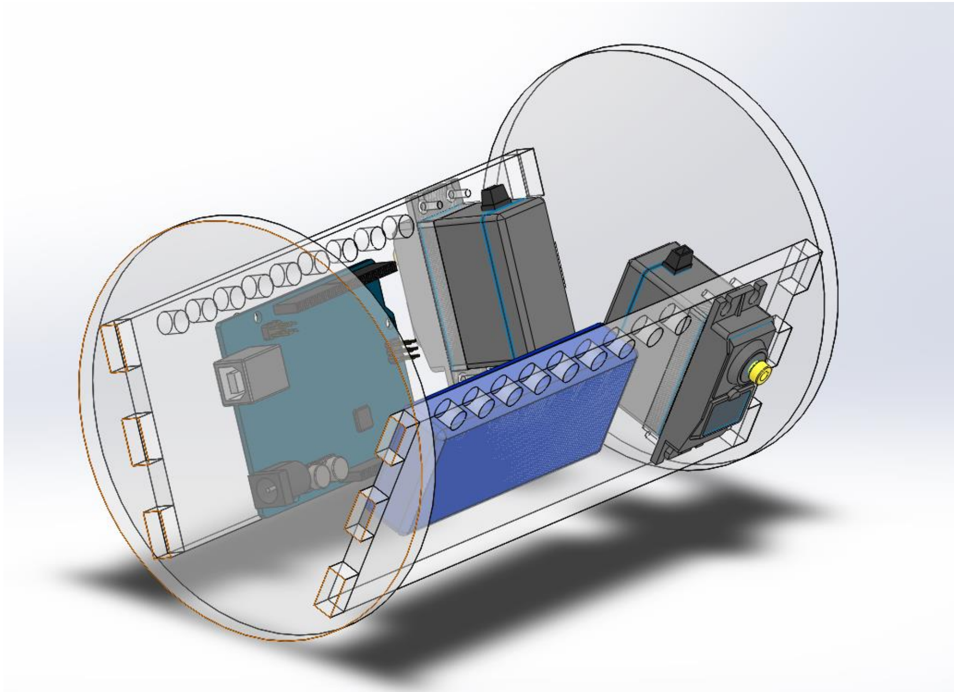


Figure 7: Model of Parafoil Actuation System, Version 3

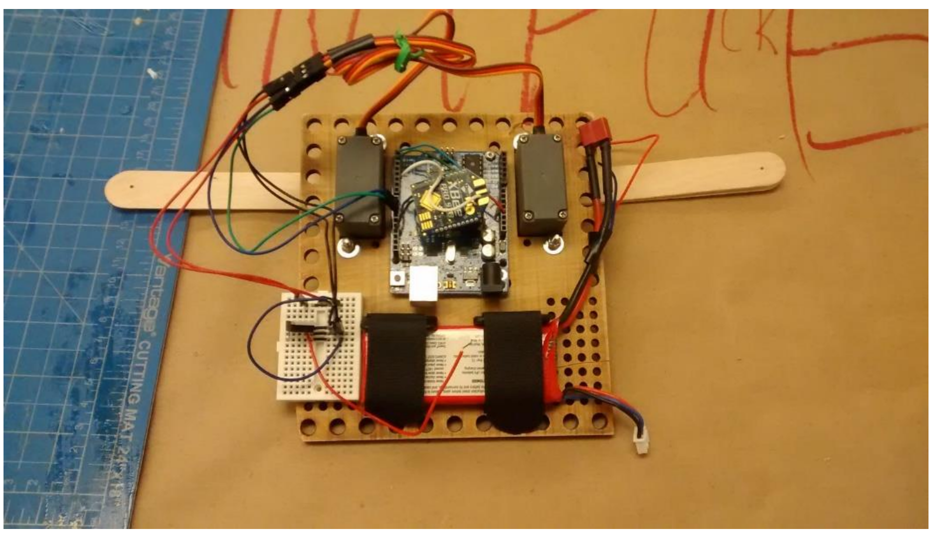


Figure 8: Parafoil Actuation System, Version 4

The team then considered several designs to actuate the final version of the parafoil. Because the rocket is space-constrained, the lever arms from the test gondolas would be impractically large. Therefore, two ideas were developed. The first is a linear leadscrew actuator (Figure 14), which would pull the line through a pulley and along a rail in order to actuate on the control lines. A leadscrew is advantageous because it is not backdrivable and unlikely to tangle. However, it is complex and limited by the length of the leadscrew. The second method is a winch (Figure 13), which would pull the line through a pulley and around a winch drum. A winch is advantageous because it has no inherent range limitations and is lighter, but it may tangle if not kept under constant tension.

3.2.5.2 Dynamics Analysis

The team created a preliminary parafoil dynamics simulation. However, it is currently untested and limited. In order to test and develop the model to the standards required for proper parafoil actuation, a Dynamics subgroup of the Payload and Recovery subteams and Avionics subteam will be formed. The group's model will be presented in depth at the Critical Design Review. Fortunately, similar projects have been done before by other rocketry groups, and information on the dynamics can be found in several professional papers.

3.3 Technical Design and Analysis

3.3.1 Parafoil Deployment System

The parafoil system consists of two components: a pilot chute and an actuated parafoil. The pilot chute will be 24in in diameter and deploy first, from a mortar on the side of the rocket. The rocket will fall under the pilot chute from apogee at 10,000ft to 5,000ft, when the parafoil will deploy. The parafoil will have weight on the order of 6lbs, and a packing volume on the order of 650in^3. In a 6in diameter rocket, accounting for margin and unusable space due to the structural supports, the parafoil bay will be approximately 33in long.

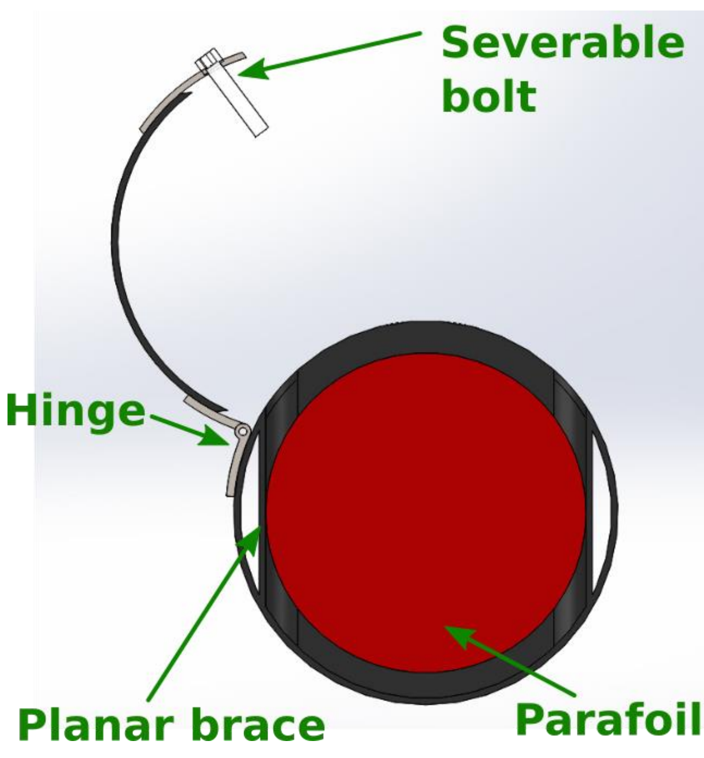


Figure 9: End View of Parafoil Bay

The parafoil (shown in red in Figure 9) will be packed in a deployment bag in the main tube. A hinged hatch will contain the parafoil on one side. Because cutting a large hole will reduce the strength of the main tube, planar braces will be installed on either side of the hatch, with suitable attachment. The braces will likely be constructed out of aluminum, carbon fiber, or fiber glass. The hatch is restrained on one side by hinges, and on the other side by nylon bolts. The nylon bolts will be severable, either by detonating pyrotechnics packed in a central bore (such as the frangible bolt in Figure 5), or by cutting the bolt with a pyrotechnically propelled cutter (Figure 10) or TKD (Figure 11).

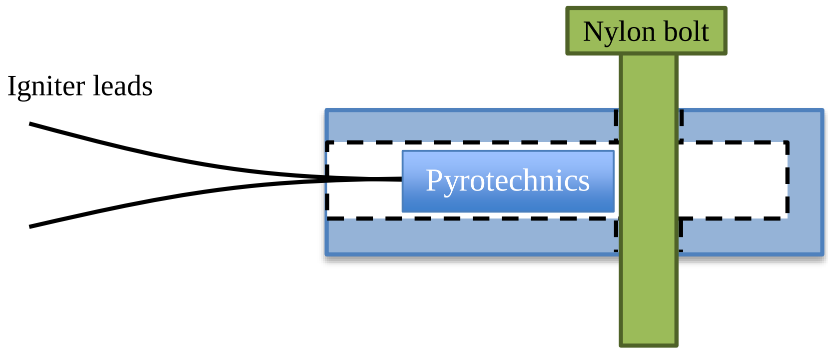


Figure 10: Pyrotechnically Propelled Bolt Cutter

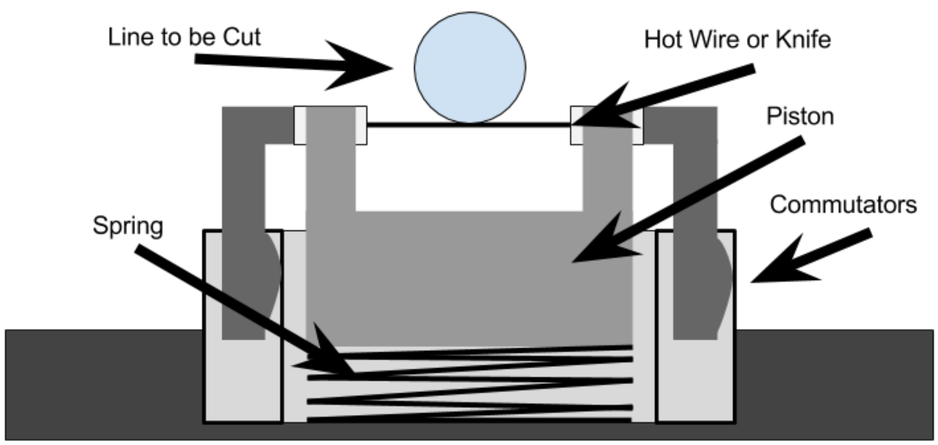


Figure 11: Thermal Knife Driver

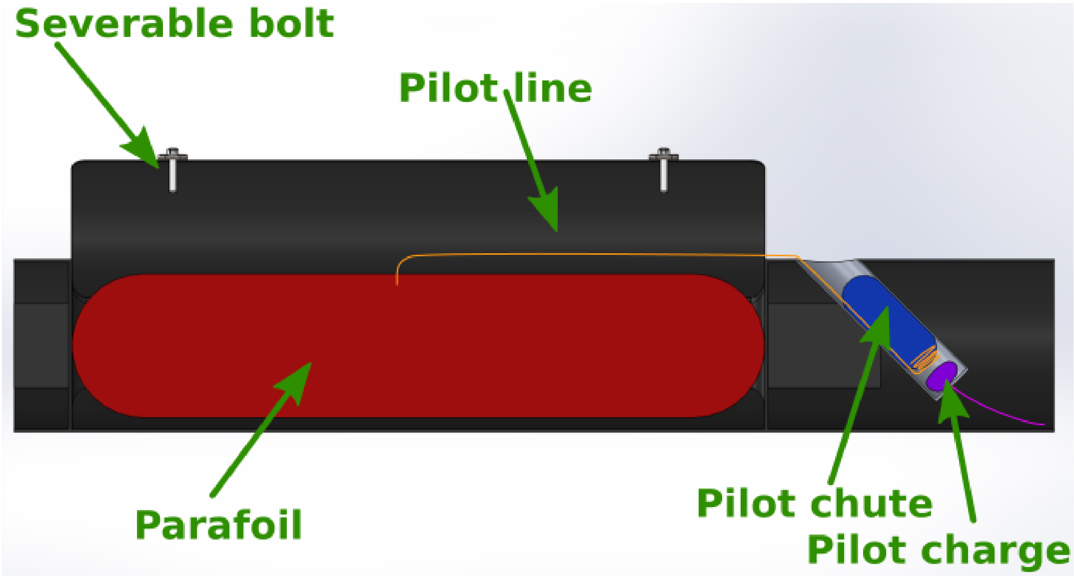


Figure 12: Cross Section of Parafoil Bay

The pilot chute will be packed into an approximately 1.5in diameter mortar tube below the parafoil, at approximately a 45˚ angle with respect to the main tube, and capped rigidly at one end. A pyrotechnic charge (initiated by an electric match) will be packed under the pilot chute, and the pilot chute will be wrapped in flame-retardant Nomex cloth. The other end of the mortar tube will open through a hole in the main tube to the free stream, and will be covered by aluminum foil or tape to minimize adverse aerodynamics. The pilot chute line will initially be coiled in the flame-retardant cloth, run along the exterior of the rocket tube, thread next to the hatch on the severable bolt side, and finally be attached to the parafoil.

When the avionics system activates the pilot chute, the charge will detonate, propelling the pilot chute out of the mortar and breaking the disposable covering. The pilot chute will inflate, and pull upwards on the parafoil, which is restrained by the hatch. When the avionics system activates the severable bolts at 5,000ft AGL, the hatch will be released on one side and will rotate to open, but will remain attached to the rocket. The parafoil will be pulled out by the drag force from the pilot chute, and inflate in the freestream.

3.3.2 Location and Tracking System

The rocket will employ a real-time tracking system in order to record the entire flight, from launch and ascent to deployment and execution of recovery events. This will allow the team to plot the rocket's path and identify its final position, thus simplifying recovery operations. It will also allow for another method of data recovery in the case of loss of rocket.

The tracking system will consist of several methods of tracking: data-based, visual, and auditory. On-board electronics will gather relevant GPS (Global Positioning System) tracking data while maintaining communication with a ground station. A radio beacon will provide another method of tracking the rocket. The rocket will also use colored smoke in order to visually identify events, including engine ignition, pilot deployment, parafoil deployment, and backup recovery system deployment. Should an anomaly occur after lift-off, this system will aid in determining probable system failures, around which a contingency recovery plan may be outlined on the launch site. Finally, the rocket will be equipped with “screamers,” small devices that emit a loud buzz when the recovery system is deployed. The screamers will provide an auditory means of finding the rocket during ground recovery operations.

3.4 Parafoil Actuation System

The parafoil control lines will be actuated with either a winch mechanism or a leadscrew mechanism.

The winch mechanism (Figure 13) would be highly constrained to avoid tangling and bear the load of the control lines. Specifically, the drum itself will be encircled by a tight-fitting housing, preventing the control line from unspooling. The motors would be COTS gear-motors, with optical encoder feedback.

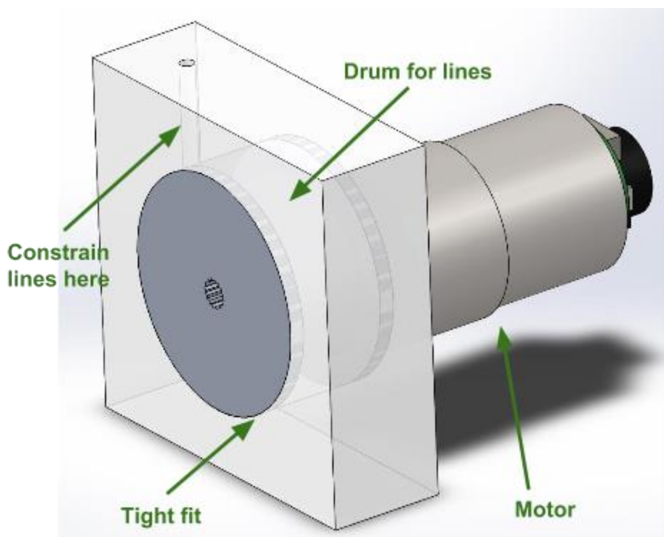


Figure 13: Winch Mechanism

The leadscrew mechanism (Figure 14) would use a rotating leadscrew and a moving sled attached to the control line. The motors would be commercial off-the-shelf gear-motors, with optical encoder feedback.

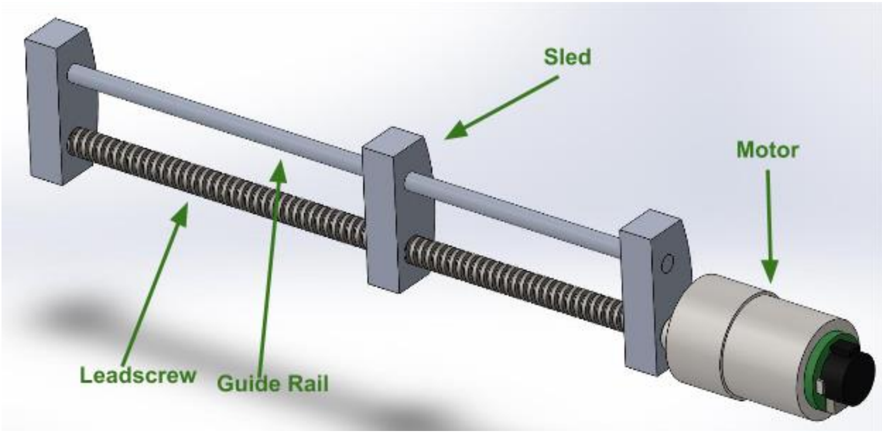


Figure 14: Leadscrew Mechanism

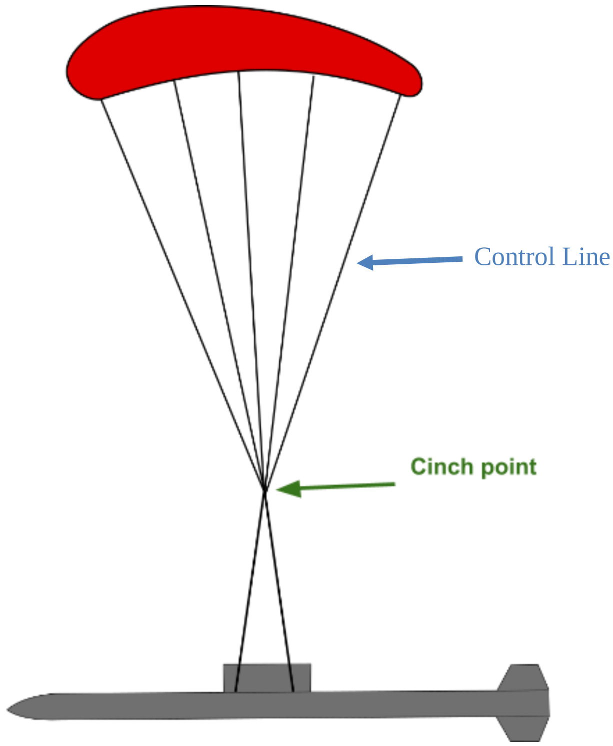


Figure 15: Control Line Routing Diagram

For either mechanism employed, the team needs to ensure sure that the actuation strategy pulls the trailing edge of the parafoil rather than rotating the rocket. To mitigate this risk, the control lines will be routed through a cinch point in the shroud lines, below which the rocket will be stably suspended (Figure 15). Therefore, the tension in the control lines will not produce a torque because the control lines pass through a common point. Additionally, the suspended weight of the rocket will create a restoring force for any pitch of the rocket.

3.4.1 Backup Recovery System

To comply with IREC and internal rules, the rocket will be equipped with a single-separation dual-deployment backup recovery system in the event of a parafoil anomaly. The backup system will consist of a 30in diameter drogue chute and a 10ft diameter main chute, packed into a single bay directly below the nose cone (

Figure 16). The main parachute will be stored in a deployment bag to increase the reliability of deployment and reduce the risk of tangling and snagging during deployment. The main will be prevented from deploying prematurely by a Tender Descender™. The backup chute is sized to provide a descent rate of about 25ft/s. This deployment scheme was selected due to its simplicity and reliability. The single-separation dual-deployment scheme was also used to recover the payload in the 2015 IREC competition, meaning that the Team is familiar with the system and how to effectively implement it.

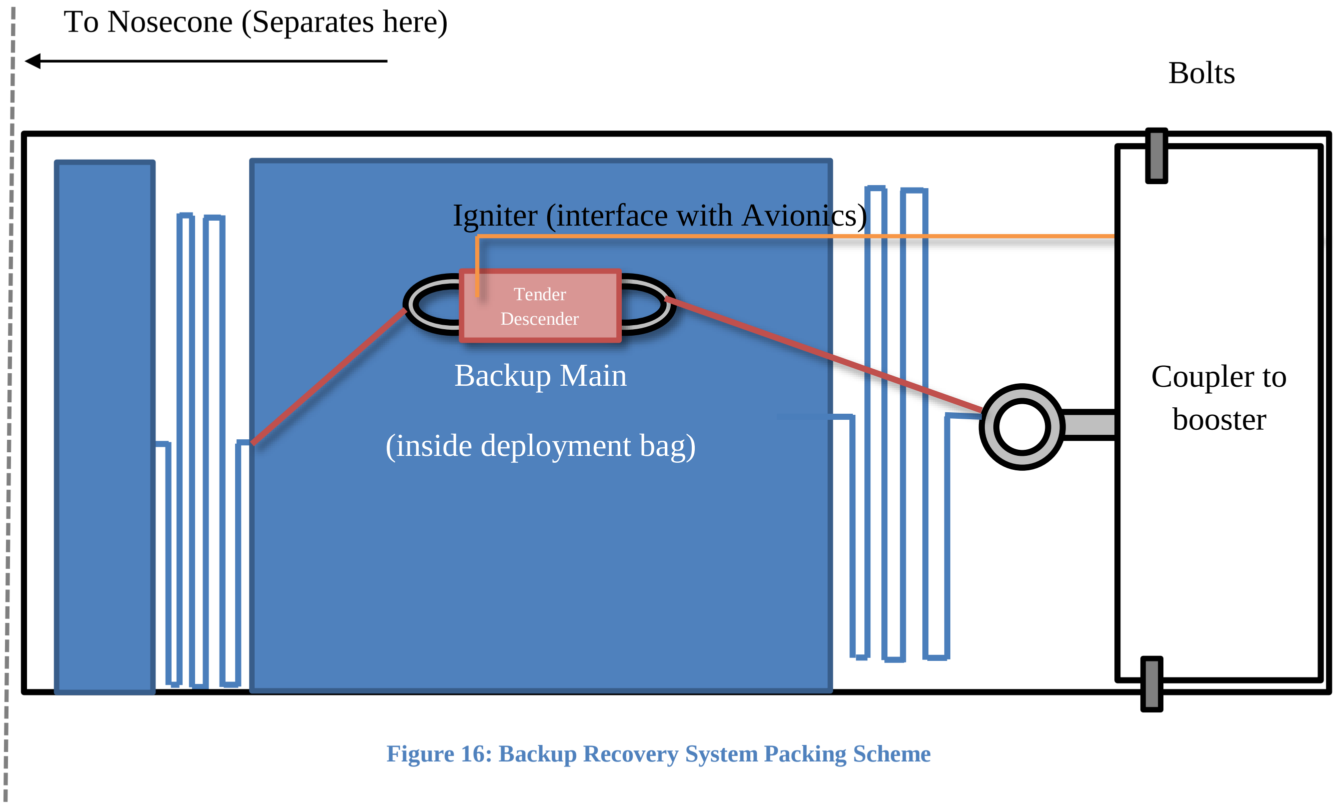


Figure 16: Backup Recovery System Packing Scheme

Bay Diameter: 6in
Bay Length: 12in
Backup Main packing volume: 140in^3 (5in packing length in 6in diameter tube)
Drogue packing volume: 20in^3 (1in packing length in a 6in tube)

The bottom of the bay will be sealed with a coupler topped by a solid bulkhead, including an eyebolt. The backup main will be folded and wrapped, then packed in a deployment bag. The lines from the backup main will be connected directly to the eyebolt with a quick link. The top of the deployment bag will connect to the lines from the drogue parachute. There will also be a Tender Descender™ system connecting the top of the deployment bag to the eyebolt at the bottom of the bay.

In the event of an anomaly, the parafoil will be cut free from the rocket using a simple TDK device to simplify the dynamics acting on the rocket. The parafoil, under no tension, will drift slowly and safely to the ground. Then, a pyrotechnic charge will separate the nosecone from the rest of the rocket, and eject the drogue parachute. The rocket will fall under the drogue parachute until 1,500ft above ground level (AGL). Until this altitude is reached, the Tender Descender will hold the deployment bag and main parachute in the tube, and prevent the main parachute from deploying. At 1,500ft AGL, the Tender Descender™ will separate and release the main parachute, which will be pulled into the free stream by the drag force from the drogue parachute. Then, the rocket will descend at approximately 20ft/s and be recovered.

3.4.2 Concept of Operations

Figure 17 details the Concept of Operations (CONOPS) of the mission:

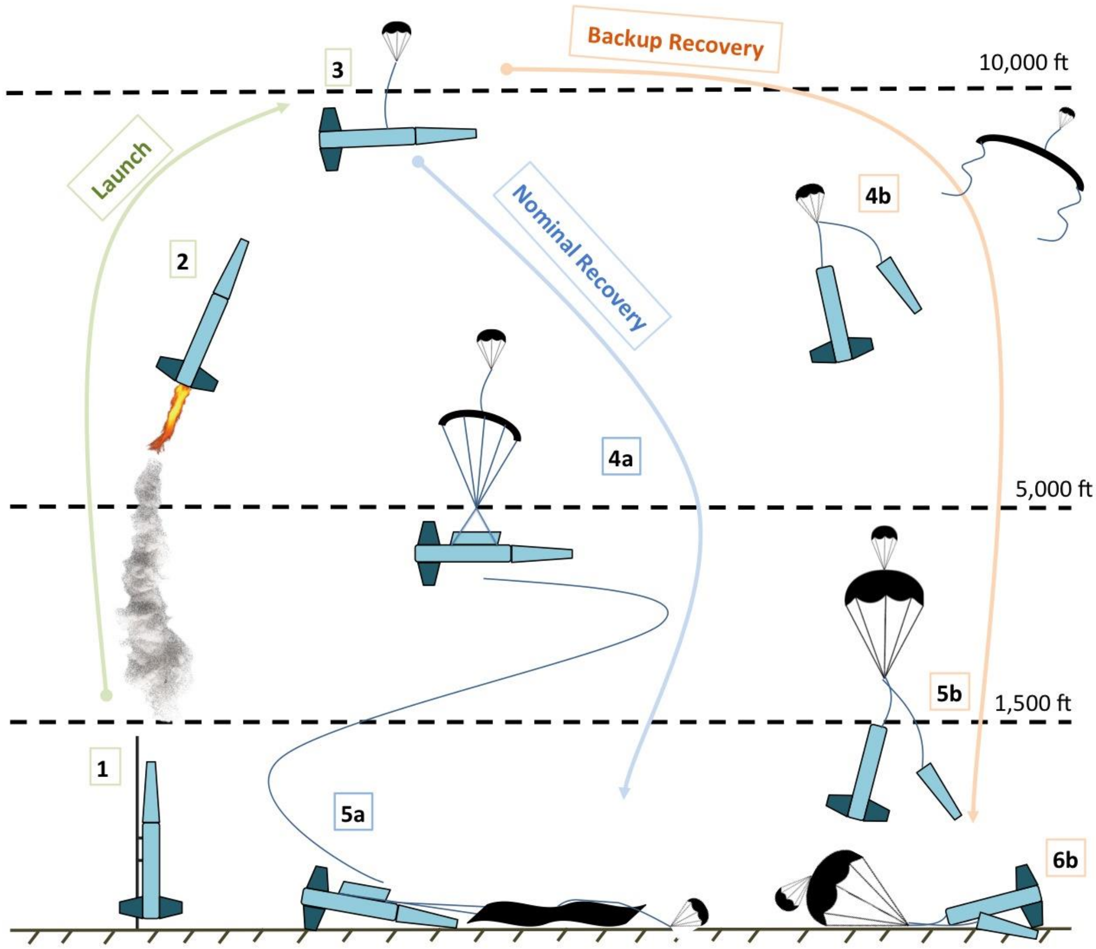


Figure 17: Concept of Operations (CONOPS)

Launch:

1. Pre-launch and Launch: GPS and radio systems live and locked.
2. Ascent: GPS transmit live location data using radio beacon aboard avionics bay.
3. Apogee: Pilot chute is deployed.

Nominal Recovery:

4a. Parafoil Deployment: Parafoil deploys at 5,000ft AGL, screamers sound, GPS transmits location data to plot rocket descent path.

5a. Landing: Rocket is recovered using the final location.

Backup Recovery:

4b. Initiation of Backup Recovery: Pilot chute and parafoil jettisoned, drogue chute deployed.

5b. Main Deployment: Main parachute deploys at 1,500ft AGL, screamers sound, GPS transmits location data.
6b. Landing: Rocket is recovered using the final location.

3.5 Key Technical Issues and Risk

To evaluate the proposed design and ensure that potential risks will be mitigated, team members identified and analyzed possible failure modes and solutions to each. Please refer to Figure 18 for an overview of the key technical issues and risks.

<u>Tender Descender Failure (1)</u>
One risk includes a failure of the Tender Descender™ system used in the backup recovery system - it could fail to separate properly, or be integrated incorrectly into the rocket. This would lead to the backup main parachute not deploying, or deploying too early. Should the backup main not deploy, the rocket would fall too fast and impact the ground, causing catastrophic loss of the rocket and potentially a safety risk. If the main were to deploy too soon, then the rocket would fall at a safe rate of descent, but would drift much farther than planned, perhaps beyond a recoverable distance. If the Tender Descender™ is not integrated into the rocket correctly, then the entire backup recovery system could separate from the rocket, leading to the rocket falling ballistically without a parachute.

This risk will be mitigated with careful use of the Tender Descender™ system, and practice integrating the rocket. This will reduce the risk of incorrectly integrating or implementing the Tender Descender™ system. The team used a Tender Descender™ in the payload recovery system for the 2015 IREC competition, thus, the team is familiar with the Tender Descender™ and how to properly implement it.

<u>Pilot Deployment Failure (2)</u>
The pilot chute line outside the rocket could detach during ascent, which could increase drag and might affect stability. This risk can be mitigated by keeping it short, under tension and temporarily adhered to the main tube with tape or a similar method.

The mortar could burn holes in the pilot chute, which would reduce its effectiveness. This can be mitigated by carefully packing the pilot chute in flame-retardant Nomex cloth, a common method of protecting parachutes during deployment.

The pilot chute could detach if its line fails, which could happen if it tears the parafoil or the line breaks. Both of these risks can be mitigated by spreading the impulse over a longer time with elastics, and by providing stress relief for the line.

<u>Hatch Failure (3)</u>
The structural bracing could fail, which would cause the main tube to catastrophically buckle near the hatch. This can be avoided by carefully designing and reinforcing the seams, as well as by keeping the hatch as close-fitting as possible so it transmits some load. This will be covered in more depth by the Structures subteam, in section 6.3.3 .

The hatch could be poorly attached, and detach during ascent or during deployment. Detachment during ascent can be avoided by ensuring a tight fit. Detachment during deployment can be prevented by using strong and potentially custom-made hinges. (i.e. steel rather than the typical brass hinges). In particular, the hatch could detach and sever recovery lines. This can be mitigated by smoothing the edges of the hatch.

Hatch opening could fail by either opening too early, or by not opening. It might open because the pilot chute overloads the hatch or nylon bolts. This risk can be determined through testing, and if necessary, be mitigated with a load-relieving Tender Descender ™ or stress-relief feature. It might not open because the bolts fail to sever, or the hinges stick. This can be tested by characterizing the bolts, and if necessary adding redundancies. Sticky hinges can be mitigated by lubrication.

Parafoil Deployment Failure (4)

Side deployment of the parafoil through the hatch could be unreliable. Potential risks include the parafoil catching on the hatch or snagging on the edge of the tube. These risks can be mitigated by sanding and waxing the braces, and by hinging the hatch away from the edge. Also, the planar braces will make the inside of the parafoil bay the same size and shape as the hatch, further reducing the risk of the parafoil snagging or tearing during deployment.

The parafoil lines could tangle while being deployed. This could result in incomplete parafoil inflation (serious), or loss of steering control (minor). By carefully folding the lines and testing the effectiveness of deployment in that scheme, the risk of tangling can be mitigated, but not eliminated. For this reason, the backup parachute provides a safety feature in case of catastrophic tangling.

There is also the risk that recovery loads break the parafoil lines, resulting in the parafoil not actuating properly, or the parafoil completely separating from the rocket. This risk is mitigated by careful sizing of the pilot chute and parafoil, as well as design of the primary recovery system. When the parafoil deploys, it will experience a shock loading as it suddenly supports the weight of the entire rocket. The parafoil will be sized to support this weight and maintain an acceptable descent rate, without providing an excessive drag force, thus shock load, when the parafoil deploys. To further reduce this risk, the parafoil lines will be sewn in parallel with strong elastic cord. The elastic cord will spread the impulse over a longer time, preventing breakage.

Custom Flight Computer Failure (5)

The onboard flight computer is designed to recognize a failure of the parafoil system - either the parafoil is guiding the rocket to the wrong location, the rocket has drifted too far and cannot be guided back, or the parafoil has not deployed properly. In the event of one of these anomalies, the flight computer triggers a switch to the backup recovery system. However, the flight computer may not trigger the backup recovery system at the appropriate time. Since the parafoil is cut off in the event of an anomaly, this would result in the rocket falling ballistically without a parachute.

This risk will be mitigated by rigorous testing of the custom flight computer, as well as the integration of a backup commercial off the shelf (COTS) flight computer. The custom computer will be tested to ensure that it reliably detects parafoil failure modes and subsequently deploys the backup recovery system. Then, the redundant COTS computer will provide an added measure of safety.

Improper Parafoil Inflation (6)

Another risk is that the parafoil will not inflate properly when deployed. This could be caused by the parafoil deploying at an unusual attitude, or unforeseen dynamics impacting how the parafoil behaves soon after deployment. Should the parafoil not properly inflate, the rocket would fall ballistically, possibly tangling the parafoil and pilot chute, and experience severe structural damage upon landing.

This risk will be mitigated through both ground and flight tests of the recovery system. Repeated tests will allow us to characterize the system and more concretely understand what would cause the parafoil to not inflate. Testing will also enable the team to modify and improve the recovery deployment scheme to increase the reliability of the system. The backup recovery system is the strongest failsafe against a ballistic descent: in the event of a parafoil failure, the flight computer will trigger deployment of the backup recovery system. While the rocket will not be recovered at the precise location, it will be recovered safely and intact via the backup recovery system.

Rapid Change in Center of Gravity (7)

Rapid change of the center of gravity (CG) after apogee is a possible risk. This could be caused by parts falling off of the rocket due to high G-loads, shock loads from recovery, or shear pins falling out. The change in CG could lead to the pilot chute or parafoil deploying incorrectly, or being unable to actuate properly and guide the rocket to the precise landing location. If the CG rapidly changes during descent under the parafoil, the rocket could begin to swing or rotate, creating unexpected dynamics that could lead the primary recovery system to fail.

This risk will be mitigated through comprehensive analysis and testing of the rocket's design. By designing, engineering, and constructing the rocket with appropriate safety margins, the risk of the rocket fracturing or pieces falling off of the rocket will be significantly reduced. The rocket will also undergo repeated ground and flight tests, which will highlight areas of the rocket that need to be improved and strengthened. Finally, the backup recovery system will continue to serve as a failsafe. In the event that a CG anomaly occurs, the backup recovery system is oriented in such a way that CG imbalances along the length of the rocket will not have a substantial negative impact on the performance of the backup recovery system.

Interfacing Failures (8)

Due to the highly integrated nature of this project, there is also risk from interfaces with other subteams, especially payload, avionics, and structures. Payload introduces the risk that the parafoil will not actuate correctly to guide the rocket to the designated landing area. In the case of avionics, the custom flight computer may not work - it may not properly provide navigational information to the payload, or the computer may not trigger deployment of the recovery system at the correct time. There is also the risk that the redundant COTS flight computer may not operate correctly, failing either positively or negatively. Finally, in the case of structures, the rocket material may not be made strong enough to withstand the loads from the recovery system, leading to the tubes breaking or zippering.

These risks can be mitigated with collaboration and communication between the various subteams. Interfacing between the subteams will ensure that each subteam is aware of the others' requirements. Payload and Avionics will work together to ensure that the parafoil actuators have the proper information to guide the rocket to the landing location. In the event that the rocket cannot be guided to the landing location, the backup recovery system will act as a failsafe to land the rocket as soon and as safely as possible. The Recovery and Avionics subteams will work together to develop and test the custom flight computer. The computer will be tested both on level I rockets and with the rest of the competition rocket system to ensure reliability and proper performance. Not to mention, the COTS computer will provide an additional level of safety in the event of an anomaly with the custom computer. Finally, Recovery will work together with Structures to ensure that the rocket tubes will withstand the recovery loads. This will involve Recovery communicating the expected loads to Structures, and Structures working with Recovery to test the tubes in ground and flight tests.

<u>Controls Failures (9)</u>

There are several factors that affect controllability of the parafoil recovery system. The three major factors that have been identified are rocket orientation relative to the parafoil, control line connections, and parafoil selection. The system also needs enough forward velocity to be able to travel against light winds, reach the target location, and so that control inputs actually yield desired responses (as the parafoil acts like a wing). It is critical that the parafoil we choose is passively stable so the controls are greatly simplified. It is critical that the line connections prevent excessive twisting of the rocket relative to the parafoil, and that the connections are at optimal locations on the parafoil so that it can be controlled. If the orientation of the rocket relative to the parafoil is not carefully chosen, it could also lead to controllability issues. From the gondola experimentation four dangerous modes were identified:

1. Spiral mode: The entire system spins around a vertical axis. There may be no method of exiting this mode. It can be induced by a strong wind gust, or excessive control input. It was directly observed in Gondola V3.
2. Twist mode: The rocket rotates relative to the parafoil causing the lines to twist. The twist adds a moment much like a torsional spring and the rocket oscillates around a vertical access.
3. Sway mode: The entire system starts to sway about the axis in the direction of motion. This could be induced by the control system.
4. Swing mode: The entire system oscillates around the axis perpendicular to the direction of motion. It was directly observed in Gondola V3. This mode prevents forward motion which is critical for controllability.

These modes must either be avoided or methods to exit these modes must be identified to achieve controllability.

Another risk is that the parafoil stalls. This is not a well-understood risk at this time; it requires accurately coordinate shroud line lengths to produce a safe angle of attack, but parafoil lift as a function of angle of attack is not known. Therefore, testing is necessary to determine the angle of attack needed, and a somewhat conservative angle of attack should be chosen. If the parachute does stall, and cannot recover, the backup parachute can be deployed.

Actuator Failure (10)

The actuators are critical to the guidance of the parafoil, and failure is a possibility. Possible failures include tangling of control lines, motor stall or failure, electrical disconnection, jamming or encoder failure. Most of these failures simply result in the loss of control of the control line in question, so backup deployment can eliminate any safety or property loss risks. Encoder failure is more serious; software should be able to detect it, but the worst case could result in parafoil collapse (due to overly retracting a control line). In this case, backup deployment is more critical to recover the rocket.

Competition Rules Risk (11)

ESRA has ruled that recovery devices do not count towards payload mass, and therefore we are not certain how much of the parafoil system will count as payload mass. Our current theory is that the actuators but not deployment devices will count for payload mass, but we are awaiting a decision from ESRA. If ESRA rules that actuators are not part of payload mass, we may need to add mass to our payload.

In the event that the Team needs to add payload mass, a sensor suite was devised. The sensor suite will consist of a COTS camera, batteries and an embedded computer with image processing software. The camera will acquire images of the ground, and the software will record said images of the ground, and possibly synthesize the images with GPS or IMU data. The hardware component of this sensor suite has minimal complexity, but the software component has the potential to be quite complex. Therefore, the team has planned ahead for software complexity by building in margin to descope. In the event the team needed to descope, the payload would simply collect images without synthesizing them with GPS or IMU data.

Finding an Adequate Parafoil (12)

Steerable parafoils are commercially available for skydivers, paragliders and kite surfers. However, only skydiving parafoils are able to inflate reliably in freefall. Unfortunately our rocket has a maximum dry mass of 50lbs, which is too light for commercial skydiving parafoils. Additionally, we need to use a parafoil that is relatively docile (stable despite potentially poor control), because our rocket will not have the finesse of a seasoned skydiver. We have considered using a parafoil that is simply too big for our mass, but this risks not creating sufficient tension to hold the shape in the parafoil.

We considered increasing the weight of the rocket to a person's weight (~110lbs minimum), but this would require a large increase in the impulse of the motor, which would make safety, handling and cost more challenging. Therefore, we need a custom-sized parafoil for our purpose. Several vendors of parafoils are being contacted. Since our parafoil would need to be custom made, the vendors so far have quoted unacceptable lead times (14-22 weeks). We are currently asking for shorter lead times, but this is unlikely to work out.

A final option is to make a custom design for a parafoil or scale down an existing design, and then either self-manufacturing or outsourcing the design to a local shop. This is difficult because it involves a deep knowledge of parachute design, which we would need to acquire quickly. It is also difficult to find a local shop willing to make a parachute (given liability concerns, etc.).

Risk	5 (high risk)				9	
	4		8,11	5	3,6	12
	3			10	2,4	1
	2			7		
	1 (low risk)					
		1 (low impact)	2	3	4	5 (high impact)
Impact (with Respect to Loss of Rocket)						

Figure 18: Payload & Recovery Risk Matrix

Each risk discussed above is placed in Figure 18 based on the likelihood of the risk occurring from 1 (low likelihood) to 5 (high likelihood) and the impact that the risk would have on the mission from 1 (low impact) to 5 (high impact). The impact was viewed in terms of loss of rocket. Thus, while a failure of the parafoil may result in a loss of mission, the backup recovery system provides an adequate failsafe such that the rocket is still safely recoverable.

Risk	5 (high risk)					
	4			9	12	
	3	11	8, 10	3, 5, 6		
	2			2, 4		1
	1 (low risk)		7			
		1 (low impact)	2	3	4	5 (high impact)
Impact (with Respect to Loss of Rocket)						

Figure 19: Payload & Recovery Mitigated Risk Matrix

3.6 Interfaces

The Recovery and Payload subteams will interface with each other and the Avionics, Structures, and Propulsion subteams. Ultimately, Recovery is responsible for packing and deploying the pilot chute, parafoil, and backup recovery system. Payload is responsible for actuating and controlling the parafoil once deployed. Avionics is responsible for data collection and transmission regarding the flight, flight computers, and providing the information necessary to guide the rocket to the appropriate landing location.

3.6.1 Recovery and Avionics

All electronic recovery components will be housed in the Avionics bay. This will include one custom flight computer, and one COTS altimeter, such as a Stratologger or Marsa. The altimeters will trigger ejection of the pilot chute and the parafoil at the proper altitudes, as well as the backup recovery system as required.

Avionics will be responsible for mounting all flight computers and creating a physical interface through which signals will be routed from the Avionics bay to the parafoil and pilot chute bay, and the backup recovery bay. The interface will likely take the form of a bulkhead with plug-and-play electrical interfaces. For each cable or wire running data out from the Avionics section, there will be a matching cable running data into Recovery bays. These cables will meet and connect at the interface bulkhead. Avionics will be responsible for wiring the Avionics side of the interface, and Recovery will be responsible for wiring the cables from the interface to the appropriate points in the Recovery bays.

Avionics will be responsible for programming the flight computers to initiate each event at the proper time during descent. Recovery will be responsible for determining the proper event initiation heights of the system and relaying this information to the Avionics team.

The rocket will use a custom flight computer to send and receive telemetry data using XBees. In the case of a lost rocket, the Recovery team will use recorded telemetry data to find the last known location of the rocket. Avionics will be responsible for all hardware and software required for transmitting, receiving, and collecting telemetry data. This data will be used by the Payload team to control the parafoil and guide the rocket to the landing location.

3.6.2 Recovery and Payload

The Payload and Recovery subteams are closely related, and have been working well together to develop the parafoil system. The subteams meet at the same time to ensure proper relaying of information between the two groups, and collaborate ideas about packing, deployment, and control. Collectively, the groups work to ensure the proper deployment and actuation of the parafoil.

Because Recovery and Payload are working on the same subsystem, there is no clear interface between the systems. Rather, a division in functionality was made between the two subteams. Recovery is responsible for the proper packing and deployment of the parafoil system. It will design and manufacture all deployment hardware for the pilot parachute and parafoil. Payload is responsible for the actuation of the parafoil once deployed. The Payload subteam will design and build the mechanical actuation system required properly guide the parafoil to a predetermined landing site. All equipment relevant to these tasks will be housed in the parafoil bay.

3.6.3 Recovery and Structures

In order to properly deploy the parafoil, recovery will employ a hatch mechanism, as described above in Section 3.3. The Structures subteam will collaborate with the Recovery subteam to ensure that the hatch maintains structural integrity throughout the flight and recovery operations. The Recovery subteam will be ultimately be responsible for detailing the hatch design, providing requirements and specifications to the Structures subteam, prototyping, and testing the hatch design. Prior to manufacturing the hatch, the Structures subteam will vet and approve the design. The Structures subteam will also be responsible for the physical manufacturing of the hatch.
In order to meet the structural size requirements of the rocket, the recovery system will maintain a specified packing volume. The Recovery subteam will propose a packing volume to the Structures subteam based on the size of the parachutes, cords, and deployment devices. The Structures subteam will approve this volume budget, and then the Recovery subteam will keep the recovery system within the budget.

3.6.4 Recovery and Propulsion

In order to ensure that the rocket has enough propulsive power to reach 10,000ft, Recovery will maintain a specific mass budget. The budget will be determined by Propulsion and maintained by Recovery.

3.6.5 Payload and Propulsion

In order to ensure that the rocket has enough propulsive power to reach 10,000ft, Payload will maintain a specific mass budget. The budget will be determined by Propulsion and maintained by Payload.

3.6.6 Interfaces Summary

This chart summarizes the interfaces between the Payload and Recovery subteams and the other subteams.

Table 6: Payload & Recovery Interfaces with Other Subteams

Output	Source	Recipient	Description
Event Initiation Times	Recovery	Avionics	Recovery will provide Avionics with the appropriate initiation times so that Avionics can program the flight computers accordingly.
Event Initiation	Avionics	Recovery	Avionics flight computers will trigger initiation events at the appropriate time during the rocket's descent.
Telemetry Data	Avionics	Payload	Real-time telemetry data must be available throughout the flight to enable tracking of the rocket, and guidance and navigation.
Proper parafoil actuation	Payload	Recovery	Once parachutes are deployed by recovery, payload must actuate parafoil to ensure proper guidance of the system.
Proper parafoil deployment	Recovery	Payload	The parafoil must deploy and inflate properly to allow for proper parafoil guidance.
Specific Mass Budget	Recovery, Payload	Propulsion	Specific mass budget must be maintained to ensure proper propulsive power.
Specific Volume	Recovery, Payload	Structures	Specific packing volume must be maintained by recovery to ensure the recovery system will fit in the rocket. Specific volume must be maintained by payload to ensure the payload system will fit in the rocket.

3.7 Going Forward Plan

Based on the design analysis, the Payload and Recovery subteams have several goals moving forward. The teams have already worked with the Avionics subteam to build and test several gondola prototypes. This is providing the teams with both qualitative and quantitative data about the parafoil, how it behaves in free fall, and effective methods for actuating the parafoil. During January, payload will build a 5th iteration of gondola, with a final design for actuators and resembling as much as possible the final payload configuration. This gondola will be also be tested by dropping from a quadcopter. In spring, payload will build a final gondola prototype, also resembling the final configuration and incorporating the sensor suite. Payload will test this final gondola prototype with a quadcopter.

The Recovery team individually has been developing several prototypes to enable the proposed recovery design, including custom-made frangible bolts and a mortar to deploy the pilot chute. These devices have already been ground tested, and have proven effective. Based on the results of the tests, the devices and the testing strategies will be modified to improve the devices and increase their reliability. Further testing will occur during January and the spring semester.

The Recovery subteam has also done a small study into ejection charge packing techniques. Several charges were prepared, some packed well to act as a control group, others intentionally packed poorly to test the effect of poor packing on charge performance. The charges were activated from a distance using long igniters and a battery, and the results were filmed with a high-speed camera. These tests gave the team qualitative insight into the performance of charges. In the future, the team plans to test charges prepared in centrifuge containers. Using these containers will increase the reliability of charges by simplifying the packing process and increasing the repeatability of making charges.

In January, the Recovery subteam plans to continue ground testing various components of the recovery system, including the backup recovery system, pilot chute mortar, frangible bolts, parafoil hatch deployment, and parafoil deployment. The team will also conduct drop tests of the parafoil and guidance system by dropping the parafoil (pre-deployed) from a quadcopter. The parafoil deployment will be tested with the pilot chute line under tension, with the pilot chute hanging from a tall support. This test will act as an effective precursor to flight testing the parafoil deployment system.

In January, payload will determine the sensor suite and its purpose. Payload will create a plan for the sensor suite, and prototype the sensor suite.

In the Spring Semester, the Recovery subteam will begin flight testing the parafoil recovery system and the backup recovery system. Since the team flew a design similar to the backup recovery system last year, most testing focus will be placed on testing the pilot chute and parafoil system. These systems will first be tested in a smaller scale with level I rockets. Then, once the system has been characterized and demonstrated with some reliability, they will be tested in full-scale.

At the end of the spring semester, the team will begin the final construction and build of our competition rocket and perform full launch tests of the flight hardware. The team will practice integration several times to ensure familiarity with the system and provide seamless integration at the competition.

In June, the team will travel to IREC and successfully complete the competition by integrating, launching, and safely recovering our rocket via an autonomous actuated parafoil.

4. Avionics

4.1 Overview of Requirements

Table 7: Avionics Requirements

Internal Requirement	IREC Requirement	Description
4.1	4.3	Electrical wiring critical to safe operation and recovery of the launch vehicle should conform to the safety-critical wiring guidelines found on the ESRA website and in the requirements under 7.x. All non-safety-critical wiring is exempted.
4.2	4.5	Launch vehicles entered into the IREC Basic Category shall carry an altitude logging COTS flight computer with on-board data storage which will provide an official record of apogee for scoring. This flight computer may also be one of those used for recovery system deployment. Although the on-board data record is considered the primary for scoring, telemetric altitude data may be used at the judging panel's discretion in the event a launch vehicle is destroyed during recovery. ESRA recommends using the Jolly Logic Altimeter Two for official altitude logging.
4.3	5.1	All “energetics” shall be "safed" until the rocket is in the launch position, at which point they may be "armed". For the purpose of this requirement, energetics are defined as all stored-energy devices, other than propulsion systems, that have reasonable potential to cause bodily injury upon energy release. An energetic device is considered safed when two separate events are necessary to release the energy. An energetic device is considered armed when only one event is necessary to release the energy. Although these definitions are consistent with the propulsion system arming definition provided in Section 3.4 of this document, this requirement is directed mainly at the energetics used by launch vehicle launch vehicle and payload recovery systems and extends to all other energetics used throughout the launch vehicle and payload. Note that Section 3.4 requires propulsion systems be armed only after the launch rail area is evacuated to a specified distance, while this requirement permits personnel to arm other stored-energy devices at the launch rail. All energetic device arming features shall be located on the airframe such that any inadvertent energy release by these

		devices will not impact the person arming them. For example, the arming key switch for an ejection charge shall not be located at the same airframe clocking position as the hatch panel jettisoned by that charge. The following table lists some common types of stored-energy devices and in what configuration they are considered non-energetic, safed, and armed.
4.4	B6, T3	The launch vehicle shall contain a custom flight computer responsible for gathering data from sensors, initiating deployment of the parafoils and parachutes, and controlling the payload upon descent.
4.4.1	B6, T3	The flight computer shall contain the following sensors with the purpose of gathering information about the rocket in-flight: Digital IMU, GPS Sensor, and Barometer
4.4.1.1	B3, B6, T3	The data generated by all sensors shall be stored in such a way that if the rocket were to take larger damage the data would not be lost. This data shall be easily recoverable.
4.4.1.2	S1	The sensor array and communication module shall be designed and installed on a printed circuit board with a port to easily connect the flight computer. The whole PCB and computer system shall take a minimal amount of space so as to easily fit within the rocket.
4.4.2	S1	The flight computer shall contain a Radio telemetry module in order to transmit the rocket's information to the ground station throughout the flight.
4.4.3	T5	The flight computer shall be programmed with a recovery destination before flight, and shall use information from the sensor array to determine appropriate controls to guide the vehicle to the destination.
4.4.4	Internal	The flight computer shall fit within the avionics bay as defined by the Structures/Avionics interface.
4.5	Internal	The avionics bay shall have connectors on each end to interface with other systems within the flight vehicle. These are defined by their interfaces.

4.2. Design Process

The Avionics subteam's design goals for the vehicle are to create a custom flight computer to gain experience necessary for competing in the Advanced category next year, while simultaneously supporting the payload's requirements for position determination. The Payload subteam was contacted to ensure that the avionics system supports all of their needs. The flight computer is intended to be modular enough for use on future vehicles. The intent is to use this custom system for telemetry and recovery. This system will be compliant with all ESRA standards. Using a custom solution naturally introduces additional risk due to relying on unproven systems. Testing has been and will continue to be the primary way of determining the flight worthiness of this system. This ensures the maximum level of reliability.

The initial step in designing the computer was to compile a list of required sensor points for all teams. The Avionics subteam collaborated with the Payload subteam to determine the set of variables necessary for accurately determining position and guiding the rocket to its destination. The determined variables were location, altitude, orientation, ground speed, and relative wind speed. The sensors that were considered to calculate the required variables include a GPS, IMU, magnetometer, barometer, and pitot tube. The final set of sensors was decided on after eliminating unnecessary sensors to reduce the complexity of the system and reduce risk. A list of commercially available sensors was then created that fulfilled these requirements. Sensors were then evaluated to determine the best option.

When necessary, the sensors under consideration were purchased and tested by the Avionics subteam members. An integrated sensor/recording/telemetry system was drop tested in a payload vehicle to verify the capabilities. This test validated the design choices so far. Different combinations of sensors and telemetry were also flown on high power rockets. These tests confirmed the findings of the drop tests. At this time, solutions for sensor interfaces, transmission, and storage were evaluated. Please refer to Section 4.4 – Key Technical Issues and Risks for details on these discussions.

Simultaneously, COTS systems were evaluated as backups to provide redundancy and to fulfill IREC requirements. Considerations for the backup system included data logging, pyro event capabilities, programmability, and usability. An abbreviated list of commercial systems considered include the Marsa54L, Stratologger CF, and the TeleMetrum.

The results of these discussions and tests were compiled into a final design, which is discussed in detail below.

4.3. Technical Design and Analysis

The primary considerations during the final design of the avionics system are as follows:

- The system needs to concurrently gather, record, and transmit data, and send commands to actuate the payload based on calculated data.
- In order to provide sufficient accuracy for payload navigation, sensors with a relatively high sample rate are required. The sample rate will be a minimum of 100Hz for all sensors except GPS which will have a minimum of 1Hz.

4.3.1. Microcomputer

Initially Arduino based flight computers were evaluated, due to their ease of use and widely supported nature. However, the AT line of processors implemented in Arduino boards was determined to be underpowered for our application.

We ultimately decided to use a Teensy 3.1 as our microprocessor. This decision was based upon the device’s compatibility with the Arduino IDE, which allows us to leverage existing libraries for our project. The Teensy 3.1 was chosen over conventional Arduino microcontrollers due to its superior processing power. The Teensy runs at 72MHz versus the relatively meager 16MHz for the Arduino Mega. The Teensy also offers superior memory, 256kB flash, versus no memory on the Arduino Mega, allowing for a feature rich program and additional onboard storage for the flight computer. The Teensy has the only drawback of smaller EEPROM (2kB versus 4kB) which will be mitigated via use of onboard flash memory. All Arduino peripheries are compatible with the Teensy. This once again allows us to utilize the ecosystem of Arduino sensors, transmitters, and communication protocols, while using the superior speed and memory of the Teensy.

Also considered, but ultimately rejected, was a Linux based system. A Linux based system would allow for the guidance and control algorithms to be implemented using python and numpy. A BeagleBone microcomputer was successfully test flown with sensors to determine the feasibility of this option. However, due to a lack of open source libraries, fully implementing a BeagleBone was determined to be impractical with the given timeframe.

At this time, the algorithms will be run on the Teensy in the Arduino language. If it should arise that the linear algebra and computations necessary to determine outputs for the parafoil become unfeasible in an Arduino environment, a system will be considered where we utilize both a Linux and Arduino microcomputer. In this situation, the Arduino system will be responsible for gathering all sensor data as currently proven and tested, and will send the appropriate inputs necessary for GNC to the Linux microcomputer. The Linux microcomputer will then perform GNC calculations and output controls directly to the payload for actuation.

The Teensy 3.1 will read sensor data, log it to onboard storage, send it to the transmitter, compute the proper control settings, and actuate the payload. It will also have self-fault detection.

Figure 20: Teensy Microprocessor. (Paul & Robin, 2015)

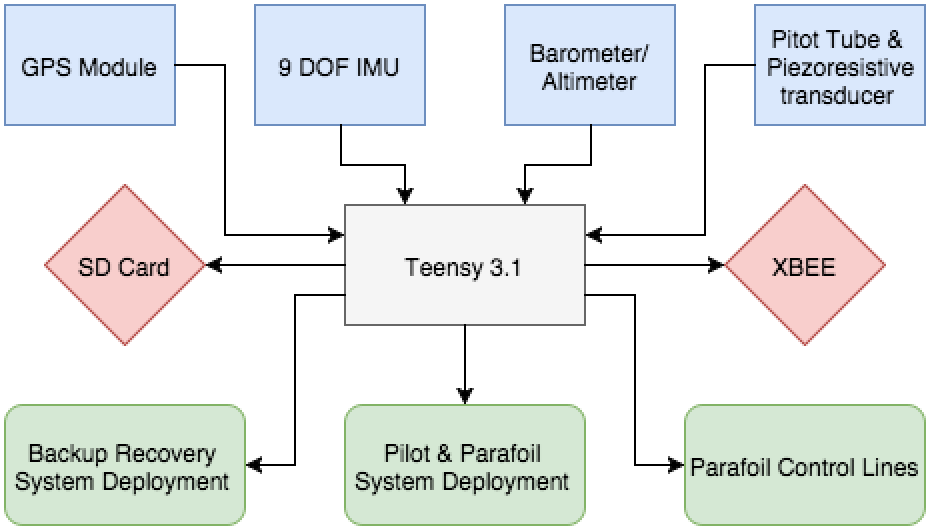


Figure 21: Avionics System

4.3.2. IMU

The Inertial Measurement Unit (IMU) chip utilized in the flight computer will be the InvenSense MPU-9250. The MPU-9250 is a 9 DOF (degree of freedom) chip that combines a 3-axis gyroscope, an accelerometer, and a magnetometer. This chip offers multiple advantages over other units; the chip has an onboard Digital Motion Processor™ that processes the raw data separately from the microcontroller, outputting the final values. This saves processing cycles for the Teensy, while eliminating a source of error. The chip communicates over I²C so it is easily integrated with the Teensy.

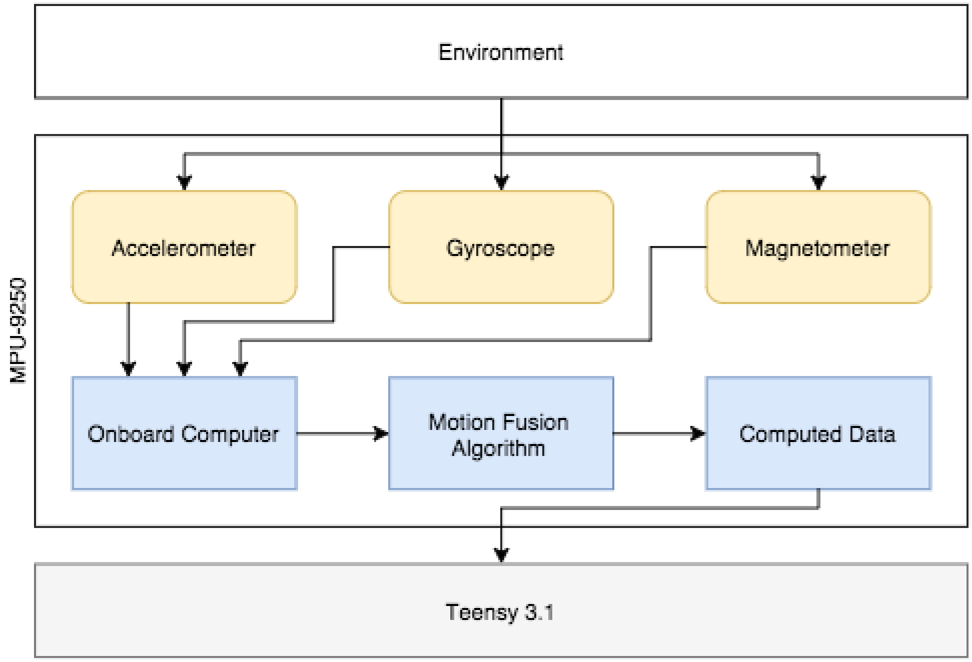


Figure 22: MPU-9250 IMU Chip

4.3.3. GPS

The GPS module used in the system will be the Venus GPS, carrying the Venus638FLPx GPS chip. The most important consideration for the GPS module was the update rate - for the most accurate estimation of the location of the rocket during descent, we need to have the GPS information update as often as possible. Originally, we tested with the Adafruit GPS, but that only provided an update rate of 10Hz. The Venus module provides an update rate of 20Hz - double the rate of the Adafruit. The disadvantage with the Venus module is that it does not come with its own patch antennae. The workaround is having an external patch antenna that will reside in the Avionics bay with the flight computer system. This configuration is optimal; a major factor when designing a PCB system to house the sensors is the EM interference from the sensors themselves. Since we will use an external antenna connected to the GPS module with an SMA connector, the potential interference will be mitigated by not housing the antenna on the same board as the rest of the sensors.

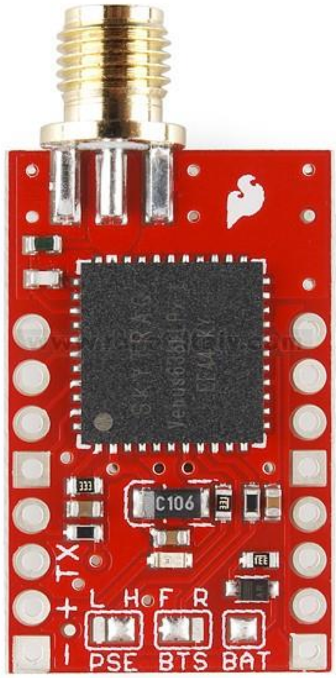


Figure 23: Venus638FLPx on a breakout board.
(Robot-Italy, 2014)

4.3.4. Barometer

Competition and payload requirements dictate that we include a barometric altimeter. This will provided additional altitude data and apogee confirmation for the system as well. We decided to use the Adafruit BMP180 Barometric Pressure, Temperature and Altitude Sensor for this task. One advantage of this barometer is that it has a very extensive library for usage with Arduino projects, making integration into our flight computer very simple. Another advantage is that the same barometer was implemented in last year's project. For these reasons, we are confident not only in our ability to use this chip because of the team's experience with it, but also in the reliability of its measurements.

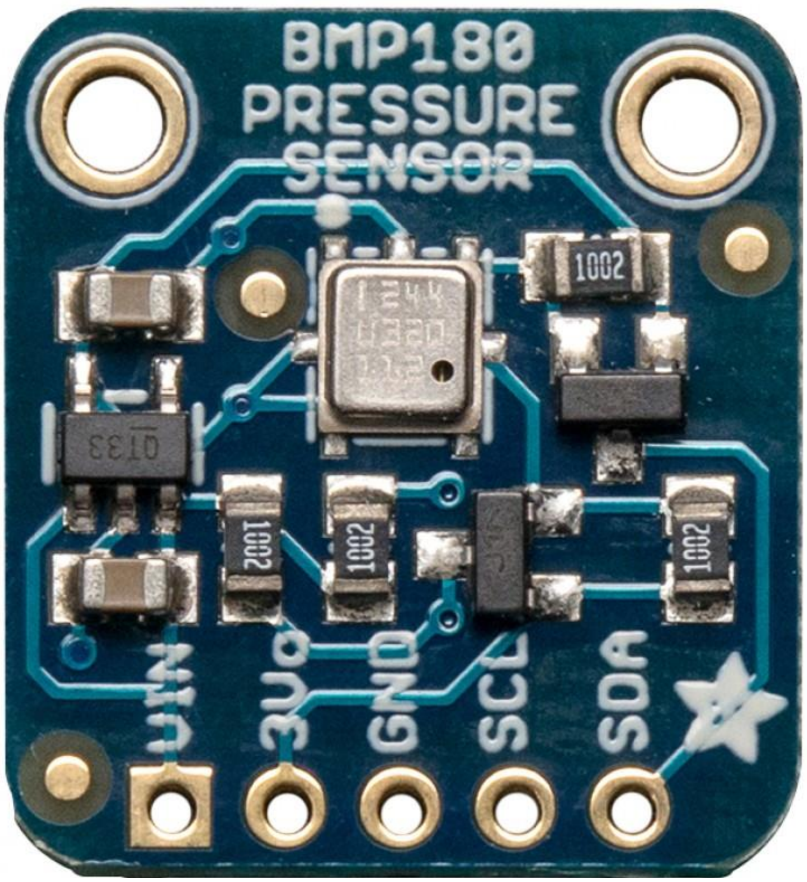


Figure 24: Adafruit BMP180 Sensor on a breakout board. (Maplin Media, 2015)

4.3.5. Pitot Tube

The pitot tube we are using is an APM 2.6 Airspeed Sensor. The sensor is offset by 2.5v so that it is possible to read low and high pressures, which is a critical capability for future use of this board at higher altitudes. The pitot tube will be mounted on the nose and connected via flexible silicone tubing to the transducer which is located on the flight computer PCB. The pitot tube will provide airspeed data during ascent and descent that will be used along with acceleration and GPS data for accurate navigation to the target destination. The transducer will interface to the Teensy through analog read pins. Power will be provided through a separate 5V source.

Figure 25: 3DR MPXV7002 Transducer. (3D Robotics, 2014)

4.3.6. Onboard Data Logging

Data will be logged to an onboard SD card. The SD card will be inserted and stored on a breakout board on the printed circuit board that will host all sensors and chips. The SD card will store higher resolution data than can be transmitted, and will safeguard against a lost signal. Additionally, in the event of a failure, an SD card is robust enough to potentially survive a serious anomaly. The Teensy will record data to the SD card along with a time stamp. Each power cycle of the flight computer is treated as a new flight, and will log data to a new file on the SD card. This will prevent accidental data loss due to overwriting. SD card's memories are nonvolatile, so unexpected power interruptions will have no effect on the data already logged. This file will store all measured parameters.

4.3.7. Telemetry

One of the goals of the team this year is to have live telemetry throughout the course of the rocket's flight. This will be accomplished via the XBee-Pro 900 XSC S3B. The XBee is an RF (radio frequency) transmitter and receiver. This requires two XBee modules - one connected onboard the flight computer for transmission, and one connected to the ground support system for reception. Because the XBee operates over Serial ports on the Teensy (just like the SD card), we can easily write the same information to both the SD card and the XBee; in essence, we can save a string of information onboard and then transmit the string very quickly. In order to enhance the reception of the XBee, we will attach antennas to both XBee modules with the antenna in the Avionics bay in line with the vertical axis of the rocket. For the antennas to work as expected, they must be parallel to each other - during ascent, the antenna on the ground will be oriented vertically to match the vertical flight of the rocket. After apogee and deployment of the pilot parachute, the rocket should ideally be oriented horizontally; at this point, the antenna on the ground will be moved to a horizontal position to ensure the best reception throughout descent. The benefit of having in-flight telemetry is not only to be able to track the rocket during flight, but, because we will be sending orientation data as well as status updates, we will be able to tell if (and how) an error occurs and the relative success of our flight.

Figure 26: XBee Pro S3B Module with Wire Antenna (will be replaced with ducky via SMA) connector). (SparkFun, 2015)

4.3.8. Printed Circuit Board

These five key components (Teensy, IMU, GPS, Barometer, XBee) will be contained in a custom designed PCB (printed circuit board) to reduce space and increase reusability. Using readily available schematics for each of the chips we plan to use, we will design a 4-layer PCB. The decision to use 4 layers was mainly to allow for the inner two layers to act as power and ground layers for all of the necessary components. The PCB will be designed using a design software such as EagleCAD or Altium, and sent to a PCB printing company such as Advanced Circuits. The PCB design will have the following specific features accessible at the edges:

- USB port to easily program the Teensy chip
- On one side:
  - ports to connect lines for e-matches (deployment charges) for the backup recovery system
  - SMA connector for XBee transceiver
- One the other side:
  - ports to connect lines for e-matches for the main recovery system
  - ports to connect control lines for payload actuation
- On a third side, SMA connector for external GPS patch antenna

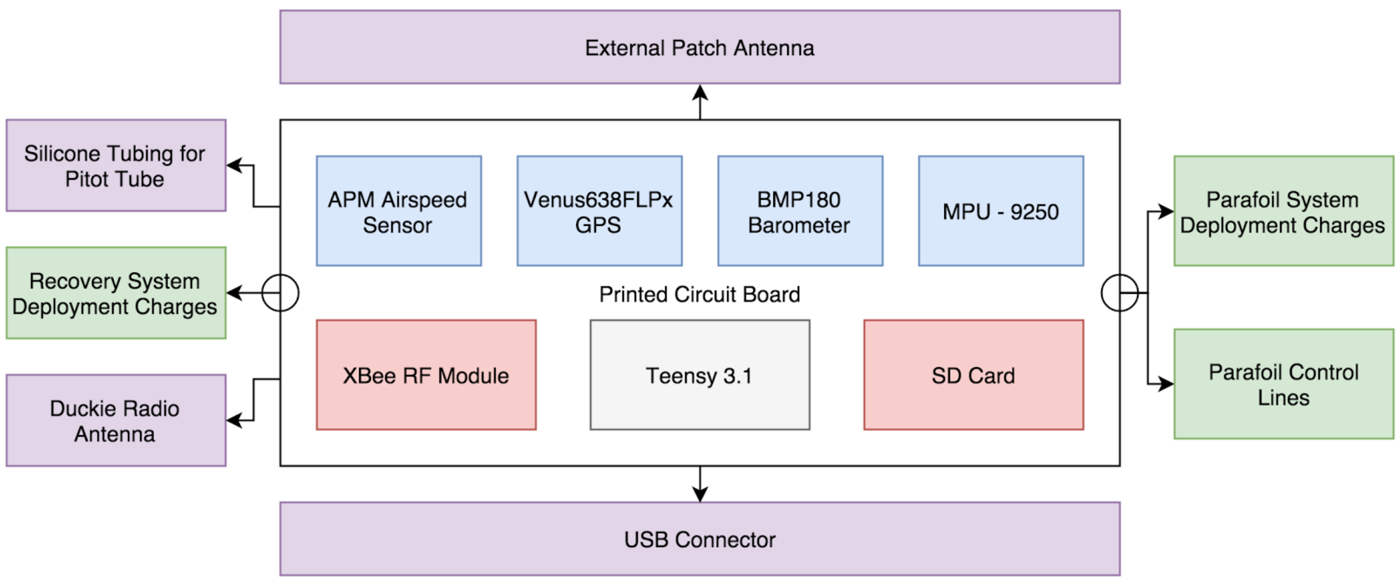


Figure 27: PCB with external connections

4.3.9. Power

Power to the entire flight computer system will be provided via a Lithium Polymer Battery (LiPo). A LiPo battery was selected since the amount of stored energy provides a sufficient amount of runtime for the system. More specifically, the power supply to be used is a 7.4V, dual cell LiPo that holds 9Wh (Watt-hours) of energy (equivalent to 1200 mAh). Because our microcomputer (the Teensy) and all our sensors operate at a voltage of 3.3V, we will have on board the PCB a LD1117-3.3 Semiconductor that will step down the input voltage (7.4V) and output a safe 3.3V. Additionally, we will have an LM7805 Semiconductor to output a safe 5V from the input voltage (7.4V) necessary for the Airspeed sensor.

4.3.10. Redundant Systems

4.3.10.1. COTS Altimeter

In order to meet IREC requirements, we must have a COTS altimeter on board. From previous competitions, we have experience with the StratoLogger CF Altimeter system. The StratoLogger stores altimeter, temperature, and battery voltage data onboard and has outputs to deploy drogue and main parachutes. As a redundant COTS system, we will be using the StratoLogger on its own power supply connected to the backup recovery system (drogue and main). In order to ensure the backup system does not interfere with our own flight computer, we will install a PNP transistor between our flight computer and the COTS deployment charges. The redundant system is for the situation that our flight computer does not properly deploy pilot and parafoil charges. If our system properly detects apogee and sends a pilot charge, it will send a current to the PNP transistor between the StratoLogger and the drogue, thereby inhibiting its ability to deploy the drogue. In the situation that we detect failure, we can still deploy the drogue via our own flight computer. To ensure this works in the proper order, the StratoLogger will be programmed with a 5 second apogee delay to ensure it does not deploy the drogue before we have a chance to disable it. The StratoLogger itself will remain active for the duration of the flight. This gives us the opportunity for redundant data collection and additional verification of our vehicle's performance.

4.3.10.2. Redundant Power Supply

To ensure the failure of the power supply does not lead to an undesirable outcome (lack of deployment, actuation, etc.), the avionics system will be supplemented with a separate external LiPo battery for power. This will mitigate the risk of losing power from a battery failure.

4.3.10.3. Failure of sensor

The number and types of sensors on board the avionics system were chosen in order to guarantee not only the parameters necessary for successful guidance, but also to ensure that the failure of a single sensor does not lead to the failure of the entire system. Table 8 shows how failures of sensors will be handled.

Table 8: Sensor failures

Sensor Failure	Parameters provided	Redundancies	Notes
Pitot Tube	Vehicle speed	GPS, IMU	
GPS	Location	IMU	Location will be approximated from last known GPS location and IMU readings
IMU	Heading	GPS, Pitot	Pitot tube will help determine velocity; GPS will be used with last known orientation for guidance
Altimeter	Altitude	GPS	Use vertical component of GPS as altitude reading

4.3.10.4. Multiple flight computers

In order to ensure more accurate readings and decrease noise, it was discussed whether or not multiple flight computers should be present on board the flight vehicle to gather sensor data. In this arrangement, a separate microcomputer (such as the aforementioned Linux-based BeagleBone) would be necessary. Each Teensy and sensor array system would operate on their own power supply to gather data and send the data to the Linux-based microcomputer. The Linux microcomputer would take the inputs and perform the GNC calculations and output controls to the payload. The benefit of this setup is two-fold. First, having multiple sensor arrays will increase the accuracy of measurements and remove random variability. Secondly, in the case multiple sensors fail, the extra sensors will still provide data to continue operation of the flight computer.

This was discussed and determined to be beyond our capabilities for implementation at the time being. We did not want to design a complex duplex or triplex sensor array system without being certain we could have it accomplished with the time frame available.

4.3.11. Backup Recovery Deployment

The backup recovery system is in place in case the parafoil system malfunctions (tangles, does not deploy) or simply does not bring us closer to our destination (cartesian distance from target repeatedly increasing). The backup system is a standard drogue and main parachute system; the drogue parachute will deploy if necessary and the main parachute will deploy at 1500 feet above ground level (1500’ AGL). The following checks are in place to determine successful operations:

- At apogee, deploy pilot chute
    - If speed of descent surpasses determined max pilot chute descent velocity, assume pilot chute did not deploy:
    - Deploy backup system
- At 5000’ AGL, check all sensors for proper operation
    - If approximate location and heading cannot be determined, assume GNC failure:
    - Deploy backup system
- Keep track of descent velocity and distance from the goal
    - If descent velocity is above a certain threshold for longer than a predetermined period of time OR…
    - If the cartesian distance between the rocket and the destination increases for longer than a predetermined period of time:
    - Deploy backup system
- During descent, keep track of status of sensors
    - If GNC status is determined impossible for longer than a predetermined period of time:
    - Deploy backup system
- The backup system consists of the following:
    - Deploy drogue parachute
    - Deploy main parachute at 1500’ AGL

The flowchart below of the backup recovery system illustrates the plan described above.

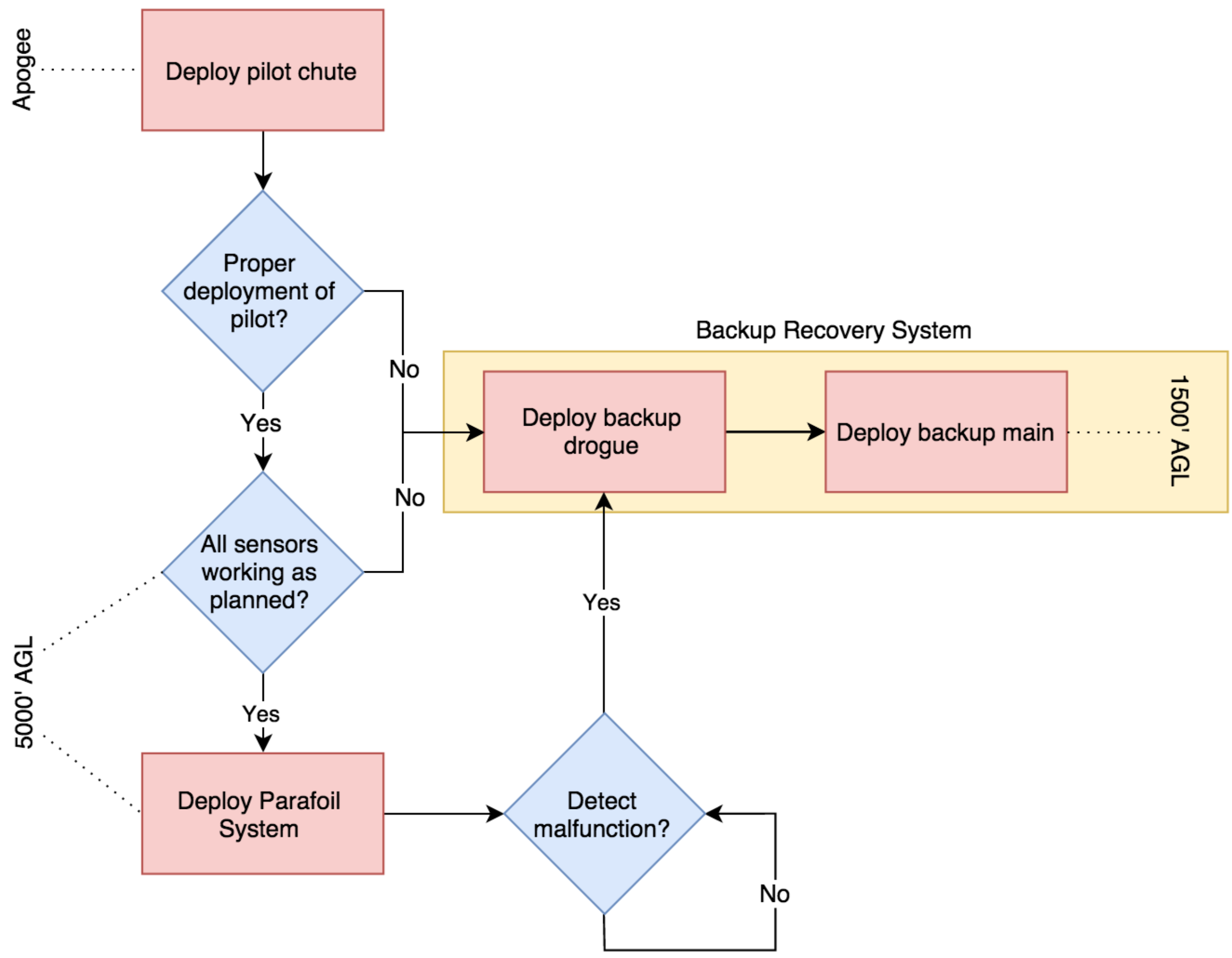


Figure 28: Backup Recovery System Flowchart

4.3.12. Parafoil Guidance, Navigation and Control

Once the parafoil is deployed, the vehicle will need to be steered to the desired landing location. Steering will be performed by guidance, navigation and control (GNC) software running on the onboard computer. In the situation that the GNC software malfunctions or does not operate as expected, the ground team will have the ability to send commands to the rocket to either manually control the parafoil system or deploy the backup recovery system. This communication will be handled via the XBee RF transceivers.[1]

[1] We are currently looking into ESRA and FAA regulations to determine the legality of allowing such a possibility

4.3.12.1. Navigation (State Estimation)

The GNC software will perform navigation, i.e. maintaining an estimate of the current dynamic state of the vehicle. The navigation software will fuse data from the various sensors with a model of the vehicle dynamics to produce a state estimate.

The estimator will track the states listed in Table 9, given the measurements listed in Table 10.

Table 9: States to be tracked by the estimator

State	Symbol	Relative to	Representation	Units	Notes
Attitude of the vehicle body	$q_{body, ef}$	Earth-fixed coordinate system	Unit quaternion	None	
Angular rates of vehicle body	w_{body}	Vehicle body	3-vector	rad/s	
Position of vehicle body	$r_{body, ef}$	Earth-fixed coordinate system	3-vector	m	
Velocity of vehicle body	$v_{body, ef}$	Earth-fixed coordinate system	3-vector	m/s	
Horizontal wind velocity	$v_{wind, ef}$	Earth-fixed coordinate system	2-vector	m/s	Optional
Orientation of the parafoil canopy	$q_{canopy\ body}$	Vehicle body	Unit quaternion	none	Optional
Sensor biases	TBD	N/A	TBD	TBD	Optional

Table 10: Measurements available to estimator

Measurement	Sensor source	Relative to	Representation	Units	States observed
Angular rates of the vehicle body	MPU-9250 IMU	Inertial frame	3-vector	Rad/s	w_body sensor biases
Acceleration of vehicle body	MPU-9250 IMU	Inertial frame	3-vector	m/s^2	d/dt (v_body_ef) q_body_ef sensor biases
Magnetic field	MPU-9250 IMU	vehicle body frame	3-vector	T	q_body_ef sensor biases
Position of vehicle body	Venus638FLPx GPS	WGS84 ellipsoid	Latitude, Longitude and elevation	Rad, m	r_body_ef
Barometric pressure	BMP180		scalar	Pa	altitude component of r_body_ef sensor biases
Vehicle airspeed	APM Airspeed Sensor	Local atmosphere	scalar	Pa	v_body_ef v_wind_ef

Kalman filters are the most widely used solution to the sensor fusion and state estimation problem. Because the vehicle dynamics and sensor measurement functions are nonlinear, the estimator will be implemented as an Unscented Kalman filter (UKF).

4.3.12.2. Guidance (Path Planning)

The GNC software will perform guidance, i.e. planning the vehicle's path to the target landing site. The guidance strategy is to:

1. If further than threshold distance from landing site:
    a. Fly directly towards the landing site
2. Else:
    a. Spiral over the landing site until landing

If we have sufficient development time, we may enhance the fly-to-target step to take the wind speed into account.

The guidance algorithm will take the following inputs:

Table 11: Guidance Algorithm Inputs

State	Symbol	Relative to	Representation	Units	Notes
Attitude of the vehicle body	$q_{body,ef}$	Earth-fixed coordinate system	Unit quaternion	None	
Velocity of vehicle body	$v_{body,ef}$	Earth-fixed coordinate system	3-vector	m/s	
Position of vehicle body	$r_{body,ef}$	Earth-fixed coordinate system	3-vector	m	
Horizontal wind velocity	$v_{wind,ef}$	Earth-fixed coordinate system	2-vector	m/s	Optional

The guidance algorithm will generate the following outputs:

Table 12: Guidance Algorithm Outputs

State	Symbol	Relative to	Representation	Units	Notes
Desired velocity of vehicle body	$v_{body,ef\ desired}$	Earth-fixed coordinate system	3-vector	m/s	

4.3.12.3. Control

The GNC software will issue control commands to the parafoil actuators.

The vehicle plant provides two actuators: ropes attached to control surfaces on the port and starboard sides of the parafoil. Opposing deflection of the surfaces controls yaw (and roll). Collective deflection of the surfaces controls lift of the parafoil, and therefore the descent rate. Note that excessive deflection of the surfaces may stall the parafoil.

The control algorithm will take the following inputs:

Table 13: Control Algorithm Inputs

Input	Symbol	Relative to	Representation	Units	Notes
Desired velocity of vehicle body	$v_{body,ef\ desired}$	Earth-fixed coordinate system	3-vector	m/s	
Attitude of the vehicle body	$q_{body,ef}$	Earth-fixed coordinate system	Unit quaternion	None	
Angular rates of vehicle body	w_{body}	Vehicle body	3-vector	rad/s	
Velocity of vehicle body	$v_{body,ef}$	Earth-fixed coordinate system	3-vector	m/s	
Acceleration of vehicle body	$a_{body,ef}$	Earth-fixed coordinate system	3-vector	m/s^2	
Horizontal wind velocity	$v_{wind,ef}$	Earth-fixed coordinate system	2-vector	m/s	Optional
Orientation of the parafoil canopy	$q_{canopy\ body}$	Vehicle body	Unit quaternion	none	Optional

The control algorithm will produce the following outputs:

Table 14: Control Algorithm Outputs

Control output	Symbol	Relative to	Representation	Units	Notes
Desired deflection of port parafoil surface	u_{port}	N/A	scalar	m	Deflection will be represented as the amount of control line to pull in or release
Desired deflection of starboard parafoil surface	u_{stbd}	N/A	scalar	m	Deflection will be represented as the amount of control line to pull in or release

The control algorithm will be as follows:

1. Given $v_{body,ef\ desired}$, $v_{body,ef}$, and $q_{body,ef}$, compute the heading (yaw) error, e_{yaw}. The heading error is the angle by which the vehicle must turn to align the horizontal components of $v_{body,ef}$ with $v_{body,ef\ desired}$.
2. Given e_{yaw} and the heading component of w_{body}, use PID control to compute the differential output u_{diff}
3. Given $v_{body,ef\ desired}$, $v_{body,ef}$, compute the descent rate error, $e_{descent\ v}$.
4. Given $e_{descent\ v}$ and the vertical component of $a_{body,ef}$, use PID control to compute the collective output u_{coll}
5. Solve for u_{port} - u_{stbd}:

Equation 1: Udiff

$$u_{diff} = u_{port} - u_{stbd}$$

Equation 2: Ucoll

$$\boldsymbol{u_{coll} = u_{port} + u_{stbd}}$$

6. Limit u_{port}, u_{stbd} to prevent stalling the parafoil.

The control algorithm described above is visually represented in the block diagram in Figure 29.

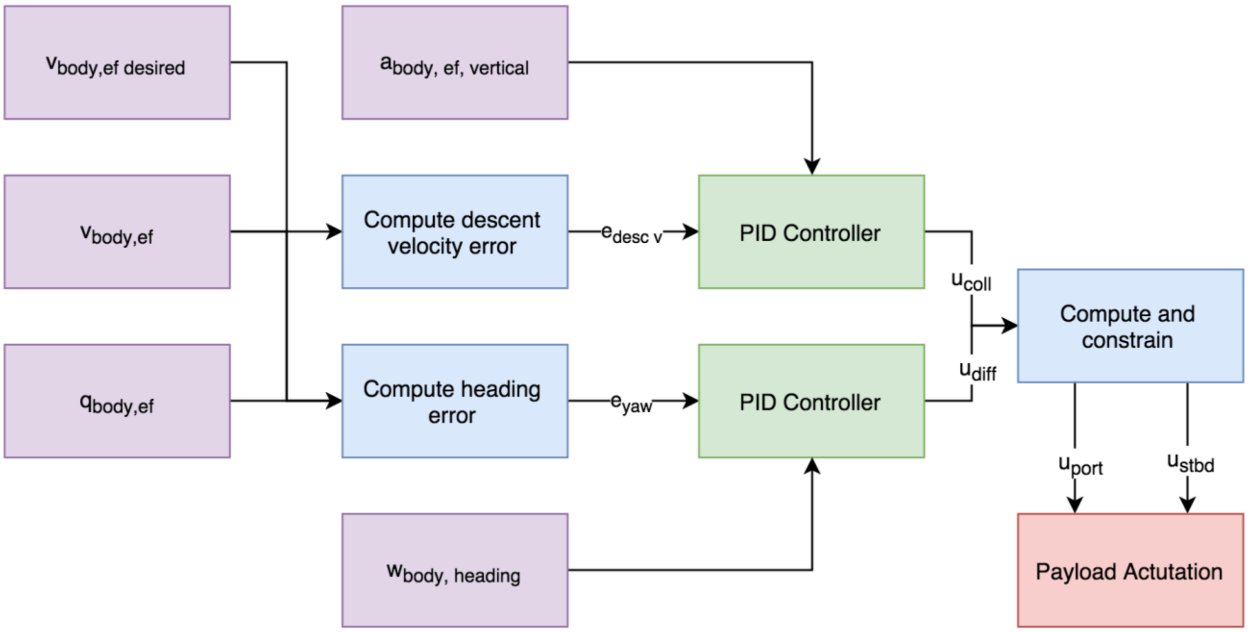


Figure 29: Control Algorithm

4.4. Key Technical Issues and Risk

4.4.1. Key Significant Avionics Risks

4.4.1.1. Sensor issues

The Avionics subteam has considered a duplex system, but determined the additional complexity may make this unfeasible. In the event of sensor failure being detected, the sensor is ruled out of the estimation program. Outlined below are the various sensors used by payload, how the sensor may fail, how to detect if the sensor failed, and finally what they system can do about it to still achieve controllability.

<u>GPS</u>

Table 15: GPS Issues

Failure Mode	Failure Detection
Unable to achieve a GPS lock	GPS will indicate when a lock is achieved, so lock state is always known

Wire or connection failure	No data will be received, easily detected within the code structure
Yielding false data	A predetermined range of values will provide a reasonable range of GPS coordinates that the system can be within. Detection of values outside this range would indicate faulty data.

IMU

Table 16: IMU Issues

Failure Mode	Failure Detection
Wire or connection failure	No data will be received, easily detected within the code structure
Yielding false data	We can determine ranges of the roll, pitch, and yaw rates it should be sensing (based on the dynamics). If it begins to sense unreasonable rates, the system will rule it out.

Barometer

Table 17: Barometer Issues

Failure Mode	Failure Detection
Wire or connection failure	No data will be received, easily detected within the code structure
Yielding false data	We can determine altitude and altitude rate ranges it should be sensing (based on the dynamics). If it begins to sense unreasonable altitudes or rates, the system will rule it out.

Pitot Tube

Table 18: Pitot Tube Issues

Failure Mode	Failure Detection
Wire or connection failure	No data will be received, easily detected within the code structure
Yielding false data	We can determine speed and acceleration ranges it should be sensing (based on the dynamics). If it begins to sense unreasonable speeds or accelerations, the system will rule it out.

4.4.1.2. Failure of controls to actuate parafoil

Due to the complexity of the system, there are many failure modes leading to this risk. Failure in physical connections could lead to no actuation. A failure in software could lead to improper controls being sent to actuators or controls that do not guide the parafoil to its destination. The environment could lead to an unresponsive system or impractical flight conditions. A failure of controls will lead to a mandatory deployment of the backup parachute if it is determined that reaching the destination is no longer a possibility or the safety of people is at risk.

4.4.1.3. Failure to deploy parafoils/parachutes

Errors in the software programming, physical packing of parachutes, and preparation of deployment hardware - eMatches, hatches, frangible bolts - can all lead to a partial or complete failure of parafoil or parachute deployment. Any failure in the deployment of recovery systems is a very high risk that may lead to total recovery failure and an unrecoverable rocket.

Table 19: Avionics Risk Matrix

Risk	5					
	4					
	3			1		
	2				2	3
	1					
		1	2	3	4	5
Impact						

4.4.2. Risk Mitigation Strategy

4.4.2.1. Sensor Issues

<u>GPS</u>

GPS lock can take up to a few minutes, and will be part of the preflight setup procedure. If for some reason a GPS lock cannot be achieved during the startup procedure we have a few options. We can delay launch until a fix is achieved, possibly removing circuitry for debugging, although if this fails we have the option to launch without a functioning GPS. While launching without a GPS poses a risk, it can reasonably be done. Similarly if a GPS lock is lost on the launch pad, and delaying launch is not an option, we can launch the rocket with a restricted mission. For any of these reasons, if the rocket reaches parafoil deploy altitude without a GPS lock, the mission must be reasonably aborted. The backup recovery system will then be deployed.

Following a GPS rule-out during flight:

The lack of location data makes getting to a target location very difficult due to errors that arise is simply approximating with IMU data. This requires a mission change. The mission would change to have the system track different headings. The heading commands would be prewritten, and the heading output would come solely from the IMU with relative wind speed provided by the pitot tubes.

IMU

Following an IMU rule-out:

Heading can still be obtained using the GPS data (although less accurate). Hardware in the loop tests should reveal performance in this circumstance. The GPS still makes directing the payload to a target location possible.

Barometer

Following a barometer rule-out:

GPS data also yields altitude data although less accurate. Hardware in the loop tests can reveal performance in this circumstance.

Pitot Tube

Following a pitot tube rule-out:

The ground speed can be determined by GPS. Perhaps relative wind speed can be determined by approximating it with the dynamics. Based on similar projects, knowing the relative wind speed is not critical to achieving heading control. The approach to this scenario is still being researched.

4.4.2.2. Failure of controls to actuate parafoil

There will be multiple rounds of testing to ensure all physical connections are secure between the parafoil system and the flight computer. Regular test launches and gondola tests will be conducted throughout the semester and all systems will be checked for response prior to launch.

There will be multiple safeguards in place to respond if the parafoil controls are not having the desired effect on the descent path of the rocket. One of these systems will be integrated with the automatic guidance of the descent. If sensors report values that suggest that the rocket is not reacting to the actuations in the predicted manner, it will trigger deployment of the backup descent systems after a long enough delay to confirm that it will not recover from the problem.

4.4.2.3. Failure to deploy parafoils/parachutes

For every deployment system there will be a redundant backup system. This includes e-matches, ignition circuitry, and deployment computer. By having two e-matches prepared to deploy parachutes/parafoils etc we will have redundancy in physical systems that are potentially prone to being displaced. Additionally, the circuitry that ignites these e-matches will be duplicated on the main control board, in case one system fails to respond. Both systems will be rigged to both e-matches, and will be set off at the same time. In case this fails, we will have another backup deployment system entirely. This will consist of the StratoLogger CF, which is capable of deploying a drogue at apogee and a main at a preset altitude. This redundant system will be rigged into the backup system, and will be always on and capable of deploying backup systems unless specifically blocked (via PNP transistor switch) by the main control board. In the event of a main board malfunction, the secondary system will be capable of deploying all necessary backup recovery systems for a safe return of the rocket.

Table 20: Avionics Mitigated Risk Matrix

	5					
	4					
Risk	3					
	2		1			
	1			2	3	
		1	2	3	4	5
Impact						

4.5. Interfaces

4.5.1. Recovery

Although the Avionics subteam will handle the deployment of the pilot parachute, parafoil, and backup recovery system, the physical deployment of the chutes falls under the purview of the Recovery subteam. This includes, but is not limited to, the packing of all parachutes in deployment bags, attaching charges to structures and custom-made frangible bolts (for parafoil deployment), and determining appropriate sizes of chutes.

Both the custom flight computer and COTS redundant system will reside in the Avionics bay, and will have connectors on either end of the Avionics bay. Recovery will be responsible for connecting e-matches and control lines to the appropriate connections.

4.5.2. Payload

The Payload subteam is responsible for the actuation of the parafoil; however, it is the responsibility of the Avionics subteam to provide controls for the payload. Therefore, the actions of the Avionics subteam and the Payload subteam are very intertwined - the distinction draws from the modularity of the rocket system. As the controls will be a part of the custom flight computer, there will be a connection necessary between the parafoil system and the avionics bay. Avionics will be responsible for programming the controls and creating a connection for control lines that will send commands to the payload system; payload will be responsible for creating the actuation system and attaching it to the rocket. They will connect the control lines to the connection on the avionics bay in order to receive commands for their payload system.

4.5.3. Structures

The Avionics subteam will collaborate with the Structures subteam to ensure that the Avionics bay remains within the allotted packing volume determined by Structures. The Avionics subteam will propose a specified volume determined by the size of the PCB and its components, the antenna, and all lines for connectors. The Structures subteam will approve this budget and the Avionics team will maintain this budget.

4.5.4. Propulsion

The Avionics subteam will collaborate with the Propulsion subteam to ensure that the Avionics bay remains within the allotted mass budget determined by Propulsion. The budget will be determined by Propulsion to ensure that the rocket has enough propulsive power to reach 10,000 ft and maintained by Avionics.

Table 21: Avionics Interfaces with Other Subteams

Output	Source	Recipient	Description
Event Initiation	Avionics	Recovery	Avionics will trigger initiation and deployment events at the appropriate time during the rocket's descent.
Event Times	Recovery	Avionics	Recovery will provide Avionics with the appropriate initiation times and situations in order to program the flight computer accordingly.
Controls	Avionics	Payload	Avionics will determine appropriate controls for Payload and send the commands for actuation
Connections	Avionics	Recovery, Payload	Avionics will provide Recovery and Payload with the necessary connections to install in their respective sections of the rocket in order to perform actions as necessary.
Volume Budget	Avionics	Structures	Volume budget must be maintained to ensure the avionics system will fit in the rocket.
Mass Budget	Avionics	Propulsion	Mass budget must be maintained to ensure proper propulsive power.

4.6. Moving Forward

The Avionics subteam has many goals for moving forward. The subteam has already worked with Payload and Recovery to build a system that utilizes the desired sensors and communication modules and test it. In its current state, the flight computer can take all measurements and save them to an SD card, as well as transmit the data via an XBee transmitter/receiver.

The Avionics team has begun designing a custom circuit board that integrates all chips as stated in the design analysis. In parallel, the team is working to test the flight computer with the redundant COTS altimeter, the StratoLogger CF. The team will be working to construct the entire system with prototyping boards, attaching the redundant altimeter, e-matches, and actuators. Once constructed, the system will be aggressively tested to ensure that, in any situation, recovery of the rocket will be successful - regardless of the performance of the custom system. After testing, the circuit board design will be printed. The entire system will be assembled and tested rigorously. This portion will be completed over MIT's Independent Activities Period (IAP) during January so that the full team can move on to controls.

During IAP and more extensively during the second semester, the Avionics subteam will collaborate with payload to analyze the dynamics of a falling parafoil and create a controls system to guide the rocket to its destination. A small task force composed of Avionics and Payload subteam members will set up hardware-in-the-loop (HITL) testing with the flight computer over IAP in order to create a system with which to test the accuracy of our controls system. Following IAP, assuming the hardware goals have been accomplished, the focus will be on finishing the controls system. Once the system has proven to be viable with HITL testing, Avionics will work with Payload to test the control system in the field. This will be done with a test gondola that will be raised to a certain height and programmed with a final destination, and allowed to drop and potentially guide itself to the target.

At the end of the spring semester, the Avionics subteam will begin the final construction of the avionics bay, mounting all flight systems and antenna in the bay and creating connections for the Recovery and Payload subteams. The team will practice arming the flight computer and integration with other subteams to gain experience with the final system and perform seamless performance at the competition in the summer.

In June, the team will travel to IREC, integrate our rocket and successfully launch our rocket.

Table 22: Gantt chart of proposed Avionics Action Plan. Dates shown are Sundays of the listed month.

Task	January					February				March				April			
	3	10	17	24	31	7	14	21	28	7	14	21	28	4	11	18	25
Design custom circuit board																	
Test full system with backup recovery																	
Finalize and assemble PCB																	
Write, test, improve controls																	
Test controls with HITL testing																	
Field test with gondola and rocket																	
Construct avionics bay																	
Practice integration and operation																	

5. Propulsion

5.1 Overview of Requirements

Table 23: Propulsion Requirements

Internal Requirement	IREC Requirement	Description
5.0	1.0, 6.1	Shall target 10,000ft AGL (Ground level is 4,300ft MSL)
5.0.1	Internal	The minimum impulse the motor provides shall be no less than 9800Ns
5.1	3.1	Propulsion shall be restricted to COTS Solid, COTS hybrid, or custom solid
5.2	3.2	Propellants shall be non-toxic
5.3	3.3	Propulsion shall be single stage
5.4	3.5	Custom propulsion shall undergo pressure testing and static fire testing as specified
5.5	6.3.1	Shall have sufficient velocity upon departing launch rail

5.2 Design Process

5.2.1 Discussions on Desired Project - Summer 2015

During the summer, much discussion occurred regarding the project decision for this year. Specific to propulsion, the considered projects were: commercial propulsion, staged propulsion (if the advanced category was chosen as the overall project), hybrid propulsion, and custom solid propulsion. Below is a discussion on different possible project, which culminated in the decision to attempt to develop a custom solid motor, with a commercial motor chosen as a descope option.

5.2.1.1 Commercial Propulsion

The primary advantage to a commercial off the shelf (COTS) propulsion system is simplicity. If the team decided to pursue a commercial propulsion system, we could be confident in the reliability of the motor, and focus the team on other projects.

The primary disadvantage to COTS for a team that has attempted complex propulsion systems in the past 2 years (namely, the liquid engine Pyralis), using a simple COTS propulsion system seemed to be a large step down that renders the propulsion team largely obsolete this year. This would cost the team a fairly large amount of institutional knowledge as many of the members who were active in propulsion last year would graduate before another propulsion system could be attempted.

5.2.1.2 Staged Propulsion

Staged propulsion was one method considered to increase the complexity of the propulsion project this year and make use of the skills in the propulsion team. However, the most recent attempt of the team to use a staged propulsion system proved exactly how complex staged propulsion is. While the staging would test the team's ability to design and perfect a structure that allows the staging to occur, it is needlessly complex for competition in the Basic category of IREC, as well as forbidden within the rules of the Basic category. Therefore, a staged propulsion system was eliminated from the potential projects very quickly.

5.2.1.3 Hybrid Propulsion

Because of the team's experience with liquid engines, a propulsive system that would take advantage of that experience without the full complexity of a liquid engine was considered. Use of a hybrid would allow the team to gain experience injector design for liquid propellants, while having less simplicity. It would also be a way to develop a more rigorous, easily applied testing protocol.

Hybrid propulsion was eliminated from consideration, however, based on the experiences of other teams we witnessed at IREC 2015 who were attempting a hybrid system, as well as the academic value of a hybrid system and the availability of test locations. A majority of the teams we saw at IREC 2015 who were attempting a hybrid motor were unable to launch due to complications with fueling, propellant storage, and weight. This lack of reliability was a major influence in our decision to pursue a much more reliable motor. Furthermore, much of the design and characterization of hybrid motors is empirical. Many processes need to occur at the same time, including vaporization of the liquid oxidizer, melting and sublimation of the wax fuel, and the actual combustion processes. Due to the interconnected, temperature dependent rates of each of these processes, modeling a hybrid motor is beyond the current capabilities of the team. Therefore, there is minimal academic value to pursuing a hybrid motor. Finally, without a known location for testing, it would be unlikely we would be able to find a place to test a hybrid motor in a reasonable time period, rendering a hybrid motor impossible, instead of merely undesirable.

5.2.1.4 Custom Solid Propulsion

The final potential project that was considered by the team was a custom solid propulsion system. One major advantage to a custom propulsion system is that by designing a custom motor this year, we establish a procedure and a production plan that will streamline the process next year when we attempt the Advanced Category of IREC. One important consideration, though, is that producing a custom motor can be very complex and difficult, requiring at minimum bench space in a fume hood. Moreover, the motor cannot be tested or flown at an NAR certified field, as it is classified as an experimental motor.

5.2.1.5 Final Decision

For the reasons listed above, neither a hybrid nor a staged propulsion system was possible for our system. That left the decision between a custom motor and a COTS motor. One of the priorities in the design this year is the ability to descope, and easily revert to a system that is nearly perfectly reliable. In the case of flying a custom motor, the descope plan is to fly a COTS motor instead. By designing the grain geometry of the custom motor such that it is able to be installed in a COTS motor casing, we are able to optionally use either custom or COTS propulsion.

The only major consideration left, then, before committing the propulsion project to a custom solid motor is the ability to produce the motor. We were encouraged to contact with Robert DeHate, the president of Animal Motor Works, as one possible path of motor production. This was done, and Mr. DeHate agreed to help us produce our custom motors, since he both the equipment and the experience required to do so safely.

Having resolved the concern about being able to produce the custom motors, the team committed to designing a formulation and grain geometry for a custom solid motor, with the stipulation that the design of the rocket be unaffected by use of a custom or COTS motor, allowing for the ability to descope at almost any time before the competition.

5.2.2 Results of Commercial Search

We began our search for a commercial motor using a scaled-up version of the Team's Scylla Rocket, which was flown in the IREC 2015 competition. The scaled-up version of Scylla is a 6in diameter, 10ft long airframe, which gave us an approximate model of our competition rocket this year. This rocket served as a preliminary design with which to simulate flights using various off-the-shelf commercial motors.

Based on mass-budget requirements from the structures subteam and payload subteam, we determined that the dry mass of our rocket, not including the motor or casing, should be roughly 45lbs. Using this mass budget as a benchmark, we decided that our motor should be capable of launching 45lbs of dry mass to 11,000ft AGL at the competition site in Utah, giving us a 1000ft margin above the target altitude. Additional ballast can then be used to tune the apogee of the rocket to the target altitude.

We included such a generous altitude margin in our commercial motor search due to the uncertainties that remain in our parafoil recovery system, payload, and structure. Because our parafoil recovery system design has not been finalized, there is the possibility that it will exceed the 10lbs mass budget that has been allotted for it in future design iterations. Because the design of our parafoil recovery system and payload influence the structural design of our rocket significantly, future design modifications to our structure are also a possibility. Our 1000ft altitude margin allows for 8.5lbs of additional weight in our rocket, which should account for any increases in mass in our parafoil recovery system, payload, and structure in our finalized design. Additionally, the design of our fins will likely differ in size from those of the Scylla model we used for simulation. Larger fins will significantly decrease our apogee, so our altitude margin will also allow for modifications to fin design that increase drag.

Given our estimated dry mass of 45lbs, and target altitude of 11,000ft, we determined that for a commercial motor to be viable, it must have a total impulse greater than 9,800Ns. Additionally, in order provide a launch rail exit velocity greater than 100ft/s, the motor must provide an initial thrust greater than 3000N in order for our rocket to reach 100ft/s off of the launch rail, as recommended in the IREC Requirements.

The commercial motor that best fit these criteria was the Pro98 9994M3400-P, from Cesaroni Technology. Through simulation of this motor in our preliminary rocket design on OpenRocket, it demonstrated that it could meet all of our design requirements. With the Cesaroni 9994M3400 motor, our rocket reaches 11,069ft, and 115ft/s launch rail exit velocity.

The Cesaroni 9994M3400's specifications can be found in greater detail in 5.3.2 .

5.3 Technical Design and Analysis

5.3.1 Overview of Design

This section is an outline of the motor specification. The design process will be presented in subsequent sections. We plan to fly the rocket using the commercial motor described in 5.3.2 . In parallel, we are developing a custom motor that, should development of the motor and both static fire and flight testing finish prior to the competition, we will use instead of the commercial motor. The grain geometry for our custom motor will be BATES, so the motor's burn profile will be neutral.

Table 24: Properties of the Proposed Custom Motor

Oxidizer	72% Ammonium Perchlorate (by mass)
Fuel	7.7% Magnesium powder (by mass)
Binder	17% HTPB, 3% curative (by mass)
Burn Rate modifier	.3% Red Iron Oxide (by mass)
Desired Average Thrust	800 lbs (3558.58 N)
Desired Burn Time	2.7 sec
Desired Isp	190 sec
Nozzle Throat Diameter	1in
Expansion Ratio (Nozzle Exit Area/Nozzle Throat Area)	15
Desired Maximum Chamber Pressure	875psi
Desire Propellant Weight	9lbs (4.08kg)

More detail on this can be found in 5.3.4 .

The grain dimensions are:

Table 25: Proposed Grain Geometry

Length	6.9in
Outer Diameter	3.86in (98mm)
Core Diameter	1.5in
Number of Grains	4

More detail about the propellant grains can be found in 5.3.3 .
The case dimensions are, in inches:

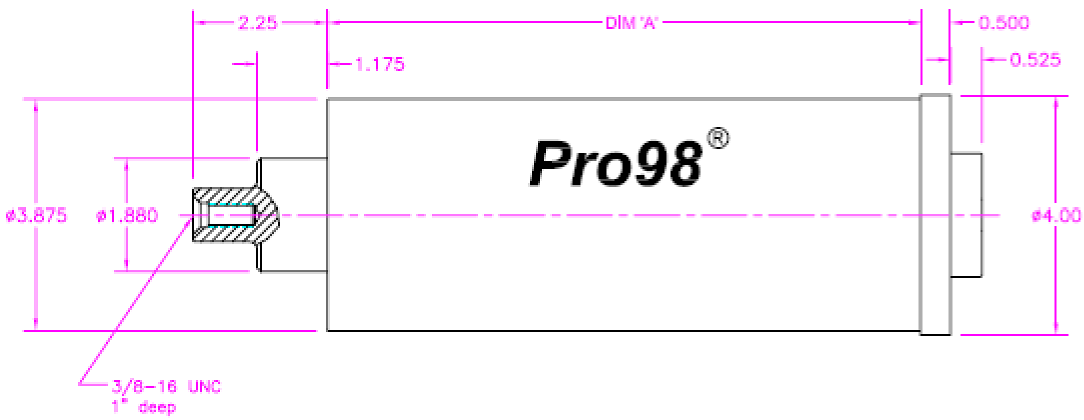


Figure 30: Dimensions of a CTI Pro98-4G case. Dim ‘A’ = 27.14 in. Drawing not to scale (Cesaroni Technology, Inc., 2009)

5.3.2 Commercial Motor

Part Number - Pro98 9994M3400-P
Manufacturer - Cesaroni Technology

Table 26: Specification for the M3400 motor. (www.thrustcurve.org, n.d.)

Manufacturer	Cesaroni Technology
Mfr. Designation	9994M3400-P
Common Name	M3400
Motor Type	Reload
Diameter	98.0mm
Length	70.2cm
Total Weight	8108g
Prop. Weight	4452g
Average Thrust	3421.1N
Maximum Thrust	3983.0N
Total Impulse	9994.5Ns
Burn Time	2.9s

Isp	229s
Case Info	Pro98-4G
Propellant Info	White Thunder

Thrust Curve:

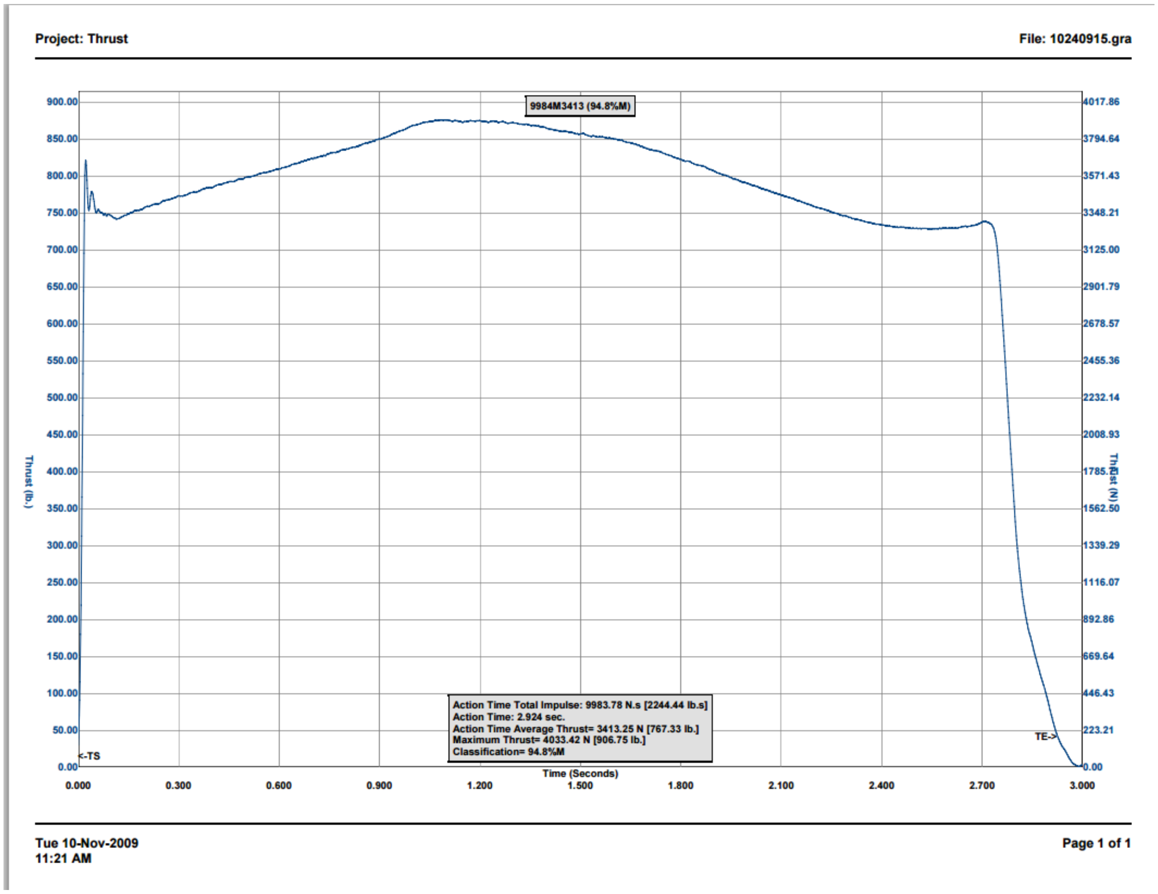


Figure 31: Thrust Curve for the M3400 motor. (Cesaroni Technologies, 2009)

5.3.3 Grain Geometry

Originally, two grain geometry options were considered: a BATES (Ballistic Test and Evaluation System) geometry and modified BATES geometry with 1 finocyl grain. In the end we decided to use a standard BATES grain, for the reasons outlined below.

5.3.3.1 Finocyl grain

One main advantage of the finocyl grain is its high initial thrust, as it has a large burning surface which results in a high chamber pressure and thus high thrust. This is important when there is a suggested velocity off the rail and the rocket is heaviest at the start of the burn, thus has a slower acceleration. However there are some disadvantages - finocyl is hard to produce, liable to break and would need grain bonding.

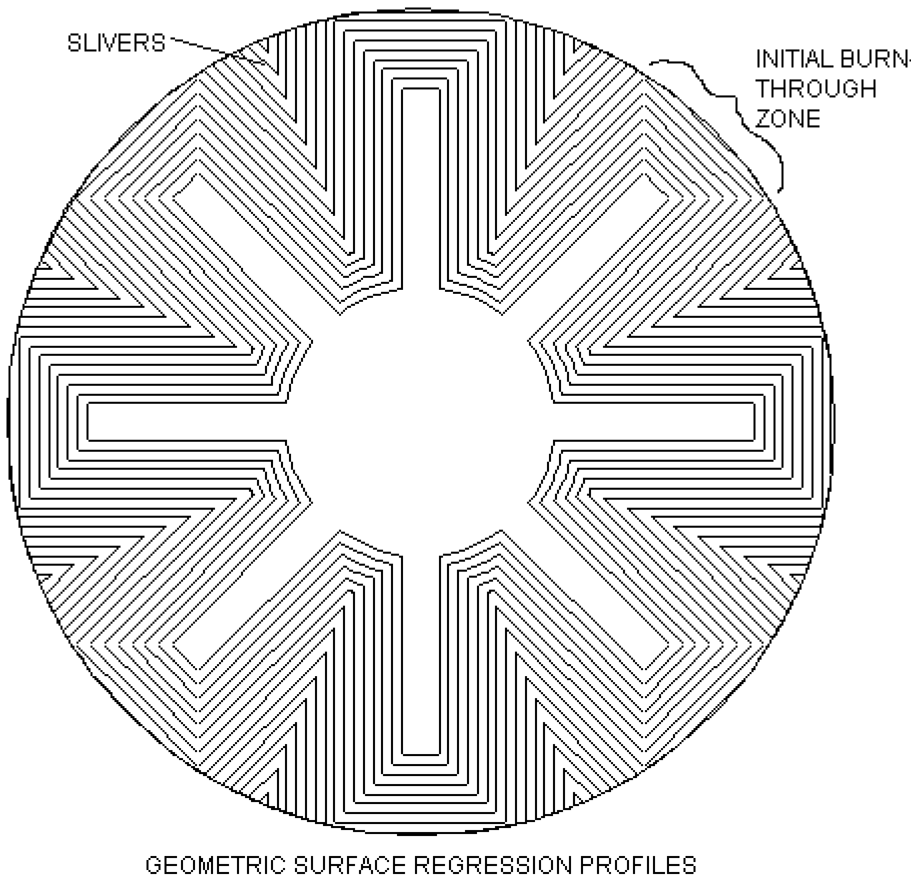


Figure 32: Finocyl Core Geometry. (Nakka, 2004)

5.3.3.2 BATES Grain

In comparison, BATES grains are easy to produce and assemble. Another advantage of BATES is that BATES grains have a mostly neutral thrust profile. However, BATES grain may not provide enough initial thrust to get off the rail at the suggested velocity. Another detriment is that it requires substantial insulation to protect the case from high temperatures, as opposed to finocyl

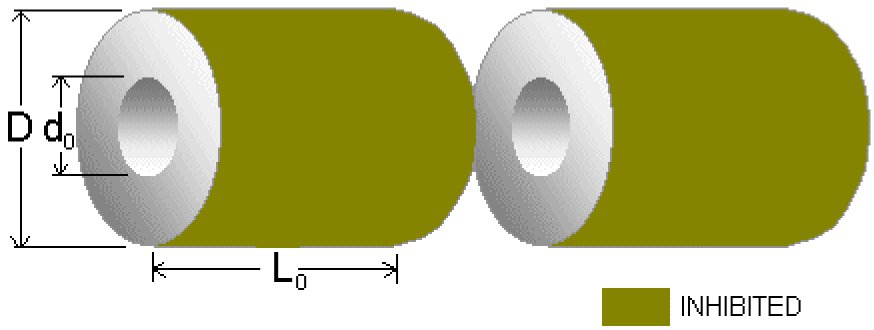


Figure 33: BATES Grain Geometry. (Nakka, 2004)

grains, which need less heat protection since it has less exposed case.

5.3.3.3 Factors Leading to Decision

The predominant reason for choosing a standard BATES grain was its simpler manufacturability. BATES grains are easy to make and fairly robust and versatile, while finocyl grains require a mandrel that can only be used for one specific finocyl configuration or a jig to mount the grain in while the fins are cut into a BATES grain with a hacksaw, which is imprecise at best. Though the thrust consideration could be an issue, it was determined not be serious because our proposed design is simulated to provide similar thrust to the CTI M3400-WT. This thrust will be enough to achieve the suggested velocity off the rail. Our simulations with the M3400-WT suggest a velocity off the rail of 116ft/s, which is well above the suggested 100ft/s. Since our motor is being designed to provide thrust similar to this motor, we will not have issues with a low liftoff acceleration.

5.3.4 Propellant Composition

We are planning to use a propellant composition listed in the following table:

Table 27: Propellant Composition

Propellant	Mass Percent
Ammonium Perchlorate (250 μm)	72%
Magnesium powder	7.7%
HTPB	17%
Curative	3%
Red Iron Oxide	0.3%
Stabilizers and Opacifiers	Trace Amounts

At present, the specific opacifiers and stabilizers we will use are unknown. These numbers are estimates based on the advice from industry and what known formulations we could find, resulting in a pourable propellant mixture. However, they are not necessarily accurate, and will be refined further based on further advice from industry experts. We predict that the properties of this formulation will be:

Table 28: Desired Properties of the Custom Motor

Density (kg/m^3)	938.34877
Specific heat ratio	1.25
Molar Mass	0.259
C* (m/sec)	1862.84616
Characteristic ISP (sec)	190
BR Coefficient (a)	0.03
BR Exponent (n)	0.4

According to our simulation, these properties- when the formulation is mixing into the grain geometry listed in 5.3.3 - will give us the desired performance metrics listed in 5.3.1 . As we go through the refinement and strand burning process, this formulation will be modified into the exact formulation that we will use.

We chose our propellant composition depending on our desired energetics values from BurnSim as well as from members in the Team who have taken the rocket propulsion class. Our design has been refined through advice from industry, namely Robert DeHate and Robert Krech.

Also, to protect our cases from the flame temperature, we will add opacifiers to the propellant, which prevent infrared radiation from heating the inside of the propellant as well as the case, and we'll be using a commercial liner, which provides several layers of protection between the engine and the case. The thermal resistance of the liner decreases the temperature at the case significantly, protecting the cases from melting.

5.3.5 Strand Burner Design

In solid motors the surface regression rate is related to pressure by the equation:

Equation 3

$$\frac{dr}{dt} = a * {P_c}^n$$

To simulate motor characteristics including thrust, burn time, and chamber pressure, our simulation software requires the burn rate coefficient and exponent of the propellant. A strand burner is a tool used to empirically measure pressure and burn rate, and using data from multiple burns at varying pressures, we can determine a and n via an exponential fit. Propellant is cast into a glass tube open at one end, and the tube is connected to a pressure chamber with adjustable blow-off valve. These valves will hold the pressure constant at the set value by releasing any addition gas produced that increases the pressure beyond the desired point. The propellant is ignited and the rate at which it burns is measured visually. By using multiple such tubes with different blow-off valve pressures, we obtain data on burn rate vs. pressure, and from those we can determine the burn rate coefficient and exponent.

Our strand burner is shown in the image below. The glass tube attaches to the right side of the apparatus and is ignited using electrical contacts.

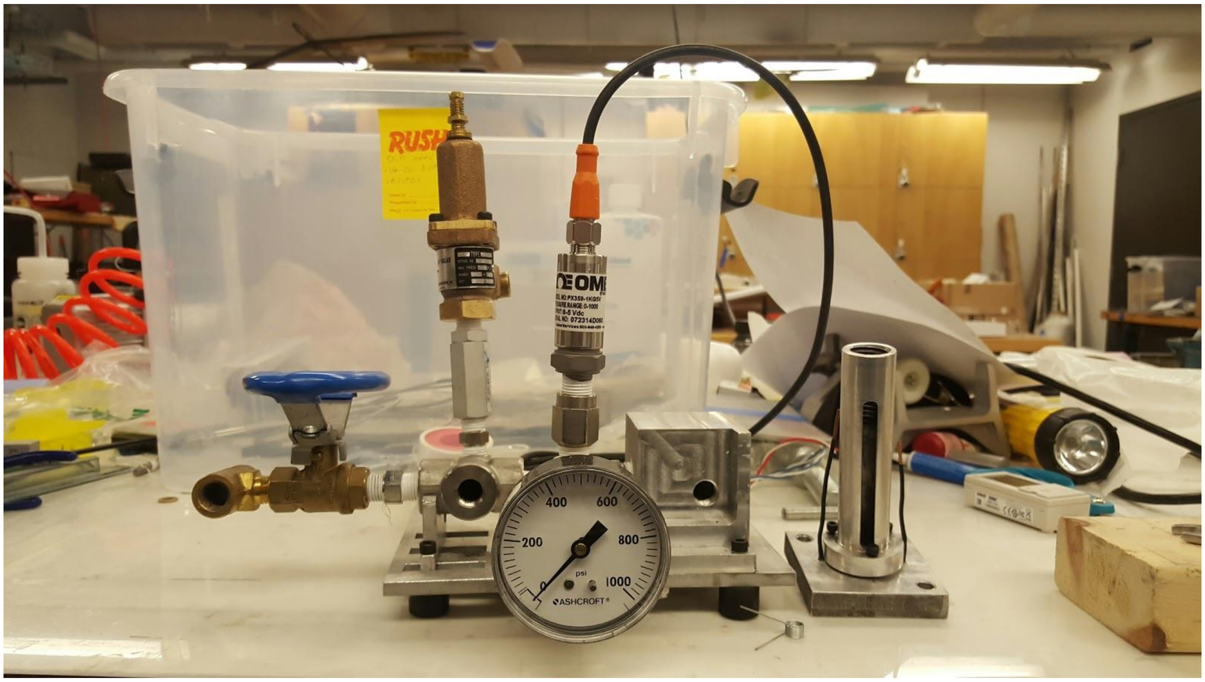


Figure 34: Strand Burner

Our strand burner will be designed to withstand pressure of up to 1500psi. This is because our motor is simulated to have a maximum chamber pressure of 900psi, and we will be characterizing the burn rate of the motor through the maximum operating pressure. (5.6.4)

5.3.6 Test Stand Design

In order to measure how much thrust our motor actually produces and verify our simulations, static fire testing is necessary. The static fire test can help us accurately evaluate the characteristics of our motor, such as the actual total impulse and the thrust stability. This section will discuss the design of the test stand for the static fire test.

The test stand must be able to hold a 98mm motor and withstand 2000lbs thrust, giving the stand a safety factor of 2. It also has to be portable such that we can easily fit it into the trunk of a small car. In order to obtain the most accurate result, the friction between the motor and test stand haves to be minimized - at most 5% of our maximum thrust in our case. Another problem we need to consider in our design is that motor failure will destroy our electronic devices if we place them too close and do not shield them correctly. Therefore, we must separate them with fireproof material, such as plexiglass. We decided to make the stand out of steel instead of aluminum because of its great strength. When compared to aluminum, steel is less likely to deform under the stresses of the test fire.

Originally, we had two potential designs: a horizontal stand on a rail mount and vertical stand on a tripod mount. The biggest difference between these two test stand is the orientation the motor is placed.

5.3.6.1 Horizontal Test Stand

In the horizontal stand, the motor is placed horizontally on a cart while the load cell is placed on a wall in front of it. The cart is mounted on a track, and will help mitigate the effects of friction during the firing of the motor. However, this design is more complicated to produce, and has a very large footprint. In addition, there is a risk of the motor detaching itself from the cart, or moving the entire test stand should it not be properly secured to the ground.

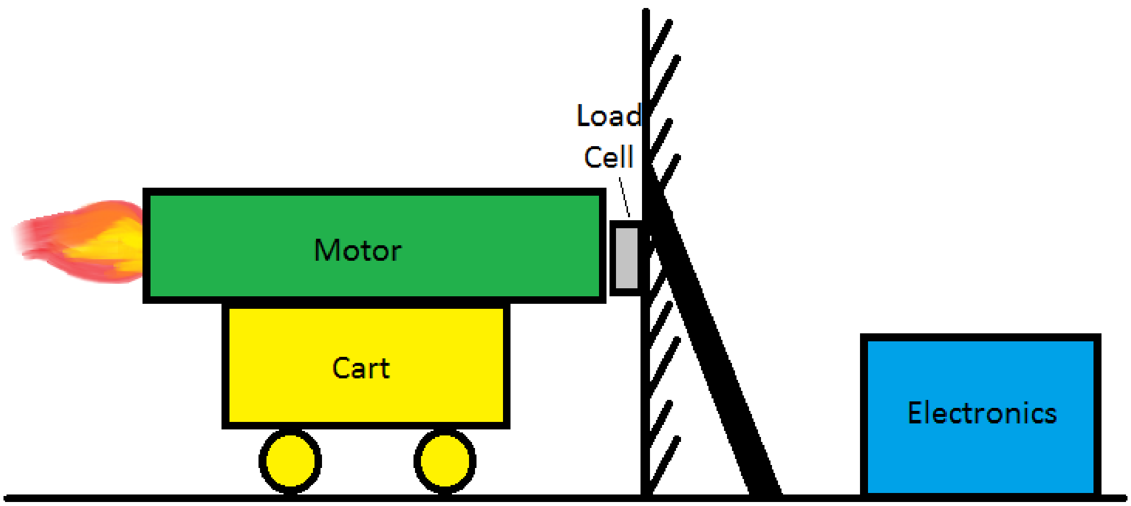


Figure 35: Horizontal-Firing Test Stand Design

5.3.6.2 Vertical Test Stand

On the tripod mount the engine is placed vertically on the stand while the load cell is sitting beneath it. The motor's thrust is pointed towards the ground, preventing the potential of the

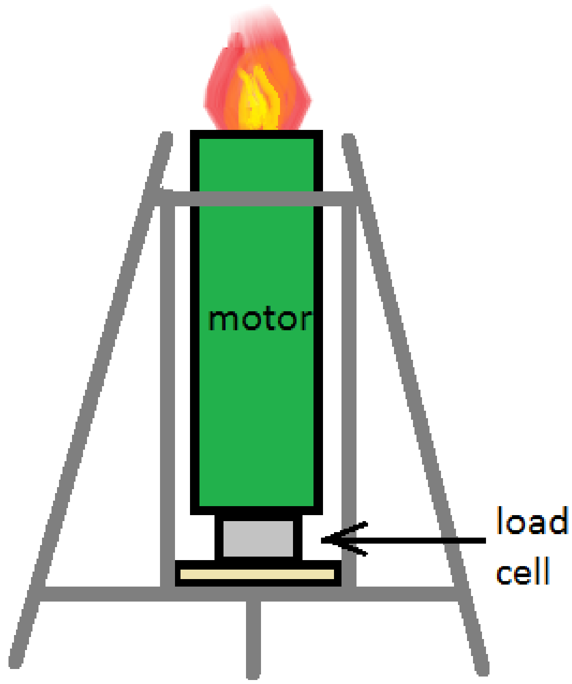


Figure 36: Vertical-Firing Test Stand Design

motor either moving the stand or detaching from the stand. One source of error with the vertical stand is that the weight of the motor needs to be subtracted from the measured load force; however, a relatively simple script in MATLAB should be able to at least approximately correct for this error.

5.3.6.3 Final Decision

In the end, we decided to use the tripod motor load cell design for testing our motor as well as building a smaller scale test stand for 38mm motor to learn how our load cell works, and to confirm that our formulation is stable in a moderately sized motor.

5.4 Key Technical Issues and Risk

While the propulsion system will be the rocket's largest source of high-impact risks, most of these are highly unlikely, and their likelihood can be mitigated by a number of strategies described below.

5.4.1 Significant Propulsion Risks

Motor over-pressurization (1)

This is highly unlikely, even with a custom propellant grain - we plan to use a commercial case designed to withstand pressures well above those generated in the chamber. However, should the case experience an anomaly, the impact would be catastrophic. This over-pressurization can come from two sources: the startup transient, or cracks in the propellant grain.

Combustion instability (2)
Combustion instability is unlikely with a well-tested custom fuel grain, and extremely unlikely in commercial motors. Still, its impact to the mission could be catastrophic.

Damage to test stand (3)
Damage to the test stand will significantly slow down or inhibit further propulsion system testing, increasing overall failure risk for the final competition design.

Damage to the test stand would be expensive to repair - the current value of the electronics on the test stand is estimated at $10,000, which will be difficult to cover in the Team's budget should a full replacement be needed.

Custom grain yields insufficient thrust (4)
It is possible that a custom grain may yield a lower thrust than predicted, as simulations cannot capture all the effects of burning, and commercial motors have been subjected to far more testing than will be possible for our motor before the competition.

Insufficient number of test launch opportunities (5)
It is reasonable to expect cancelled launches throughout the spring, as New England winters and early springs tend to be windy. It is important that we verify our design with at least two test launches prior to the competition.

Risk	5					
	4					
	3		5			
	2				3	2, 1
	1				4	
		1	2	3	4	5
Impact						

Figure 37: Propulsion Risk Matrix, Assuming Custom Grain used in Motor

5.4.2 Risk Mitigation Strategy

Motor over-pressurization (1)
The risk of motor over-pressurization is significantly reduced by descoping our design to use a commercial motor - the motor we have selected has been subjected to far more extensive testing than is possible for this project and successfully flight-proven on hundreds of occasions.

For the custom-grain motor, we intend to reduce our risk as much as possible by conducting extensive strand testing to refine our burn simulation and better understand the risk. We will only move into ground testing of the motor and launch testing if the strand tests yield promising results, and will descope to a commercial motor if the custom grain is not verified on at least two test launches.

<u>Combustion instability (2)</u>
Like over-pressurization, the risk of combustion instability will be significantly reduced by descoping our design to use a commercial motor.

For the custom-grain motor, we plan to conduct extensive strand testing as detailed above.
If the results of the strand testing indicate that we can safely and reliably fire our custom grain, we will conduct at least 3 static-fire ground tests of a motor using our custom grain.
The custom grain will be launch-tested only if the static-fire tests are successful; at least two launch tests of the custom grain will be conducted. Only if both launch tests are successful will we use the custom grain in the competition.

<u>Damage to test stand (3)</u>
In order to reduce the risks of testing and cost of damage to the test stand should an anomaly occur, we plan to install a protective Plexiglas barrier between the motor and the electronics.
Furthermore, we plan to refine our motor burn simulation to improve accuracy using the data collected from strand testing. This will reduce risk of damage to the test stand by enabling us to recognize potential failure modes before moving into ground testing of the motor.

<u>Custom grain yields insufficient thrust (4)</u>
This will be mitigated by refining our burn simulation model using more accurate calculations and data from strand testing.

<u>Insufficient number of test launch opportunities (5)</u>
This risk is difficult to mitigate, given the impossibility of controlling weather patterns. However, it may be possible to verify our design with only one test launch if extra ground testing of all subsystems is conducted.

	5					
	4					
Risk	3	5				
	2					
	1			3,4		2,1
		1	2	3	4	5
Impact						

Figure 38: Mitigated Propulsion Risk Matrix

As shown in the mitigated risk matrix, 3 of 5 of our risks can be moved into the safe zone by adoption of the strategies described above. Risks 1 and 2 moved closer to the safe zone, but cannot be mitigated further due to their extremely high level of impact. Still, this should be tolerable, as the probability of these events is very low.

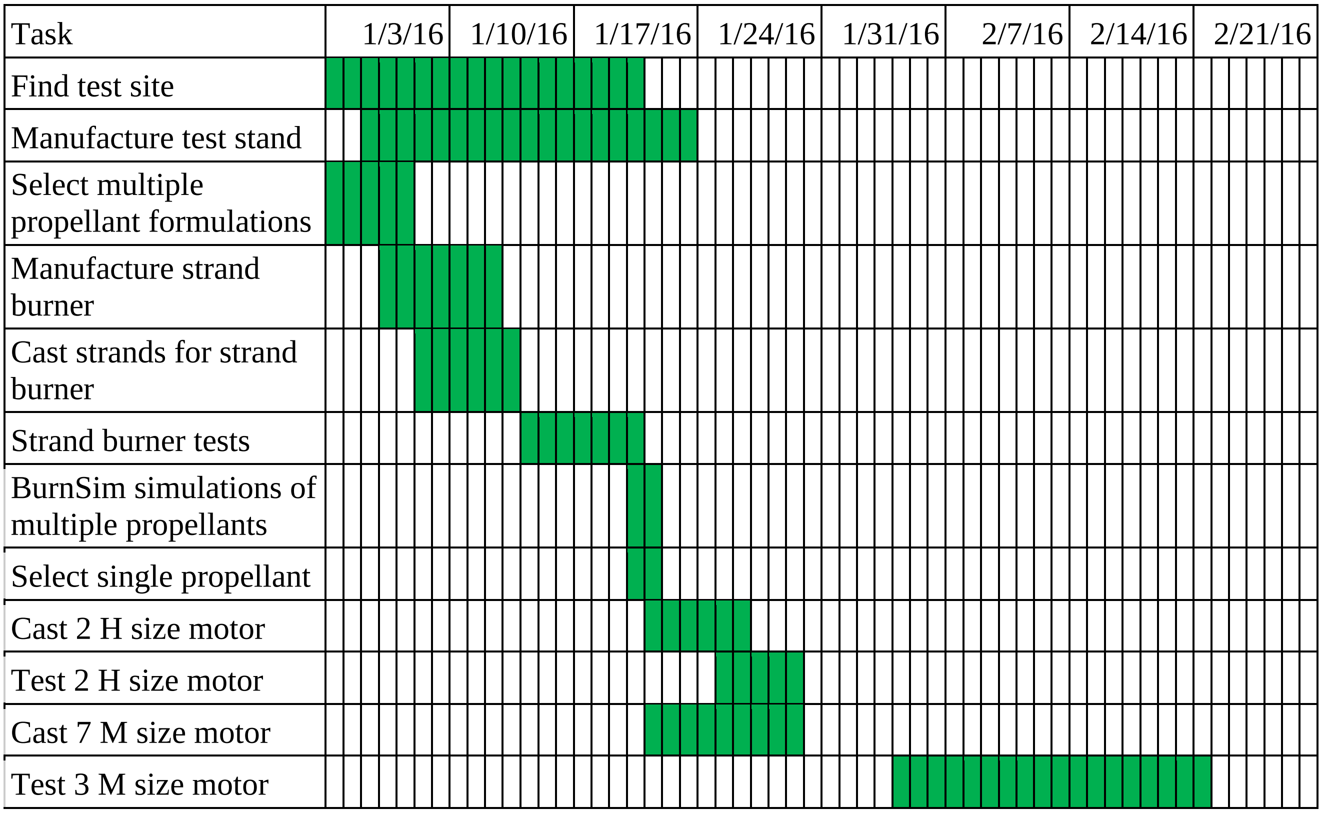
5.5 Interfaces

Table 29: Propulsion Interfaces with Other Subteams

Output	Source	Receiver	Description
Thrust Profile	Propulsion	Structures	The thrust curves of both the COTS motor and the custom motor are needed by the Structures team in order to design the structure to handle the acceleration provided by the motor
Case Dimensions	Propulsion	Structures	Both the COTS and custom motor are able to fit in the same case, allowing the structure team to design the motor retention around the case, regardless of the motor used.
Total Dry Mass	Structures	Propulsion	In order to make sure the motor is appropriately sized, and can provide the desired velocity off the rail and provide enough impulse for the rocket to reach the target altitude, the total dry mass of the rocket is needed from the Structures subteam.
Rocket Diameter	Structures	Propulsion	Based on other inputs from other subteams, the Structures subteam decides on the diameter of the rocket. As this increases the drag force experienced by the rocket, the current diameter of the rocket is needed by Propulsion to guarantee that the motor is appropriately sized for the rocket.
Mass Budget	Propulsion	Recovery, Payload, Avionics, Structures	The Propulsion subteam will inform other teams as to the maximum mass the rocket can be while still being lifted to the target altitude. This mass budget shall be based on the models being made by the Structures subteam.

5.6 Going Forward Plan

Table 30: Gantt Chart of Proposed Propulsion Plan. The dates shown are the Sunday of the listed week.



5.6.1 Test Site

We will be searching for a site where we can safely static fire our motors. Potential sites include gravel and dirt suppliers, which will provide protection from flying debris, as well as space for participants to observe from a safe distance. We will be considering a safe distance to 150% of the NAR minimum safe distance for an M motor, or 750ft. We will look for sites that meet these requirements and contact their owners to request permission to use their sites for testing.

5.6.2 Test Stand

We have access to a 1,000 or 3,000lb load cell, pressure transducer, and thermocouple, which we will borrow from Robert DeHate. We will construct two different test stands, one for testing small 38mm motors, and one for full size 98mm motors, so that we can static test both H and M motors (see Section 5.3.6 for design). Burning motors on the thrust stands will provide more accurate thrust, pressure, and temperature data than BurnSim simulations.

5.6.3 Propellant Formulations

Our initial formulation was 75% ammonium perchlorate, 14% aluminum powder, 11% HTPB, and trace amounts of red iron oxide, based on MIT class material on solid propulsion. Our current formulation (see Section 5.3.4) was suggested by Robert Krech who recommended that we reduce the solid content from 89% to 80% to produce a more pourable propellant mixture and more favorable mechanical properties of the cured propellant, i.e. a smaller propensity for cracking. We will create three to four additional formulations, based on further discussion with Mr. DeHate, with slightly different solid content and/or with copper oxide as a catalyst in place of red iron oxide. All four to five of these formulations will be tested in the strand burner (see Section 5.3.5). On further discussion with industry, we also decided to change the metallic fuel from aluminum powder to magnesium powder, since aluminum burns slowly when compared to the residency time of the propellants in the motor.

5.6.4 Strand Burner

To use BurnSim to predict motor performance, we first need to know the burn rate of each propellant. This will be determined empirically with a strand burner. We will manufacture a high pressure strand burner to visually measure the burn rate of each candidate propellant at 16 different pressures between 200 and 1000psi (see Section 5.3.5). We will cast 16 samples of each candidate propellant in glass tubes to be tested in the strand burner. This will provide us the data about each propellant's burn rate and its dependence on pressure. This data is what will be input into BurnSim (see Section 5.6.5).

5.6.5 BurnSim Simulations

Based on the data obtained from strand burning, candidate propellants will be eliminated should they have very undesirable burn rate properties. Data about the remaining candidate propellants will be used to run simulations in BurnSim. We desire a neutral thrust curve, similar to that of a COTS CTI M-3400-WT. Given the grain geometry described in Section 5.3.3 , the burn rate coefficient and exponent from the strand burning, and the density of the propellant, BurnSim can predict thrust and pressure curves, allowing us to select the propellant that gives us the thrust curve most similar to our desired thrust curve.

5.6.6 Casting and Testing Motors

After a propellant is selected, production of full motors will begin. In total, two 38mm H (161-320Ns), and seven full size 98mm M (at least 9800Ns) motors will be produced. The H and three M motors will be static fired on the thrust stands; two M motors will be used for flight testing of the rocket; and the remaining two M motors will be reserved for competition flight.

Up to this point, the only propellant that will have been combusted will be small (approximately 20g) samples in the strand burner. To ensure that unexpected propellant properties on a larger scale do not lead to catastrophic outcomes in an M motor, smaller motors will be tested first. First the two H motor will be static fired. If the H motors are safe and their thrust and pressure data is similar to that expected by BurnSim, thus verifying the propellant's properties, then an M motor will be fired. If the M is safe and its performance aligns with BurnSim's predictions as well, two more M's will be fired to provide more reliable empirical thrust data. We previously considered producing and static firing one or more K size motors as an intermediate step between the H and the M motors, but this was deemed unnecessary as it would provide minimal information beyond that obtained from testing H motors alone before the M motors. There would be value in mixing an intermediate motor if we were casting the motor ourselves. However, because Animal Motor Works is casting the motor, and have established how to mix large amounts of propellant, there is no need for us to produce a K level motor.

6. Structures

6.1 Overview of Requirements

Table 31: Requirements for Structures

No.	Source	Description
6.1	4.6	Structure shall be reusable after recovery
6.2	7.1.2	MIT RT shall use the ESRA provided launch control system.
6.2.1	6.2	Rocket shall launch at elevation angle between 83 and 85 degrees
6.2.2	7.1.2	Rocket shall attach to IREC-supplied launch rails via a minimum of two rail guides. These rail guides shall support the vehicle’s fully loaded launch weight when suspended horizontally, and the aft most rail guide must support the launch vehicle’s fully loaded launch weight while vertical.
6.2.3	6.3.2	Rocket shall have a stable angle of attack. Based on launch wind speed and exit rail velocity, we need an angle of attack less than 26 degrees.
6.2.4	6.3.2	Rocket shall remain stable for entire ascent
6.2.5	7.3	A person shall stand no higher than 4ft on a ladder to access the rocket on the launch pad
6.3	7.2.2.2	Any single point failure shall be prevented by a removable jumper or key.
6.4		Combined mass of fuselage, fins, internal support, bulkheads, nose cone, and other structural components shall be less than 6kg.
6.5	4.6	To allow for tracking mechanisms to be placed inside the rocket, the body material shall be radio transparent.
6.5.1	6.3.2	Rockets shall be statically stable, but not overstable, off the launch rod and for the entire ascent. Goal for static margin is between 1 and 2 calibers.
6.6	Internal	Structure shall bear all loads associated with launch, flight, landing.
6.6.1	Internal	Fuselage shall be able to withstand bending moment from aerodynamic pressure at expected maximum angle of attack.
6.6.2	Internal	Structure shall be able to withstand 3,915N of thrust.
6.6.3	Internal	Structure shall be able to bear forces due to parachute deployment mechanisms.
6.6.4	Internal	Recovery bulkheads shall be able to withstand maximum load applied by shock cord during parachute deployment and descent. Rocket body shall be designed to allow for side parafoil deployment, and it shall be able to support these loads on the side of the body. Structure shall not crack due to force of

		parachute lines.
6.6.5	Internal	Structure shall bear the maximum load due to the rocket landing under parachute recovery.
6.6.6	Internal	Materials shall tolerate temperature and heat flux from motor and flight conditions.
6.7.1	Internal	Due to the potential for fins to break, the fins shall be able to be easily replaced.
6.8	T1	Avionics, recovery, payload, and propulsion shall be easily accessible. Payload shall be accessible within a maximum of 5 minutes, and the maximum integration time shall be 10 minutes.
6.9	B6	In order to prepare for entering the advanced category in future years, the body tube and nosecone shall be either entirely manufactured by students or shall be substantially modified from its off-the-shelf configuration. Reinforcement of commercial, off-the-shelf airframe components to withstand predicted loads is sufficient, but complete student manufacture is desired.
6.10	Internal	Due to the size of the payload and recovery systems, the body tube diameter will be 6in.

6.2 Design Process

Due to constraints from the recovery and payload subteams regarding parafoil dimensions, the diameter of the rocket is set at 6in inner diameter in order to safely pack the parafoil. Based on component dimensions, the Structures subteam estimates a 2ft section for the propulsion system, a 1ft section for the avionics components, and a 2ft nose cone. Based on packing estimates, the Structures subteam estimates a 2.5ft long bay for the parafoil and a 2ft long bay for the secondary recovery system. With these estimates, Structures designed a 10ft rocket, with 8ft of useable body tube space.

A fiberglass construction was chosen in order to satisfy the radio transparency requirement. Although carbon fiber is stronger per mass than fiberglass, fiberglass will be adequately strong to withstand the loads. Additionally, fiberglass reduces the cost of the rocket.

Propulsion has allowed structures a large mass budget of 6kg, well above what is necessary to support the rocket. While important, mass will not be our primary concern.

6.3 Technical Design and Analysis

6.3.1 Composites Processes

In order to meet the internal student manufacturing requirement, the structure will be laid up by hand. All body tubes, bulkheads, couplers, and the nose cone (except the aluminum tip of the nose cone) will be a fully composite layup. For body tubes, the layup will consist of two layers of Eglass sleeve with a modulus of 34Msi and a tensile strength of 640ksi. In both cases, this strength is more than adequate for the predicted load cases. Additionally, the main loading on the tube will be compressive, so the tensile strength of the fibers is less important than other properties.

The layup of body tubes will be performed using a custom layup jig (**Error! Reference source ot found.**). The jig holds a cylindrical tool and sleeve upright in between the two pulleys. The sock, with a cylindrical mold in it, will be suspended between the two pulleys by ropes tied and weights. The weights provide even tension to create a smooth, uniform, and strong layup. This process can be applied to either one sock or multiple layers. The jig will hold the fibers in correct orientation and also hold the tube upright without contacting other surfaces. Other cylindrical layups, like couplers, will be performed using this same process.

Figure 39: Composite Layup Jig

The body tubes will be laid up using either 2 or 3 layers of fiberglass depending on the results of a Finite Element Analysis (FEA) simulation of the rocket body. All layers will be laid up and bonded simultaneously in order to provide the highest bond strength possible. After the layup is complete, the ending 0.5in of material on either side of the body tube will be removed because the edges cause poor fiber orientation. The tube mold will be wrapped in waxed paper in order to facilitate the removal of the fiberglass from the tool after the layup is cured. All layups will cure for 24 hours in a well-ventilated room.

Couplers will follow the same cure cycle and process of the body tubes, except with appropriately sized molds. After the layup is complete, a piece of larger tube will be fit onto the middle of the coupler to complete it (Figure 40). The bulkhead will be cured using 0-90 weave fiberglass sheets and a vacuum table and bag process that has been used successfully in the past. This will ensure the strength of the bulkhead material, which will then be cut to shape with a waterjet.

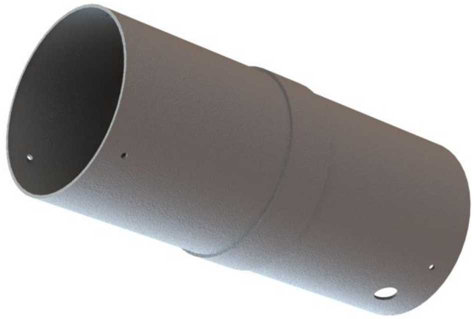


Figure 40: Coupler

The nose cone will be manufactured on an aluminum tool which will be made on the CNC lathe. This tool will be coated in about 7 layers of buffed mold release wax before use. The end of the tool will be cut off for easy machining and also to accommodate an aluminum tip to the nose cone to deal with aerodynamic heating.

6.3.2 Motor Retention and Fin Can Assembly

A preliminary CAD model of the motor retention and fin can subassembly is shown in Figure 41. This assembly mounts the motor and three fins to the rocket body and is then attached to the main body tube via a coupling. Figure 42 is a CAD model detailing the thrust ring and fin attachment rings.

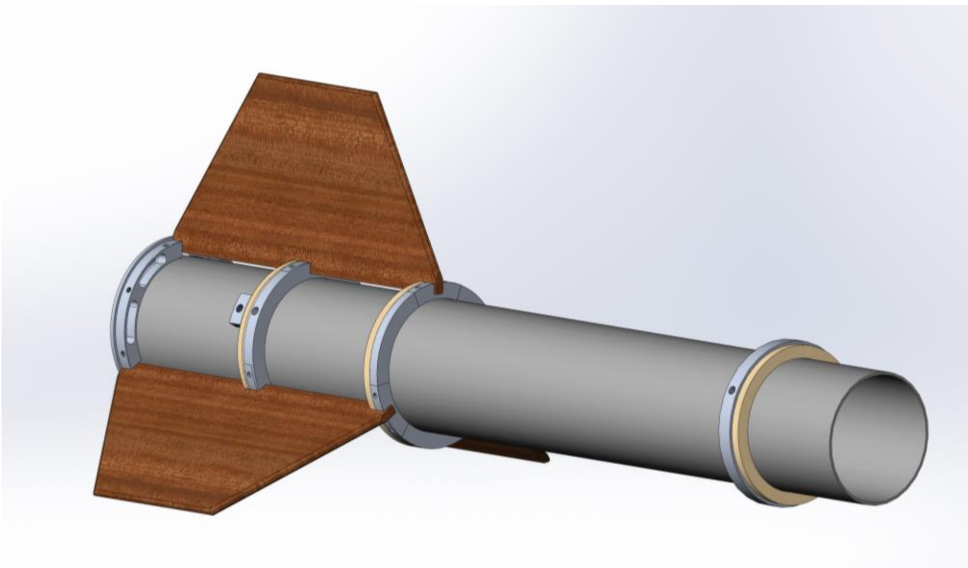


Figure 41: 3D CAD model of the motor retention and fin can subassembly.

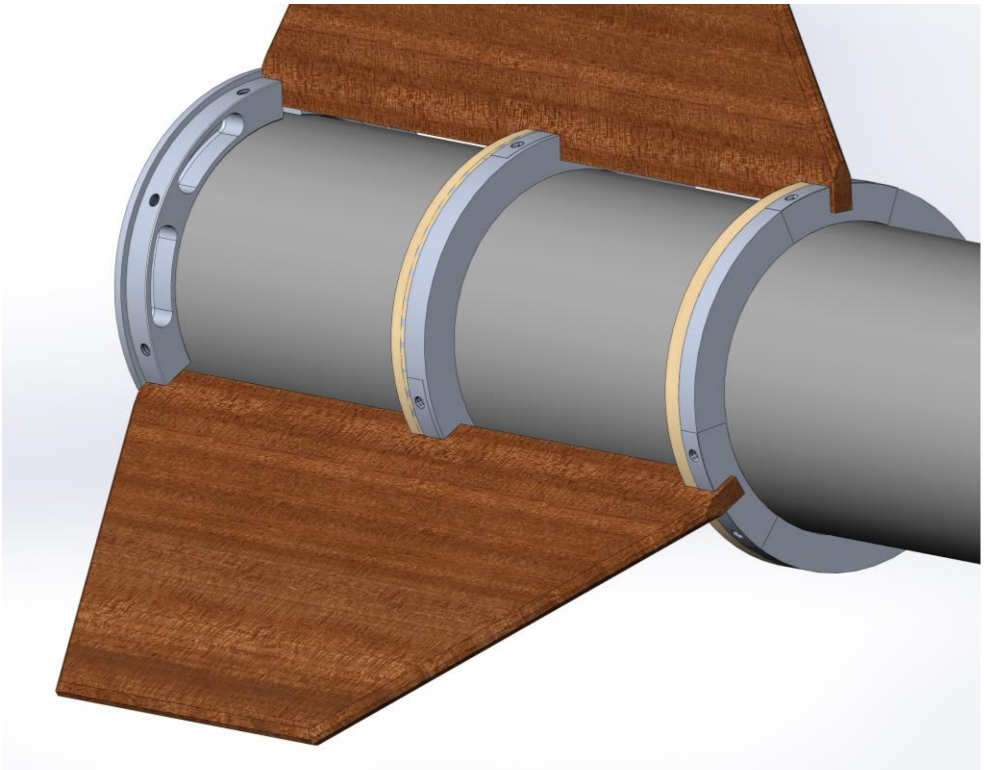


Figure 42: A close up the motor thrust ring (left) and fin mounting rings (middle, right).

This subassembly is comprised of two concentric tubes (only the interior tube is shown in the figures) with CNC machined ¼in aluminum rings attached between the two tubes. These rings will be chamfered on the top edge for ease of assembly. The inner tube will be phenolic, because there is not enough of a load on the inner tube to justify the weight and manufacturing complexity of fiberglass. The outer tube will be carrying most of the load and thus will be made from fiberglass. The tubes and aluminum rings are secured to each other with 10-32 steel screws. In our preliminary design, fins made of carbon fiber sandwich panel are press-fit and epoxied to the rings. The structures subteam will be working on a system that will allow the fins to be attached more robustly while still being interchangeable. Slots in the outer tube allow the fins to be attached to the inner tube, increasing the integrity of the bond between the fins and the body tube. The rocket motor is inserted into the tube and fastened to the rings using screws. The motor case has one flanged end that protrudes from the bottom of the rocket. This flange lays flush with the bottom surface of the thrust ring to ensure that thrust is directly transferred to the rocket body.

Finite element analysis and simple closed-form algebraic equations will be used to design and analyze these components. When designing fin mounts, the drag equation (Equation 5) will be used to predict the large drag forces on the fins based on the required fin geometry. Press fit geometry and epoxy requirements for attaching the fins can be calculated once the expected drag force is known.

Equation 4: Drag Equation

$$\boldsymbol{F_{drag} = \frac{1}{2}\rho A C_D v^2}$$

Equation 5: The Drag Equation

A finite element analysis of the thrust ring in ABAQUS by Dassault Systemes will be performed. A thrust profile of the motor will be input as the applied load and stress, deformation, and buckling of the ring will be checked. These results will also help optimize part geometry to efficiently transfer load to the rocket body while removing ring material where not necessary to conserve rocket weight. Similar analysis of the fin attachment rings will be performed in ABAQUS. Standard hand calculations can be used to the fasteners used in the motor retention and fin can subassembly.

6.3.3 Structural Effects of Payload Hatch

To safely recover and land the rocket, a pilot chute and parafoil will be stored inside of the body tube and deployed at a rectangular catch in the side of the rocket. Figure 43 shows a CAD mockup of this hatch on a 48in long 4in diameter body tube. The cutout of fiberglass material for the hatch will create a local structural weakness in the rocket body. In the area around the hatch, the material discontinuity will make the structure prone to higher stresses, larger deformations, and will likely induce a buckling mode that is triggered at lower critical compressive load.

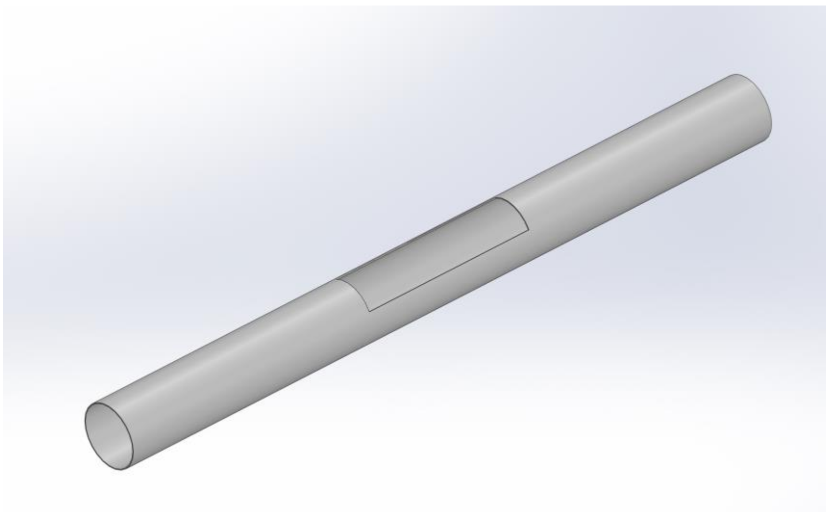


Figure 43: 3D CAD model of the body tube with the parachute hatch.

To mitigate the negative structural effects of the hatch, structural bracing will be designed for the hatch area to restore maximum stress, displacement, and buckling conditions as close as possible to those of an unaltered body tube. The bracing will be two metal plates running along the long axis of the hatch, as detailed in 3.3.1 This design process will begin with a finite element analysis of a fiberglass body tube. The composite modeler in ABAQUS by Dassault Systemes will be used to predict the stress, deformation, and buckling response of the rocket body under expected thrust and drag loading conditions, which form an axially compressive load pair. These results will create the benchmarks that the support plates and body tube with the hatch must meet.

Buckling at the location of the hatch is expected to be the most critical design constraint. Specifically, the edges of the hatch opening parallel to the axis of the body tube will likely be the buckling location due to a decreased moment of inertia in the cross section and a free edge boundary condition. Therefore, the initial plate design will aim to provide stiffness to those two edges, hopefully removing a buckling mode located at the hatch opening. The structural plates will likely be machined from ¼in thick aluminum 6061-T6. Another finite element analysis in ABAQUS of the tube with the hatch and bracing will optimize the geometry of the structural bracing for the required structural performance and mass.

6.3.4 Payload Section Trade Study

Three designs were compared for initial rocket structure. Version 1 consists of a 4in diameter tube for both the payload and the booster section (Figure 44).

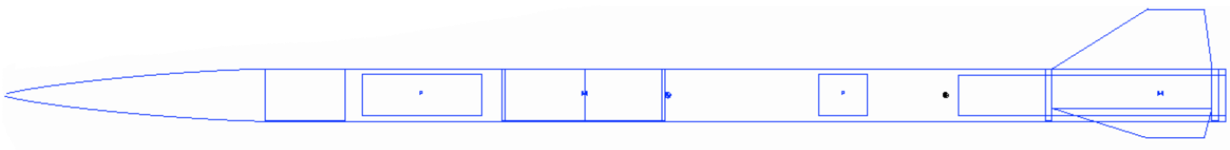


Figure 44: Version 1 of Rocket (4" Payload Section)

Version 2 consists of a 4in diameter payload section with a transition down to a 75mm diameter tube for the booster (Figure 45). The same fins and tube length were used in both version 1 and 2; however the length of the rocket was increased slightly due to the transition section.

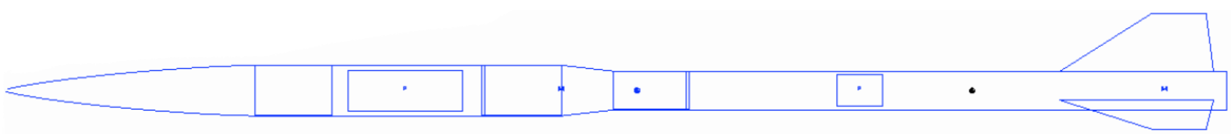


Figure 45: Version 2 of Rocket (5" Payload Section)

Version 3 consists of a 6in diameter tube for the payload with a transition down to a 4in diameter tube for the booster (Figure 46). Because of the larger tube diameter, the overall length of the rocket was increased by both the transition section and by the nose cone and some of the fin dimensions (length, semi-spam and sweep length were also increased. All three versions use a 75mm motor mount and 10lbs added mass for the payload. A summary of mass, stability and simulation differences is described in the table below:

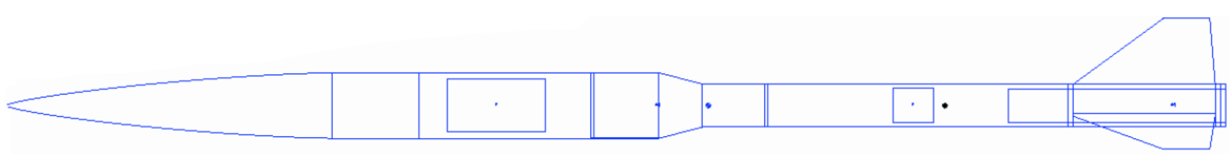


Figure 46: Version 3 of Rocket (6" Payload Section)

Table 32: Mass, Stability, and Simulation Differences

Version	Dry Weight (lbs)	Alt on CTI L800 (ft)	Stability (with L800)	Stability (dry)

Version	Dry Weight (lbs)	Alt on CTI L800 (ft)	Stability (with L800)	Stability (dry)
1.0	18.76	10,468	2.9	5.29
2.0	17.35	11,894	3.79	6.66
3.0	21.99	8,258	1.99	3.62

NOTE: CTI L800 was used only to show approximate altitude and stability differences

From the data above, the best design is Version 1: a rocket with no transition section. Increasing to 6in payload adds weight to the final design and decreasing the booster from 4in to 3in only saves 1.41lbs while adding a more challenging construction process with the transition and surface mounted fins.

6.4 Key Technical Issues and Risk

Table 33 outlines the risks, probability, and impact on project. To minimize the risks, the structures subteam created a risk reduction plan for each risk. Figure 1 Table 33: Risk and Risk Reductionis a stoplight diagram to better show the probability of risk and the impact.

Table 33: Risk and Risk Reduction

	Risk	Probability	Impact on Project	Risk Reduction Plan
1.	High Crosswinds on Launch Site	Low	Low	If we have easily replaceable fins, have a second set of windy-weather fins, otherwise wait for the next day to launch.
2.	Rocket Departs from Expected Trajectory	Medium	High	Reduce mass, check that fins are equally sized and spaced, adjust CP (center of pressure) and CG (center of gravity), and perform stability calculations in OpenRocket.
3.	Separation Failure	Very Low	High	Ensure that all couplers fit without sticking under flight-accurate transverse loads (with safety margin) and that shear pins sized properly for charge size.
4.	Motor Mount	Very Low	Very High	Test all mounts with a smaller

	Failure			motor first in a test fire to be sure they can handle the full motor sizing.
5.	Rocket Unstable or Weakly Stable after Launch	Medium	Medium	Test in wind tunnel and make necessary modifications to increase stability, including modifying fins, decreasing weight, etc.
6.	Delamination or Other Damage to Fiberglass	Medium	High	Handle fiberglass with caution (low compressive strength compared to carbon fiber), layer fiberglass in different directions to increase strength
7.	Fins Detach upon Launch	Low	High	Load test fins to ensure they can handle launch loads, regardless of whether or not they are detachable. If they are detachable, add in an extra margin of safety
8.	Rocket over Mass Budget	Very Low	High	Make sure that subteams are constantly updating their sections in the BOM so we know where all the mass on the rocket is and where it is.

		Impact				
		Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)
Probability	Very High (5)					
	High (4)					
	Medium (3)			5	2, 6	
	Low (2)		1		7, 9	
	Very Low (1)			8	3	4

Figure 47: Structures Mitigated Risk Matrix

6.5 Interfaces

Table 34 includes interfaces with other subteams. In addition, structures will maintain the OpenRocket model, CAD model, and mass budget.

Table 34: Structures Interfaces with Other Subteams

Output	Source	Receiver	Description
Case Diameter	Propulsion	Structure	A case that is able to fit both COTS and custom motor will be created by the propulsion team which will allow the structure team design the rest base on the case instead of the motor.
Deployment Mechanism Design	Payload& Recovery	Structure	A side-hatch deployment mechanism will be developed by the payload and recovery teams for deploying the parafoil while its structural support will be built by the structure team.
Material of Avionics Bay	Structure	Avionics	The rocket will be made out of fiberglass to be sure that the avionics antennas will be able to be used and get signal.
Position of Avionics Bay	Avionics	Structure	The position of avionics bay is determined by the avionics team which will be situated between the backup chutes and the parafoil for easier connections to both the backup parachute and the control lines for the payload.
Rocket Diameter	Structure	Propulsion	The rocket diameter is necessary for the propulsion team to determine if the current motor is the appropriate size for our goal.
Rocket Diameter	Payload & Recovery	Structure	The structure team decides the diameter of the rocket based on the needs of the payload and recovery teams. It is possible having a fairing specifically for the payload section. However, due to the increase of drag, we will most likely not have a fairing.
Specific Mass Budget	Structure	Propulsion	The structure team will estimate the specific mass budget base on each team's need. The total dry mass will be needed for propulsion team to determine if the motor is appropriately sized while being able to provide the desired velocity off the rail and enough impulse to reach the target altitude.
Specific Packing	Structure	Payload &	The structure team will determine the specific packing volume for the payload and recovery

Volume		Recovery	sections base on the dimension of the rocket. The specific packing volume is needed to calculate the dynamics as well.
Thrust Profile	Propulsion	Structure	The thrust-time curve of the motor is needed from the propulsion team for designing a structure that is able to stand the body force produced by the motor.

6.6 Going Forward Plan

Beginning in early January, the structures subteam will work towards perfecting the layup technique. Currently, structures attempted to use a cardboard tube covered in mold release wax as a mold, but this did not come cleanly out of the carbon fiber layup. Structures will try other methods of releasing the mold, such as covering the tube in wax paper, a plastic sock, and using a different material for the mold.

Once the layup technique has been finalized, structures will determine the ideal fiber angle for the airframe tubes by testing 90-0, 60-30, 50-40, and 45-45 degree angle weaves under axial compression and bending moments to determine the strength of each weave.

The structures subteam will simultaneously work on developing an accurate OpenRocket model and CAD model of the full rocket, both of which will be finished before the end of January. These models will continue to be updated over the course of the year to reflect changes in the designs of other subteams.

Structures will also interface with payload and recovery to refine the parafoil deployment hatch and support structure in the month of January. A part of this process is building a prototype of the hatch and confirming the design proposed in 3.3.1 works as intended. Testing the hatch will begin in February.

Towards the end of January, structures will design a fin jig to allow accurate mounting of the fins. By creating such a jig, the fins will be able to be attached to the rocket far more accurate than by simply approximating when the fins appear to be straight on the rocket. Structures will also use the OpenRocket model being developed earlier in January to size the fins so that the stability requirement is met.

Developing a CAD model of the rocket and sizing the fins prepares Structures to begin machining parts of the rocket and to begin assembling the system at the end of February, with the goal of finishing construction on the first version of the rocket by the beginning of March.

Structures will interface with other subteams to practice integrating the rocket prior to the first launch opportunity either late February or early March. More specific dates are summarized in Table 35 and Table 36.

Table 35: January Schedule

	Task	1/3/2015	1/10/2015	1/17/2015	1/24/2015
1	Perfect layup technique				
2	Full OpenRocket model				
3	Refine hatch and payload support				
4	Full CAD model				
5	Redesign fin jig				
6	Size fins				
7	Determine fiber angle for fin tubes				
8	Test strength of tubes				
9	Machine parts				
10	Test hatch				
11	System assembly				
12	Practice integration				

Table 36: February Schedule

	Task	1/31/2015	2/7/2015	2/14/2015	2/21/2015	2/28/2015
1	Perfect layup technique					
2	Full OpenRocket model					
3	Refine hatch and payload support					
4	Full CAD model					
5	Redesign fin jig					
6	Size fins					
7	Determine fiber angle for fin tubes					
8	Test strength of tubes					
9	Machine parts					
10	Test hatch					
11	System assembly					
12	Practice integration					

7. Summary of System Level Concerns and Risks

Specific subteam risks are discussed in the above subteam sections. The following is a reiteration of the most significant risks the Team faces, as well as significant system-level and administrative concerns.

Schedule Slip: (1)

The development of the rocket and all of its subsystems may take longer than expected given the complexity of our system. We are also unsure about exact flight test opportunities until the dates for the next launches are released. To mitigate this, an extra month is built in beyond the 4 flight test opportunities for backlog. Also, we can usually consult Scott Costigan, one of the chairs of the Maine Missile Math and Science Club, the club that runs the launches in Berwick, ME, if we need a shorter-notice opportunity.

Loss of Rocket: (2)

Testing the rocket could result in non-recovery of the rocket, and physical loss. Loss would be a significant setback for the project, both in budget and schedule. To mitigate this risk, we plan to manufacture or purchase redundant copies of parts that have a long lead/manufacturing times. Also, a detailed record of the build process will be kept to decrease the time and effort required for a rebuild in case of a test launch failure.

Preventing Injury to Team Members: (3)

Team members will abide by the rules given by ESRA and as defined in is document, including, but not limited to:

- Wearing protective equipment around energetic devices
- Storing and using flammables safely
- Operating machinery safely

Finding a Parafoil: (4)

Sourcing and purchasing a suitable parafoil is one of the biggest risks to our schedule. Since our rocket weighs significantly less than the average skydiver, most commercially available parafoils have surface areas that are not appropriate for our application. Custom parafoils would also pose significant risk, as they have lead times of 14-22 weeks. Kites and paragliders (which are less expensive and available in smaller sizes) will not reliably inflate after a deployment event.

The Team is exploring several ways to mitigate this risk. First, the Team could use a commercially available parafoil. This would decrease the descent rate significantly, but risks improper parafoil inflation due to insufficient weight. Second, the Team could acquire a custom parafoil on a rush schedule. Unfortunately, this option would be very costly. Third, the Team could acquire or design a pattern for a parafoil, and either self-manufacture or contract out this design to be made quickly. However, this increases the workload on the Team.

Risk	5					
	4				4	
	3				2	
	2				1	
	1					3
		1	2	3	4	5
Impact						

Figure 48: Systems Risk Matrix

8. Conclusion

The Team plans to fly a rocket to 10,000ft for the 2016 IREC, featuring a guided parafoil system for descent. The rocket will ascend using a commercial solid motor to 10,000ft and at apogee deploy a pilot chute at apogee. At 5,000ft, the parafoil will deploy, and the guidance system will use the sensor suite to steer the rocket to a predetermined landing site. In case of failure, a drogue will deploy above 1500ft, and a backup parachute will deploy just under 1500ft to ensure a safe recovery.

Appendix A: Combined Requirements Table

Internal #	Source	**Requirement**	**Subteam lead responsible**
1.0	1.0	Shall be safe for all personel involved	ALL
1.1	7.2.2.1	Personnel shall stand minimum 400ft from launch pad to permit launch	Exec
2.1	8.0, 4.1.2	Shall keep ESRA apprised of plans if using parafoil	Exec
2.2	8.0	Shall provide ESRA progress reports and Test reports as tests are completed.	Exec
3.1	2.1	Payload shall weigh more than 10lbs	Payload
3.2	2.3	Payload shall be capable of being weighed independently of the rocket	Payload
3.3	4.1	Shall be recovered in reflyable condition	Recovery
3.4	4.1.1	Shall follow dual-event CONOPS	Recovery
3.4.1	4.1.1.1	Initial deployment event shall occur at apogee and stabilize vehicle attitude	Recovery
3.4.2	4.1.1.2	Second deployment event shall occur at an altitude no higher than 1,500ft AGL, reducing descent velocity to less than 30ft/s	Recovery
3.5	4.2	Shall incorporate redundant recovery system electronics, with separate power supply	Recovery
3.6	4.6	Shall carry a radio beacon or similar transmitter aboard each independently recovered body.	Recovery
3.7	2.2	Launch vehicles entered shall be able to recover themselves independent of active or passive payload function	Recovery
3.8	4.7	Recovery system shall be successfully tested by ground or flight testing	Recovery
4.1	4.3	Electrical wiring critical to safe operation and recovery of the launch vehicle should conform to the safety-critical wiring guidelines found on the ESRA website and in the requirements under 7.x. All non-safety-critical wiring is exempted.	Avionics
4.2	4.5	Launch vehicles entered into the IREC Basic Category shall carry an altitude logging COTS flight computer with on-board data storage which will provide an official record of apogee for scoring. This flight computer may also be one of those used for recovery system deployment. Although the on-board data record is considered the primary for scoring, telemetric altitude data may be used at the judging panel's discretion in the event a launch vehicle is destroyed during recovery. ESRA	Avionics

		recommends using the Jolly Logic Altimeter Two for official altitude logging.	
4.3	5.1	All “energetics” shall be "safed" until the rocket is in the launch position, at which point they may be "armed". For the purpose of this requirement, energetics are defined as all stored-energy devices, other than propulsion systems, that have reasonable potential to cause bodily injury upon energy release. An energetic device is considered safed when two separate events are necessary to release the energy. An energetic device is considered armed when only one event is necessary to release the energy. Although these definitions are consistent with the propulsion system arming definition provided in Section 3.4 of this document, this requirement is directed mainly at the energetics used by launch vehicle launch vehicle and payload recovery systems and extends to all other energetics used throughout the launch vehicle and payload. Note that Section 3.4 requires propulsion systems be armed only after the launch rail area is evacuated to a specified distance, while this requirement permits personnel to arm other stored-energy devices at the launch rail. All energetic device arming features shall be located on the airframe such that any inadvertent energy release by these devices will not impact the person arming them. For example, the arming key switch for an ejection charge shall not be located at the same airframe clocking position as the hatch panel jettisoned by that charge. The following table lists some common types of stored-energy devices and in what configuration they are considered non-energetic, safed, and armed.	Avionics
4.4	B6, T3	The launch vehicle shall contain a custom flight computer responsible for gathering data from sensors, initiating deployment of the parafoils and parachutes, and controlling the payload upon descent.	Avionics
4.4.1	B6, T3	The flight computer shall contain the following sensors with the purpose of gathering information about the rocket in-flight: Digital IMU, GPS Sensor, and Barometer	Avionics
4.4.1.1	B3, B6, T3	The data generated by all sensors shall be stored in such a way that if the rocket were to take larger damage the data would not be lost. This data shall be	Avionics

		easily recoverable.	
4.4.1.2	S1	The sensor array and communication module shall be designed and installed on a printed circuit board with a port to easily connect the flight computer. The whole PCB and computer system shall take a minimal amount of space so as to easily fit within the rocket.	Avionics
4.4.2	S1	The flight computer shall contain a Radio telemetry module in order to transmit the rocket's information to the ground station throughout the flight.	Avionics
4.4.3	T5	The flight computer shall be programmed with a recovery destination before flight, and shall use information from the sensor array to determine appropriate controls to guide the vehicle to the destination.	Avionics
4.4.4		The flight computer shall fit within the avionics bay as defined by the Structures/Avionics interface.	Avionics
4.5		The avionics bay shall have connectors on each end to interface with other systems within the flight vehicle. These are defined by their interfaces.	Avionics
5.0	1.0, 6.1	Shall target 10,000ft AGL (Ground level is 4,300ft MSL)	Propulsion
5.0.1	Internal	The minimum impulse the motor provides shall be no less than 9800Ns	Propulsion
5.1	3.1	Propulsion shall be restricted to COTS Solid, COTS hybrid, or custom solid	Propulsion
5.2	3.2	Propellants shall be non-toxic	Propulsion
5.3	3.3	Propulsion shall be single stage	Propulsion
5.4	3.5	Custom propulsion shall undergo pressure testing and static fire testing as specified	Propulsion
5.5	6.3.1	Shall have sufficient velocity upon departing launch rail	Propulsion
6.1	4.6	Structure shall be reusable after recovery	Structures
6.2	7.1.2	MIT RT shall use the ESRA provided launch control system.	Structures
6.2.1	6.2	Rocket shall launch at elevation angle between 83 and 85 degrees	Structures
6.2.2	7.1.2	Rocket shall attach to IREC-supplied launch rails via a minimum of two rail guides. These rail guides shall support the vehicle's fully loaded launch weight when suspended horizontally, and the aft most rail guide must support the launch vehicle's fully loaded launch weight while vertical.	Structures
6.2.3	6.3.2	Rocket shall have a stable angle of attack. Based on launch wind speed and exit rail velocity, we need an angle of attack less than 26 degrees.	Structures

6.2.4	6.3.2	Rocket shall remain stable for entire ascent	Structures
6.2.5	7.3	A person shall stand no higher than 4ft on a ladder to access the rocket on the launch pad	Structures
6.3	7.2.2.2	Any single point failure shall be prevented by a removable jumper or key.	Structures
6.4		Combined mass of fuselage, fins, internal support, bulkheads, nose cone, and other structural components shall be less than 6 kg.	Structures
6.5	4.6	To allow for tracking mechanisms to be placed inside the rocket, the body material shall be radio transparent.	Structures
6.5.1	6.3.2	Rockets shall be statically stable, but not over stable, off the launch rod and for the entire ascent. Goal for static margin is between 1 and 2 calibers.	Structures
6.6		Structure shall bear all loads associated with launch, flight, landing.	Structures
6.6.1		Fuselage shall be able to withstand bending moment from aerodynamic pressure at expected maximum angle of attack.	Structures
6.6.2		Structure shall be able to withstand 3,915N of thrust.	Structures
6.6.3		Structure shall be able to bear forces due to parachute deployment mechanisms.	Structures
6.6.4		Recovery bulkheads shall be able to withstand maximum load applied by shock cord during parachute deployment and descent. Rocket body shall be designed to allow for side parafoil deployment, and it shall be able to support these loads on the side of the body. Structure shall not crack due to force of parachute lines.	Structures
6.6.5		Structure shall bear the maximum load due to the rocket landing under parachute recovery.	Structures
6.6.6		Materials shall tolerate temperature and heat flux from motor and flight conditions.	Structures
6.7.1		Due to the potential for fins to break, the fins shall be able to be easily replaced.	Structures
6.8	T1	Avionics, recovery, payload, and propulsion shall be easily accessible. Payload shall be accessible within a maximum of 5 minutes, and the maximum integration time shall be 10 minutes.	Structures
6.9	B6	In order to prepare for entering the advanced category in future years, the body tube and nosecone shall be either entirely manufactured by students or shall be substantially modified from its off-the-shelf configuration. Reinforcement of commercial, off-the-shelf airframe components to withstand predicted loads is sufficient, but complete student manufacture	Structures

		is desired.	
6.10		Due to the size of the payload and recovery systems, the body tube diameter will be 6in.	Structures
7	ESRA Wiring Rules	Wiring critical to safe operation and recovery of the rocket shall conform to the wiring rules. Other wiring is exempt.	All
7.1	ESRA Wiring Rules	All wire shall be stranded, insulated, 22 AWG or larger. Strands shall be copper, plated with either silver or tin (entire wire, not just the ends).	All
7.1.1	ESRA Wiring Rules	When an off-the-shelf component includes flying leads, those leads may be used unmodified. For example, an E-match may contain solid wire, a battery connector may integrate 26 AWG wire, etc.	All
7.1.2	ESRA Wiring Rules	Stranded wire of sizes smaller than 22 AWG may be used only when required by an off-the-shelf component. For example, if the terminal block on an altimeter is sized to accept 24 AWG wires then that is the size of wire that should be used for that portion of the circuit.	All
7.1.3	ESRA Wiring Rules	Wire strands shall never be removed in order to allow a wire to fit into a smaller hole or terminal. Use smaller wire for this purpose.	All
7.2	ESRA Wiring Rules	Wire shall be stripped only with a wire stripping tool of the correct gauge. Any severed strands shall be cause for rejection.	All
7.2.1	ESRA Wiring Rules	The best wire stripping is achieved with thermal strippers and Teflon/Tefzel wire; however these are not absolutely required. PVC-insulated wire is acceptable and may be stripped with thermal strippers	All
7.2.2	ESRA Wiring Rules	Personnel using a new stripper for the first time should practice on a piece of scrap wire the same gauge and type as will be used. Strip a short length and then strip more insulation from the same wire. If you can now see scratches or nicks in the wire strands from the first strip, something is wrong with either tool or technique.	All
7.2.3	ESRA Wiring Rules	Pocket knives and teeth are prohibited for wire stripping.	All
7.3	ESRA Wiring Rules	Each end of a wire shall be terminated in one of the following approved methods, with exceptions in 7.4 and 7.5 below:	All
7.3.1	ESRA Wiring Rules	Crimped into a crimp terminal (preferred). This includes crimp terminals on multi-conductor connectors such as 9-pin D-sub connectors (see table below).	All

7.3.2	ESRA Wiring Rules	Screwed into a binding screw terminal (acceptable).	All
7.4	ESRA Wiring Rules	Note: for the purposes of this document, “terminal blocks” have screw-driven clamping mechanisms for clamping in wires, enclosed within a plastic housing. The wire connections are inside a cavity and are often difficult to inspect and test for security. Wires shall be terminated into a terminal block, only if a piece of off-the-shelf equipment (i.e. an altimeter) has built-in terminal blocks and so there is no other choice. Two-piece terminal blocks must be positively secured together – friction fit is insufficient.	All
7.5	ESRA Wiring Rules	Wires shall be terminated by soldering, only if a piece of off-the-shelf equipment (i.e. an arming key switch) has built-in solder terminals and so there is no other choice.	All
7.5.1	ESRA Wiring Rules	Solder is discouraged because the reliability of a solder joint cannot be established by the judges by visual inspection alone. There are a number of process parameters (temperature profile, solder alloy, flux, gold removal, etc.) that must be well controlled to give reliable results and these cannot be inspected post-fact.	All
7.6	ESRA Wiring Rules	All crimp operations shall be performed with the correct tooling, using crimp terminals sized for the appropriate wire gauge. Where multiple wires are crimped into a single terminal, calculate the effective gauge (for example, two 22 AWG are effectively 19 AWG).	All
7.6.1	ESRA Wiring Rules	Crimp tooling shall not be improvised from pliers, vices, or other incorrect tools. Crimp features of multitools (Leatherman, Gerber, etc.) shall not be used.	All
7.7	ESRA Wiring Rules	Terminals with insulated plastic sleeves (usually color-coded to indicate barrel size) shall not be crimped.	All
7.7.1	ESRA Wiring Rules	If a terminal is supplied with an insulated plastic sleeve, it shall be removed prior to use. It may be necessary to adjust the crimp tooling to get a tighter squeeze.	All
7.7.2	ESRA Wiring Rules	The crimp quality of insulated terminals is difficult to inspect. There is normally no need for insulation when terminals are mounted properly in barrier blocks. If insulation is required, add clear heat-shrink tubing.	All

7.8	ESRA Wiring Rules	When a bare wire is held down by a binding screw terminal the wire shall make a 180 degree hook and strands must be visible exiting the screw head. Only one wire shall be permitted per screw. The wire bend shall be clockwise, so that it will tighten as the screw is torqued.	All
7.9	ESRA Wiring Rules	When ring or spade terminals are held down by binding screw terminals, a maximum of two terminals are allowed per screw.	All
7.10	ESRA Wiring Rules	A maximum of three wires shall be crimped into a single terminal barrel. Butt-splice terminals are considered to have separate barrels in each end.	All
7.11	ESRA Wiring Rules	If two or more wires must be joined, one of the following approved methods shall be used: Note: for the purposes of this document, “barrier blocks” have screw terminals between insulating barriers, and often have metal jumpers between screws to allow electrical connections of screws across the block. The screws are usually larger than those in terminal blocks and are easily visible for inspection. The screws are designed to allow the connection of bare wires (turned in a clockwise “J” shape) or ring terminals.	All
7.11.1	ESRA Wiring Rules	Crimp a ring terminal onto each wire, and then screw them into a barrier block. Add approved barrier block jumper pieces if many wires must be joined.	All
7.11.2	ESRA Wiring Rules	Screw bare wires under binding head screws in a barrier block. Add approved barrier block jumper pieces if many wires must be joined.	All
7.11.3	ESRA Wiring Rules	Crimp the wires into an un-insulated butt-splice terminal, and then insulate with clear heat-shrink tubing.	All
7.11.4	ESRA Wiring Rules	Any wire-twisting splice method (including wire nuts) is explicitly forbidden.	All
7.12	ESRA Wiring Rules	All insulating tubing (usually heat-shrink) shall be transparent.	All
7.13	ESRA Wiring Rules	No tape, glue or RTV shall be used to insulate or bundle any element of the wire harness.	All
7.14	ESRA Wiring Rules	The following rules apply to connectors:	All
7.14.1	ESRA Wiring	They shall use crimp contacts, as soldering has been forbidden.	All

	Rules		
7.14.2	ESRA Wiring Rules	They shall use a positive locking mechanism to keep the two halves mated under vibration and tension. Friction fit alone is not acceptable.	All
7.14.3	ESRA Wiring Rules	Plastic connector latches shall not be used (such as found on automotive applications), but circular connectors with plastic coupling nuts are acceptable.	All
7.15	ESRA Wiring Rules	Individual wires shall be bundled together to make a harness (factory multi-conductor wiring in a common outer jacket is also acceptable). The safety critical harness shall be kept separate from the payload harness (if any). Bundling shall be accomplished by:	All
7.15.1	ESRA Wiring Rules	A light twist (for mechanical reasons only, no EMC mitigation is intended).	All
7.15.2	ESRA Wiring Rules	Short (1 cm) lengths of clear heat-shrink tubing or zip-ties every 5 cm.	All
7.15.3	ESRA Wiring Rules	Wire mesh sleeving, provided it allows for inspection of the wiring inside.	All
7.16	ESRA Wiring Rules	The harness shall be supported by plastic P-clamps. It shall not be permitted to touch any sharp edge or screw thread.	All
7.17	ESRA Wiring Rules	All items that are connected by the harness (barrier blocks, sensors, batteries, actuators, switches, etc.) shall be rigidly fixed to the rocket structure so that they cannot move. Rigid fixing implies attachment with threaded fasteners or a solid glue bond. Cable ties and/or tape are not acceptable examples of rigid fixing.	All
7.18	ESRA Wiring Rules	No wire shall be tight. All wire must have some slack, demonstrated by a curve at its termination.	All
7.19	ESRA Wiring Rules	Batteries shall be connected appropriately:	All
7.19.1	ESRA Wiring Rules	9V transistor batteries shall be secured in clips, and connected using proper snap terminals.	All
7.19.2	ESRA Wiring Rules	Gel-cell batteries shall be secured with clamps, and connected using “faston” crimp terminals.	All
7.19.3	ESRA Wiring Rules	Cylindrical batteries (AAA, AA, C, D, etc.) shall be mounted into commercial holders. The holders shall be rigidly secured to the structure, and the batteries	All

shall then be strapped into the holders.

Appendix B: Resources

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