HPRC
WPI AIAA

Proposal

NASA University Student Launch Initiative
September 21st, 2020

Worcester Polytechnic Institute
100 Institute Road, Box #5719
Worcester, MA 01609

AIAA
WPI STUDENT BRANCH

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3 Acronyms

1. 3D: Three Dimensional
2. AARD: Advanced Retention Release Device
3. ABS: Acrylonitrile Butadiene Styrene (FDM Filament)
4. AGL: Above Ground Level
5. AIAA: American Institution of Aeronautics and Astronautics
6. APCP: Ammonium Perchlorate (Composite Solid Fuel)
7. BRC: Bridgeton Area Rocket Club
8. COVID-19: Coronavirus Disease 2019
9. CMASS: Central Massachusets Space Modeling Society
10. CNC: Computer Numerical Control
11. CRMRC: Champlain Region Model Rocket Club
12. CTI: Cesaroni Technology Incorporated
13. EBI: Ensign-Bickford Industries, Inc.
14. E-Match: Electric Match
15. EnP: Electronics and Programming
16. FAA: Federal Aviation Administration
17. FDM: Fused Deposition Modeling (3D Printing Technology)

18. GPS: Global Positioning System
19. HPR: High Power Rocketry
20. HPRC: High Power Rocketry Club
21. IDE: Integrated Development Environment (For Software Development)
22. LiPo: Lithium Polymer (Battery)
23. LoRa: Long Range (Wireless Protocol)
24. LWHPR: Lake Winnipesaukee High Power Rocketry
25. MQP: Major Qualifying Project (Senior Project)
26. MSFC: Martial Space Flight Center
27. NAR: National Association of Rocketry
28. NASA: National Aeronautics and Space Administration
29. NFPA: National Fire Protection Association
30. PC: Polycarbonate (FDM Filament)
31. PLA: Polylactic Acid (FDM Filament)
32. PLAR: Post Launch Assessment Review
33. PPE: Personal Protective Equipment
34. PWM: Pulse Width Modulation
35. RSO: Range Safety Officer
36. SGA: Student Government Association
37. SLI: Student Launch Initiative
38. STEM: Science, Technology, Engineering, and Mathematics
39. STM: ST Microelectronics
40. TPU: Thermoplastic Polyurethane
41. TRA: Tripoli Rocketry Association
42. UAV: Unmanned Arial Vehicle
43. URRG: Upstate Research Rocketry Group
44. USLI: University Student Launch Initiative
45. WPI: Worcester Polytechnic Institute

4 Executive Summary

This document is the written proposal of Worcester Polytechnic Institute's (WPI) American Institute of Aeronautics and Astronautics (AIAA) chapter for the National Aeronautics and Space Administration's (NASA) University Student Launch Initiative (USLI) competition. The Academic Affairs Office at NASA Marshall Space Flight Center (MSFC) conducts the Student Launch Initiative (SLI) each year.

The goal of WPI's USLI team, called WPI High Power Rocketry Club (HPRC), is to design a rocket and payload to complete the requirements outlined in the Student Launch Handbook. In summary, these goals are to launch a rocket containing a selected payload, which will upon decent between 500 and 1,000 ft deploy and complete the autonomous self-righting and photo tasks. In order to achieve these requirements, the team has split into two divisions: a rocket team and a payload team that further split into smaller sub-teams working on individual components of the rocket or payload. Each division will collaborate and design compatible parts to launch and deploy in sequence, land, and complete the outlined objectives. Upon test launches, and per NASA's suggestions, minor changes will be made based on experimental data to ensure the success of our goals. All changes made will be reviewed by the team's mentor, NASA SLI representative and Range Safety Officer (RSO) to ensure that they comply with safety protocols outlined by the National Association of Rocketry (NAR) and the Federal Aviation Administration (FAA).

5 Mission Statement

Through this competition, our team aims to help our members develop an understanding of teamwork, rocketry, robotics, and the engineering design processes and to share the knowledge we gain through this competition with our community to promote interest and excellence in STEM.

6 General Information

6.1 Team Mentor

Jason Nadeau
Lake Winnipesaukee High Powered Rocketry
(978) 761-9790
jabikeman@aim.com

6.2 University Advisor

John J. Blandino
Associate Professor, Mechanical Engineering
(508) 831-6155
blandino@wpi.edu

6.3 Executive Leads

6.3.1 Captain

Kirsten M. Bowers, *Class of 2022*
Major in Aerospace Engineering, Minor in Electrical Engineering.

kmbowers@wpi.edu, 716-255-3417

Responsible for the operation of the team as a whole and represents the team for both NASA and WPI. The Captain must manage and coordinate the Division Leads to meet competition deadlines, as well as ensuring leads and officers are not lax in their duties. The Captain is also responsible for maintaining a team roster and is the final arbitrator of all disputes.

Kirsten Bowers is a Junior pursuing an Aerospace Engineering major and Computer Science minor. She has participated in HPRC since the foundation of the club, and previously served as Interim Rocket Lead and Treasurer. She currently has a level 1 high powered rocketry certification and is pursuing a level 2 certification.

6.3.2 Rocket Lead

Troy M. Otter, *Class of 2022*
Major in Aerospace Engineering

tmotter@wpi.edu, 508-455-8828

Responsible for leading the design, construction, and documentation of the launch vehicle. In charge of maximizing the participation of their members through delegation and education.

Troy Otter is a Junior pursuing a dual B.S./M.S. in Aerospace Engineering. He has participated in HPRC for 2 years, and previously served as Logistics Officer and Fin Can and Motor Retention System Lead.

6.3.3 Payload Lead

Thierry L de Crespigny, ***Class of 2022***
Major in Aerospace Engineering

tldecrespigny@wpi.edu, 650-515-0615

Responsible for leading the design, construction, and documentation of the payload. In charge of maximizing the participation of their members through delegation and education.

Thierry de Crespigny is a Senior pursuing a dual B.S./M.S. in Aerospace Engineering. He has participated in HPRC since the foundation of the club and before in other competitions and this is his second year serving as Payload Lead

6.4 Safety Officer

Michael J. Beskid, ***Class of 2023***
Major in Aerospace Engineering, Major in Robotics Engineering.

mjbeskid@wpi.edu, 518-526-8359

Responsible for the duties of a Safety Officer as laid out in the most recent version of the NASA Student Launch Handbook in addition to safety documentation, safety education, and overseeing construction and launch activities to maintain a safe environment. The Safety Officer may override decisions made by any officer, excluding the Captain, if those decisions would create an unacceptable safety risk.

Michael Beskid is a Sophomore pursuing a double major in Aerospace Engineering and Robotics Engineering. He is currently pursuing a level 1 high powered rocketry certification and plans to complete his certification flight in the near future. This is his second year with the team after gaining critical experience in high powered rocketry and knowledge of relevant safety information during the design, construction, and testing for last year's competition. Michael is an Eagle Scout with significant experience in first aid, lifesaving, and emergency preparedness. His experience in high powered rocketry from working on the team and pursuing his personal certification in addition to his leadership and emergency preparedness skills as an Eagle Scout make Michael well qualified to serve as the Safety Officer for WPI HPRC.

There are inherent risks involved in the fabrication and launch of a class 2 high powered rocket which, if not understood and managed effectively, have the potential for severe consequences. For this reason, safety is of the utmost importance and the highest priority of WPI HPRC. It is the responsibility of the Safety Officer to analyze all hazards and identify any potential risks throughout the design, construction, testing, and flight of the launch vehicle and payload, in addition to any other team activities. Our Safety Officer, Michael Beskid, will have a central role in writing and maintaining a safety plan to recognize and mitigate all hazards posed by facilities, procedures, and materials used by the team. The Safety Officer will have a detailed knowledge of the NAR High Powered Rocketry Code and ensure compliance at all team events. He will work closely with division and sub-team leads to monitor safety at all team events and ensure that safety is the primary consideration in design, construction, testing, and launch. Finally, the Safety Officer will be responsible for educating all team members in necessary safety information and procedures through mandatory safety training presentations, requiring all members to acknowledge a written safety agreement, and fostering a culture of safe and responsible practices.

6.5 General Officers

6.5.1 Treasurer

Kevin G. Schultz, *Class of 2023*
Major in Aerospace Engineering.

Responsible for documenting and managing the budget as well as handling purchasing. They will coordinate with the Treasurer of AIAA.

6.5.2 Logistics Officer

Nikita Jagdish, *Class of 2022*
Major in Mechanical Engineering, Minor in Aerospace Engineering and Computer Science.

Responsible for planning associated with getting the team, equipment, rocket, and payload to and from events including the competition and other launches. This includes securing living accommodations while at the competition.

6.5.3 Engagement Officer

Connor Walsh, ***Class of 2022***
Major in Aerospace Engineering, Minor in Astrophysics.

Responsible for organizing and hosting club engagement events and STEM outreach events. The Engagement officer also coordinates with local organizations to organize collaborative outreach events.

6.5.4 Sponsorship Officer

Julia Sheats, *Class of 2023*
Major in Mechanical Engineering.

Responsible for creating the sponsorship package, making connections with potential sponsors, and securing sponsorship or grant funding for the team. The Sponsorship Officer must actively maintain positive relationships with sponsors and ensure sponsors receive the appropriate benefits per their contribution level.

6.5.5 Documentation Officer

Christian M. Schrader, *Class of 2021*
Major in Aerospace Engineering, Minor in Computer Science.

Responsible for the organization and formatting team documentation in order to meet both competition and team standards. The Documentation Officer must also educate members to enable them to meet those documentation standards as well as maintain team repositories and organizational systems.

6.5.6 Public Relations Officer

Christopher Davenport, *Class of 2022*
Major in Aerospace Engineering.

Responsible for the team's social media presence, merchandise, the website, and the team brand.

6.6 Team Structure

Due to COVID-19, the team will have to change and be adaptable to the way it is structured and run. In order to mitigate the effects and spread of COVID-19, all non-construction or testing meetings will be held virtually for at least the first semester of this school year. The heavier enforcement of subteams will help ensure that when the team does construct, they will be doing so predominately with only their subteams of around three to six people. This year the team is also implementing a task tracker as a way to assign tasks and hold people or groups accountable for internal deadlines. This also helps with communication and transparency on that every part of the team is working on.

6.6.1 Officer Structure

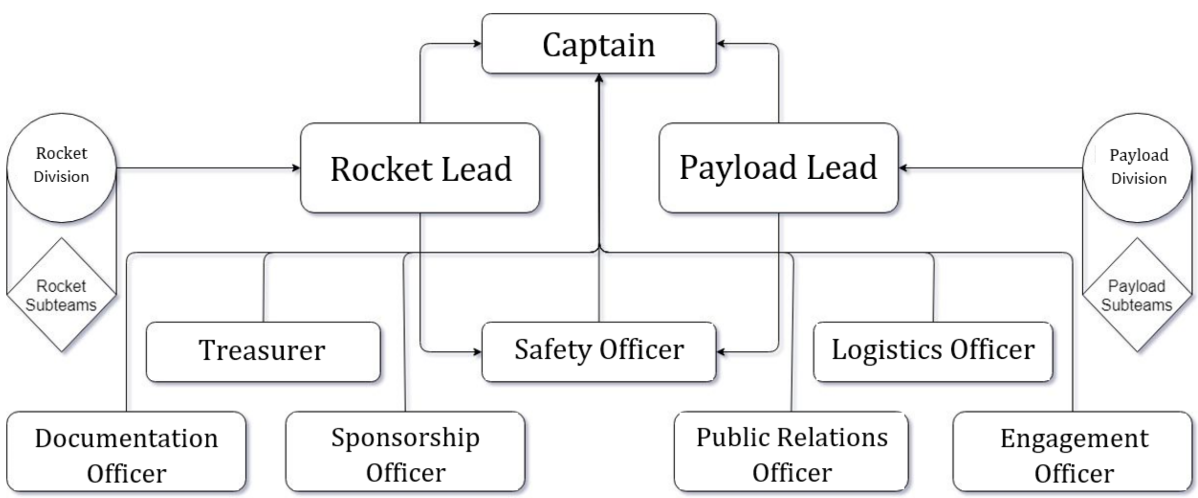

Figure 6.1 Chain of Command

The above image shows the organization of the officer board. At the head is the captain who oversees all the officers in their duties. The rocket lead, payload lead, and captain form the executive board of the team which makes high level team decisions. Each lead is responsible for their respective division and subteams while ensuring that all of their respective aspects of the project are completed. They are also overseen by the safety officer who ensures all member are conducting their work in a safe manner. Below them are the officers for documentation, sponsorship, public relations, engagement, logistics, and treasury who report to the captain.

This year, the stricter implementation of subteams allows members to focus and develop knowledge within a specific discipline of their division that interests them. This is also useful during the COVID-19 pandemic as this allows for teams to meet and construct safely with a fewer number of people.

6.6.2 Subteams

Both divisions have multiple subteams that focus on a certain discipline and competition task of their division. Each subteam would be in charge of designing, selecting, simulating, constructing and testing each of their components. The subteam names are generally straightforward but a brief description of each will be provided.

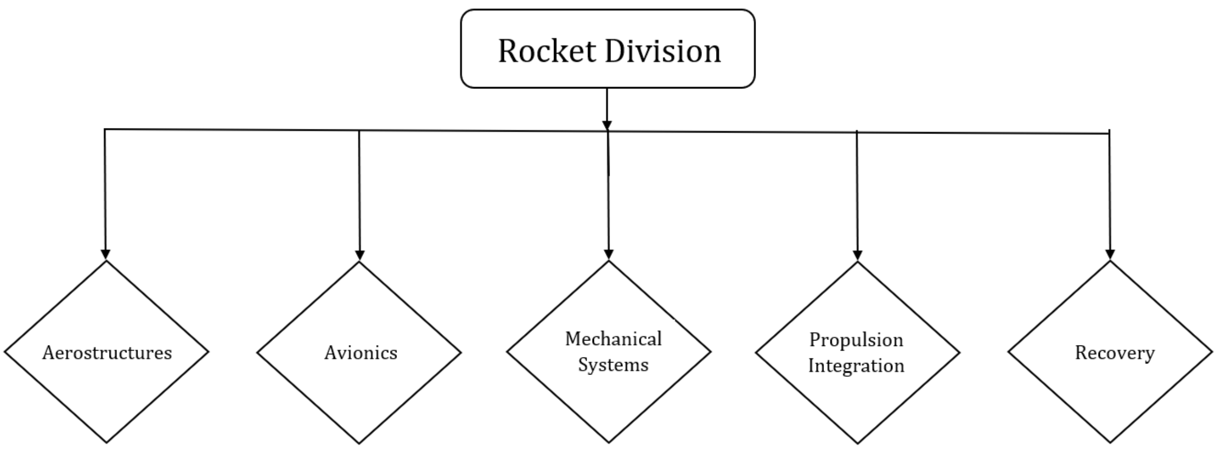

Figure 6.2 Rocketry Subteams

The rocketry division is split in to five subteams: aerostructures, avionics, mechanical systems, propulsion integration, and recovery. Aerostructures is responsible for components such as: the nosecone, airframe, component connections and fins. Propulsion Integration is in charge of motor selection, the fin can and motor retention. Mechanical Systems deals with the airbrakes and payload integration. Avionics holds the tasks that typically relate to the electronics bay, such as sensors, flight computer, flight software, and the electronics bay itself. Finally, Recovery focuses on recovery electronics, chute deployment, chute retention, and chute selection.

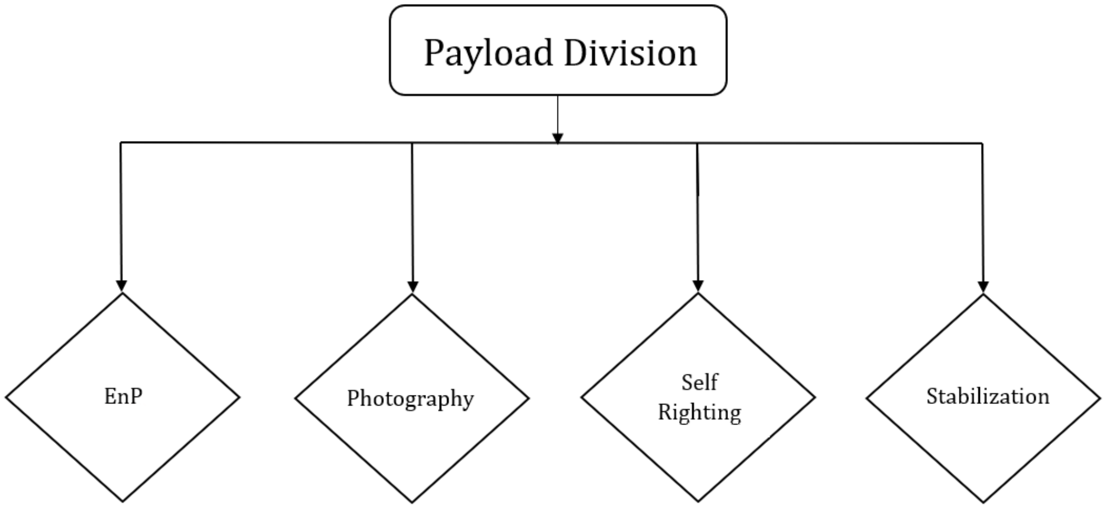

Figure 6.3 Payload Subteams

The payload division is split in to four subteams: Electronics and Programing (EnP), Photography, Self Righting, and Stabilization. EnP is responsible for the control and wiring of the payload. Self Righting's focus is on the mechanism that bring the payload into a position to be stabilized. Then, Stabilization is in charge of the mechanisms which bring the payload to within the five degree tolerance. Photography is responsible for the mechanisms that will take the 360 degree photo.

6.6.3 General Members

Beyond the Officer Board, the team is made up of general members with each one being a part of one division. As of the time of submission, the team has around 57 general members. Over the course of the year, this number is expected to fall slightly as a few members lose interest, shift their time elsewhere, or realize the competition is not for them. This number has significantly increased from our beginning year and has sustained and grown slightly since last year where we reported 44 members at the time of proposal. Thanks to this significant and now retained growth, the team expects to both decrease the workload per student and increase the quality of mentorship, analysis, testing, and design.

6.7 Time Spent on Proposal

With the way our team is split into both divisions and subteams, there have been many meetings on proposal within the just over a month of its announcement. Since school started, we have had one general body meeting that was 1.5 hours long. This meeting introduced the newer members to the competition and guidelines while also brainstorming.

There have been two rocket division meetings in which members brainstormed at the first and reviewed their design ideas in the second. Each of these also took an hour, totaling two hours. Between all the rocket division subteams, there have been a total of 15 meetings, each approximately one hour long.

There have been three payload division meetings thus far, the first two each being around one hour and the last 1.5 hours. In the first two, needs and wants were discussed for ideas to brainstorm, and in the third, an overall design was chosen. These subteams have only just begun meeting after their final design was chosen and have each had one around one hour meeting.

Thus far, each general member has worked approximately 2-4 hours on documentation and design outside of their meetings. This would be shifted up to around 5-7 hours per officer board member and subteam lead. Totaling all the hours above would give an estimated total of over 215 hours working on the proposal.

6.8 Launch Planning

For subscale model launches, the team hopes to launch with the Central Massachusetts Space Modeling Society (CMASS) in Amesbury Massachusetts. CMASS is a NAR Section #464 site, where WPI USLI team members have launched from on multiple occasions, for individual NAR level one certifications. A backup location is White's Field, used by CATO (lacking an official acronym) Rocketry Club NAR #581 in Durham Connecticut. Both primary and backup sites have a FAA waiver for launches up to at least 2,000 ft., which will satisfy the requirements of our sub-scale test vehicle.

Test launches of our competition vehicle will hopefully take place primarily at the Lake Winnipesaukee High Power Rocketry (LWHPR) Club on Lake Winnipesaukee in New Hampshire (NAR #834) which has an FAA waiver up to 16,000 ft. WPI has worked with the President, Jason Nadeau in the past, as he is our mentor, and test launched the 2019 and 2020 competition rocket from this site. The launch site is limited by the weather, as it does not become operational until the ice on the lake has frozen sufficiently, usually opening in January. Since it would be beneficial for us to launch our full-scale rocket prior to January, additional launch sites were selected for earlier launches. Earlier launches may take place at the Champlain Region Model Rocket Club (CRMRC), Bridgeton Area Rocket Club (BARC), or the Upstate Research Rocketry Group (URRG).

URRG (NAR #765) has an FAA waiver of 18,000 ft and is located in Youngstown, NY. CRMRC (NAR #635) has a FAA waiver of 10,000 ft and is located in St. Albans, VT. BARC (NAR #775) has a base FAA waiver of 5500ft with special clearance up to 8000ft and is located in Bridgeton NJ. URRG, CRMRC, and BARC will only be considered if all other sites are unavailable, as they are farthest from WPI.

Since this year's competition falls during unprecedented times, if we cannot launch at one of these sites for subscale, we will look into launching on a low power motor at a park nearby. Due to COVID-19, WPI has enforced a strict travel policy. As of the time of the proposal there is no domestic or international travel allowed and very limited travel allowed within only the city of Worcester. We plan to petition the school to allow a few of our members, following proper safety procedures, to attend a launch at any of the NAR locations previously listed if they are open at the time.

7 Facilities and Equipment

As students of WPI, we have access to many facilities on campus and the ability to use the various equipment with the proper certifications. It should be noted that due to COVID-19, our school has limited its resources to the students due to safety reasons. In order to support our WPI aerospace MQPs, Higgins Labs is not open to HPRC's use for at least the first semester of this school year. The Robotics Pit may be open to the use of ours and other clubs, but WPI is still debating how to use this space. Both the Foisie Innovation Studio and the Washburn Shops and Manufacturing Labs are open but limited to reservations only. As of now, the team will safely use these two locations for construction when it comes to that time during the process. The team will follow all safety rules and regulations of these locations, including their COVID-19 policies for proximity and capacitance.

7.1 Foisie Innovation Studio

WPI's Foisie Innovation Studio is a modern addition to the WPI campus and serves as a center for student design and engineering. The facility is open to all trained students to complete individual and classroom projects and will serve as the primary workspace for the payload division of our team. For the use of all equipment at the studio, there will be training sessions, so every team member is competent and safe when managing and using any of the equipment. The building hosts several conference rooms, lab spaces, tech suites, and a makerspace for students, only the makerspace and lab space will be used. The area also has a rapid prototyping lab which contains a LPKF ProtoLaser ST Printed Circuit Board machine, a Full Spectrum P-Series 48in x 36in laser cutter, 24 Fused Deposition Modeling (FDM) printers. Training is required to operate the laser cutter and three dimensional (3D) printers. 3D printer models include LulzBot Taz6, Ultimaker 3 and Ultimaker 3 Extended. There are 8 Taz6 printers, which have an 11" x 11" x 9.8" printing area and prints in Polylactic Acid (PLA) a standard material in the 3D printing world. There are 18 Ultimaker 3 printers, which have a print area of 7.75" x 8.4". The difference between the Ultimaker 3 and the Ultimaker 3 Extended is the print height; the normal Ultimaker has a height of 7.8in and the extended has a height of 11.8". The Ultimakers have the ability to print PLA, Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Thermoplastic Polyurethane (TPU), and Nylon. The laser cutter can cut materials such as wood and acrylic, up to ¾". These 3D printers and laser cutters will be used to produce much of the payload. Parts for the rocket and payload can be kept in storage lockers available in the Foisie makerspace until they are ready to be added to the full system. Foisie also houses basic and advanced hand tools available for rental at the front desk. Tool training is required to ensure a safe workspace. The makerspace is open but has adjusted hours and capacity due to COVID-19. Members must go through the new reservation system to use the space. The workbenches have been modified to be reserved for 1-3 people, which we intend to use for small subteam meeting when necessary for construction. Their hours remain Monday through Thursday 7:30am-12am, Friday 7:30a-1am, Saturday 8am-1am and Sunday 8am-12am.

7.2 Robotics Pit

The Robotics Pit is a space typically used for robotics competitions and their workspace in the first basement of the Sports and Recreation Center on WPI's campus. Our team will use this space to work on the launch vehicle and payload, as well as storage of the main assembly. There are work surfaces provided in the robotics pit, however, no machines or tools are provided, therefore students have free access without the need of supervision or training. This space has not yet been granted to us for use, as WPI is debating what the space will be used for.

7.3 Washburn Shops and Manufacturing Labs

The Washburn Shops and Manufacturing Labs are a series of WPI classrooms and lab spaces open to all students within WPI. These Labs contain larger equipment relative to the Foisie Studio and as such requires more supervision and a larger degree of training. To use the materials and equipment in the Washburn Shops, each user must complete a Basic User Training. This allows for access to the shops, as well as use of hand tools and the laser cutter. To gain access to all equipment, a user must go through the Advanced User Training, during which you get certified on each machine individually. No matter if a user has advanced or basic training, he or she must check in with a Lab Monitor before using the Washburn Shops, as well as work under the supervision of one. Washburn shops is supplied with equipment such as a Universal Laser VLS4.60 laser cutter, a MakerBot Replicator 2x 3D printer, a Prusa 3D Printer and a welding station. The shops are also equipped with a number of machines from HAAS including a ST-30SSY computer numerical control (CNC) Lathe, a VM2 vertical mill, a ST10 CNC lathe, a Mill Drill Center, two SL10 CNC lathes, and three MiniMills. Each SL10 CNC lathe and MiniMill have their own computer workstation equipped with training materials, computer aided manufacturing software packages such as Esprit, MasterCam, and SurfCam, and all design and programming software supported on campus. The shop is also supplied with an array of manual tools such as; two vertical band saws, one horizontal band saw, one sheet metal shear, two drill presses, one belt sander, one grinder and one polishing wheel. The facility has two computer classrooms which hold eight to twelve computer workstations, conference tables, whiteboards, and a ceiling mounted projector. The team will be using these machines as needed in the creation of the launch vehicle and unmanned aerial vehicle (UAV) payload systems. This space also runs on a reservation system due to COVID-19 policies and will be used for on campus machining. The hours of operation are Monday through Friday 9am-12pm, 1pm-5pm and 6pm-9pm.

7.4 Higgins Laboratory

Higgins Laboratory is home to the Mechanical Engineering department, which, at WPI, Aerospace Engineering shares. Higgins Labs serves as the location for many Aerospace classes, research, organizations, and projects. The building is accessible 24/7 for all students through key card access. Most of this facility is not open to our use as of this semester of school, due to COVID-19 guidelines. It is included on the chance that the team may work here again during the second semester. The Project Laboratory is a space reserved for Major Qualifying Projects (senior projects), in that space we would typically have access to vacuum pumps and space to work with carbon fiber and accessed with key card access held by members of a Major Qualifying Project or through permission of Professor Blandino. Access to the Machine Shop in Higgins requires getting qualified through a head or qualifying lab monitor. Once you are qualified, you are free to use the Machine Shop whenever there is a lab monitor present. They have dedicated hours from 3:00 – 5:00 on weekdays. In the Machine Shop, there are two CNC Machine tools, a Haas Tool Room min and Haas Tool Room Lathe, there are two DoALL Mills and a DoALL Engine Lathe, as well as a drill press, two band saws, and assorted hand tools.

8 Safety

Safety is the highest priority of WPI HPRC. All team activities throughout the process of design, fabrication, testing, and launch will be conducted with the safety of team members and others as the primary consideration. The Safety Officer will be responsible for maintaining all necessary safety documentation, educating team members about safety procedures, and fostering a safety-first culture to ensure that the appropriate procedures are followed and enforced at all times. The team will maintain a safety plan including detailed hazard analysis and risk mitigation for all facilities, tools, and materials used by the team. Furthermore, WPI HPRC is committed to full compliance with the NAR High Power Safety Code, the FAA and all local rules and regulations governing high powered rocketry. The team agrees to follow the instructions of the RSO at all launch events and will take guidance from our NAR certified mentor to ensure that safety standards are met. All HPRC team members will play an active role in ensuring that safety procedures are followed and will be required to accept a written safety agreement to acknowledge this responsibility.

8.1 Facilities

All machining, construction, and assembly work during the fabrication of the launch vehicle and payload will occur only in the designated facilities. Only team members that are properly certified for each workspace will be permitted to engage in fabrication work. All team members will be briefed by the Safety Officer on the appropriate safety information and procedures for each facility before they are permitted to begin work in that facility. An experienced team member will be present at all times during any construction and assembly activities and will be responsible for ensuring that all safety procedures are followed.

8.1.1 Robotics Pits

The Robotics Pits will be the primary cutting and assembly workspace for the team. It is a large indoor construction space that can facilitate work on multiple projects simultaneously. The team will not perform any heavy machining or handling of hazardous materials with inhalation risks as the facility does not have the appropriate tools or ventilation system. These activities will be conducted in Washburn Shops. Some work on materials which pose inhalation risks may be performed outdoors with proper ventilation and PPE.

8.1.1.1 Dremel

Hazards	Causes	Effects	Mitigation Plan
Laceration injury	Appendage caught by slipping Dremel	Up to and including severe lacerations or amputations.	Participants will be trained in proper use of Dremel. Gloves will always be worn by operator
Clothing/Jewelry damage/destruction	Loose clothing/jewelry stuck in rotating blade	Up to and including destruction of stuck material and increased potential for laceration injury.	Participants will be instructed to not wear loose clothing/jewelry when using a Dremel
Inhalation injury	Dust particles inhaled by user or bystanders	Throat/Lung irritation. Potential for Fibrosis	Participants will be instructed to wear a safety mask while using or around someone using a Dremel.
Eye injury	Eyes struck by flying objects created by Dremel	Up to and including severe eye injury and partial or total loss of site in affected eye.	Participants will be instructed to always wear safety glasses when using or around someone using a Dremel.

Table 8.1 Dremel Safety

8.1.1.2 Angle Grinder

Hazards	Causes	Effects	Mitigation Plan
Laceration injury	Appendage caught by slipping or kickback from Angle Cutter.	Up to and including severe lacerations or amputations.	Participants will be trained in proper use of Angle Cutter. Gloves will always be worn by operator
Clothing/Jewelry damage/destruction	Loose clothing/jewelry stuck in rotating blade.	Up to and including destruction of stuck	Participants will be instructed to not wear

		material and increased potential for laceration injury.	loose clothing/jewelry when using an Angle Cutter.
Inhalation injury	Dust particles inhaled by user or bystanders.	Throat/Lung irritation. Potential for Fibrosis.	Participants will be instructed to wear a safety mask while using or around someone using an Angle Cutter.
Eye injury	Eyes struck by flying objects created by Angle Cutter.	Up to and including severe eye injury and partial or total loss of site in affected eye.	Participants will be instructed to always wear safety glasses when using or around someone using an Angle Cutter.

Table 8.2 Angle Grinder Safety

8.1.2 Foisie Innovation Studio Makerspace

The team will utilize the Foisie Innovation Studio Makerspace primarily for requesting FDM 3D printed parts, and for laser cutting parts. WPI Students must complete online safety certifications to be granted access to use the 3D printers and laser cutter in the makerspace.

8.1.2.1 FDM Printers

HPRC team members will not be operating the FDM Printers themselves for work on HPRC projects. Instead, team members will submit a print request to the Foisie printer queue for all 3D printed parts and will only handle finished prints. The prototype lab staff will conduct the actual printing of parts.

8.1.2.2 Laser Cutter

Hazards	Causes	Effects	Mitigation Plan
Eye Injury	High energy laser beam not contained by glass doors.	Up to and including blindness and severe burns.	Participants will not be permitted to use laser cutter without proper training. Participants must use safety glasses when around laser cutter. Participants will be instructed to not look at cutter when in operation.
Burns and other Fire Injuries	High energy laser beam not contained by glass doors.	Up to and including severe burns on any body part in contact with fire or the laser beam. Potential	Participants will not be permitted to use laser cutter without proper training. Participants must wear gloves

	Fire caused by improper use of laser cutter settings.	destruction of laser cutter, material being cut, and surrounding area.	when operating the laser cutter.
Inhalation Injury	Inhalation of fumes released by laser cutter. Improper use of ventilation system. Cutting materials not cleared for the laser cutter.	Up to and including severe sickness and death caused by inhalation of toxic fumes.	Participants will not be permitted to use laser cutter without proper training. Participants will be instructed to shut down the laser cutter if ventilation system fails.

Table 8.3 Laser Cutter Safety

8.1.3 Washburn Shops

Washburn Shops will be the site of heavy machining, cutting, and manufacturing of rocket parts which cannot be done in the Robotics Pits. WPI students are required to complete an online safety certification before they are allowed access to Washburn. The Basic User Certificate allows access to hand tools and the laser cutter. Students may become advanced users by completing additional training and may use any tools in the shop for which they have received formal training. A trained lab monitor must be present any time the lab is open, and a minimum of two certified users must be present when work is performed in the lab. A user may not use the lab for more than 12 hours in any 24 hour period and must take a 10 hour break after working for a period exceeding 8 hours.

8.1.3.1 Haas ST30 SSY CNC Lathe

Hazards	Causes	Effects	Mitigation Plan
Blunt force trauma	Improperly securing rotor and subsequent ejection.	Up to and including death due to massive blunt force trauma	Participants must be trained on proper usage of CNC Lathe before any work is done with it. All safety procedures supplied by Washburn Shops will be followed.
Avulsion/ amputation	An appendage stuck in the Lathe due to improper use or attire	Up to and including amputation of appendage caught in lathe	Participants must be trained on proper usage of CNC Lathe before any work is done with it. All safety procedures supplied by Washburn Shops will be followed.
Clothing/Jewelry/Hair damage/destruction	Loose clothing, jewelry, hair or gloves	Up to and including complete destruction	Participants will not be permitted to use the

	caught in the rotating Lathe	of material caught. Greatly increased risk of avulsion and amputation.	CNC Lathe when wearing loose clothing, jewelry, or have long hair that is not contained by hat, hairnet, or similar means.
Eye injury	Eyes struck by flying objects created by improper use of Lathe.	Up to and including severe eye injury and partial or total loss of site in affected eye.	Participants will not be permitted near the CNC Lathe without safety glasses.
Hearing Injury	High decibels caused by Lathe.	Up to and including hearing loss.	Participants must wear hearing protection when near the CNC Lathe.
Foot Injury	Heavy materials falling out of Lathe land on foot.	Up to and including bruising and crushing injuries to affected foot.	Participants must wear closed toed shoes when using the CNC Lathe.

Table 8.4 Haas ST30 Safety

8.1.3.2 Haas MDC Vertical Mill

Hazards	Causes	Effects	Mitigation Plan
Avulsion/ amputation	An appendage stuck in the Mill due to improper use or attire.	Up to and including amputation of appendage caught in Mill.	Participants must be trained on proper usage of Vertical Mill before any work is done with it. All safety procedures supplied by Washburn Shops will be followed.
Clothing/Jewelry/Hair damage/destruction	Loose clothing, jewelry, hair or gloves caught in the rotating Vertical Mill.	Up to and including complete destruction of material caught. Greatly increased risk of avulsion and amputation.	Participants will not be permitted to use the Vertical Mill when wearing loose clothing, jewelry, or have long hair that is not contained by hat, hairnet, or similar means.
Eye injury	Eyes struck by flying objects created by improper use of Mill.	Up to and including severe eye injury and partial or total loss of site in affected eye.	Participants will not be permitted near the Vertical Mill without safety glasses.

Hearing Injury	High decibels caused by Mill.	Up to and including hearing loss.	Participants must wear hearing protection when near the Vertical Mill.
Foot Injury	Heavy materials falling out of Mill land on foot.	Up to and including bruising and crushing injuries to affected foot.	Participants must wear closed toed shoes when using the Vertical Mill.

Table 8.5 Haas MDC Mill Safety

8.1.3.3 Haas Minimill

Hazards	Causes	Effects	Mitigation Plan
Avulsion/ amputation	An appendage stuck in the Mill due to improper use or attire.	Up to and including amputation of appendage caught in Mill.	Participants must be trained on proper usage of Minimill before any work is done with it. All safety procedures supplied by Washburn Shops will be followed.
Clothing/Jewelry/Hair damage/destruction	Loose clothing, jewelry, hair or gloves caught in the rotating Minimill.	Up to and including complete destruction of material caught. Greatly increased risk of avulsion and amputation.	Participants will not be permitted to use the Minimill when wearing loose clothing, jewelry, or have long hair that is not contained by hat, hairnet, or similar means.
Eye injury	Eyes struck by flying objects created by improper use of Mill.	Up to and including severe eye injury and partial or total loss of site in affected eye.	Participants will not be permitted near the Minimill without safety glasses.
Hearing Injury	High decibels caused by Mill.	Up to and including hearing loss.	Participants must wear hearing protection when near the Minimill.
Foot Injury	Heavy materials falling out of Mill land on foot.	Up to and including bruising and crushing injuries to affected foot.	Participants must wear closed toed shoes when using the Minimill.

Table 8.6 Haas Minimill Safety

8.2 Materials

Team members will be handling some hazardous materials during the fabrication and hands on work on the rocket and payload. To minimize the risk of injury, it is important that such materials are handled safely following proper procedures. No team member will be permitted to use any hazardous materials without completing a safety briefing given by the Safety Officer which will cover the potential hazards of these materials and the proper procedures for handling them safely. Members will be instructed in the use of Personal Protective Equipment (PPE) as well as essential first aid information and what to do in the event of an accident. All work done with hazardous materials will occur under the supervision of a team member experienced in the safe handling of the material and with the necessary protective equipment.

8.2.1 Carbon Fiber

Use	Hazards	Mitigation
Fins	Can cause eye, skin and upper respiratory track irritation; vapor or fumes may cause eye and respiratory tract irritation; fibers and dust are electrically conductive and may create electrical short-circuits.	Will be stored sealed in a cool, dry place. When working with the material members will wear safety goggles, gloves, long pants and long sleeve shirts to avoid eye and skin irritation. The material will not be heated to avoid hazardous fumes and vapor. We will be working with carbon fiber in well-ventilated spaces to control dust levels

Table 8.7 Carbon Fiber Material Hazards

8.2.2 Aluminum

Use	Hazards	Mitigation
Bulkheads, fasteners, coatings, shielding	Dust or fumes can cause eye, skin and respiratory track irritation; chips and dust react violently and/or explosively with water, steam or moisture; air sensitive.	Will be stored in a cold, dry, well-ventilated place, away from ignition sources and materials that can cause a reaction. When working with the material members will wear safety goggles, gloves, long pants and long sleeve shirts to avoid eye and skin irritation. Will be used in adequately ventilated spaces.

Table 8.8 Aluminium Material Hazards

8.2.3 Fiberglass

Use	Hazards	Mitigation
Airframe	Can cause a rash to appear when the fibers become embedded in the outer layer of the skin; eyes may become red and irritated after exposure to	Will be stored in a cool, dry, well-ventilated area. Members will wear loose-fitting long-sleeved clothing, gloves, safety glasses, and a respiratory mask

	fiberglass; soreness in the nose and throat can result when fibers are inhaled; temporary stomach irritation may occur if fibers are swallowed.	when handling fiberglass to reduce skin irritation and prevent breathing in fibers. Work will be conducted in a well-ventilated space and a shop vacuum will be used afterward to clean up any dust and fibers.

Table 8.9 Fiberglass Material Hazards

8.2.4 NylonX

Use	Hazards	Mitigation
3D printing parts	Solid or dust may cause eye irritation; when heated can cause thermal burns on the skin, vapors can cause eye irritation; burning can produce toxic fumes.	Will be stored in a cool, dry area with no direct sunlight. Members will wear safety goggles when machining the material. Gloves will be worn for thermal or mechanical protection if needed. Will not be used or stored near flames, sparks and heat generators.

Table 8.10 NylonX Material Hazards

8.2.5 PLA

Use	Hazards	Mitigation
3D printing parts	Can cause eye and skin irritation; burning can produce obnoxious and toxic fumes; dry powders can build static electricity charges.	Will be stored in a cool, dry, well-ventilated area. Members will wear safety goggles, gloves, long pants and long sleeve shirts when machining the material to avoid eye and skin contact. Will be machined in ventilated places to avoid dust accumulation. Will not be used or stored near flames, sparks and heat generators.

Table 8.11 PLA Material Hazards

8.2.6 Epoxy

Use	Hazards	Mitigation
Conjoining parts of the rocket, filling holes	Can cause eye and skin irritation; prolonged and reputative skin contact can cause chemical burns; burning releases toxic fumes; when cured in big quantities can	Will be stored in a cool, dry place in a tightly sealed container, far from heating or ignition sources. When working with epoxy members will wear safety goggles, gloves, clothes that protect the skin from

	cause ignition of surrounding material.	coming in contact with the material. Proper mixing and curing technics will be used to avoid ignition.

Table 8.12 Epoxy Material Hazards

8.2.7 Delrin

Use	Hazards	Mitigation
Airbrake System	Acetal delrin plastic contains a small concentration of formaldehyde which is a highly toxic chemical. Fumes produced can be an inhalation hazard if the material is overheated, and molten material poses a risk of thermal burns.	Will be stored in a cool, dry, well ventilated area away from heating or ignition sources. Wash skin with soap and water after exposure. If material is overheated and fumes are produced, move to fresh air immediately. If molten material contacts the skin, apply cold water to the affected area and seek medical attention.

Table 8.13 Delrin Material Hazards

8.2.8 LiPo Battery

Use	Hazards	Mitigation
Payload component	Can cause chemical burns if contacts skin or eyes; heating can cause fire.	Will not be dismantled. Will be stored in a cool, dry place in a tightly sealed container, far from heating or ignition sources. When handling members will wear safety goggles, gloves, long pants and long sleeve shorts to avoid contact with skin and eyes. Will be handled carefully, not heated, shook or short-circuited.

Table 8.14 Lipo Battery Hazards

8.2.9 Black Powder

Use	Hazards	Mitigation
Used to separate sections of the airframe and to release the retention system from the airframe.	Explosive; highly flammable; fire, blast or projection hazard; can cause serious eye irritation, an allergic skin reaction; can cause damage to organs through prolonged and repetitive exposure.	Will be stored in a tightly closed original container in a cool, dry, well-ventilated place away from all sources of ignition, heat, incompatible materials. Will not be subjected to mechanical shock. Only people who are trained in working with black

		powder will be allowed to handle it. They will wear safety goggles, gloves and protective clothing to minimize risk of contact with skin and eyes. Clothing that has black powder on it will be washed in special conditions.

Table 8.15 Black Powder Hazards

8.2.10 Ammonium Perchlorate Composite Propellant (APCP)

Use	Hazards	Mitigation
Used in the motor	Flammable; explosive; can cause eye irritation, in the form we are using it is a low hazard for skin.	Will be stored in the original container in a cool, dry place away from sources of heat or ignition. Safety goggles, protective clothing will be worn by members to avoid contact with skin or eyes.

Table 8.16 APCP Hazards

8.2.11 Igniter Pyrogen

Use	Hazards	Mitigation
Used for ignition	Flammable; explosive; can cause eye irritation, in the form we are using it is a low hazard for skin.	Will be stored in the original container in a cool, dry place away from sources of heat or ignition. Safety goggles, protective clothing will be worn by members to avoid contact with skin or eyes.

Table 8.17 Pyrogen Hazards

8.2.12 General Materials Rules

In addition to the information above specific to each material, the team will abide by the following general guidelines for the safe handling and use of all materials and chemicals. WPI HPRC will maintain safety documentation including hazard analysis and safe handling procedures for all materials and substances used by the team. All materials and substances will be well labeled and stored safely according to the documentation. Proper PPE such as safety glasses and respiratory masks will be worn when handling hazardous materials. Members will not consume or inhale any substance, or any fumes, vapors, or byproducts created while handling materials. If a hazardous material contacts the eyes or skin of any team member, the Safety Officer will be immediately notified, and safety procedures will be followed to mitigate injury and irritation. In the event of a spill, fire, or other threat to the safety of HPRC team members, work will stop, safety procedures will be implemented to mitigate the danger, and the appropriate safety agency will be contact immediately if required.

8.3 NAR Compliance

NAR and Tripoli Rocketry Association (TRA) personnel will follow all NAR High Power Safety Code requirements. WPI HPRC and all team members agree to comply with all NAR High Power Safety Code requirements and to follow the instructions of the RSO at the launch site for all launch events.

8.3.1 High Power Safety Code

8.3.1.1 Certification

High powered launch vehicle operators will only fly high power launch vehicles or possess high power launch vehicle motors that are within the scope of their certification and required licensing. The team mentor will transport and handle all motors before and during launches.

8.3.1.2 Materials

Operators will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass or, when necessary, ductile metal, for the construction of the launch vehicle.

8.3.1.3 Motors

Operators will be required to only use certified, commercially made launch vehicle motors, and will not tamper with these motors or use them for any purposes except those recommended by the manufacturer. Operators must ensure there is no smoking, open flames, nor heat sources within 25ft of the launch vehicle motors.

8.3.1.4 Arming Energetics and Launch Vehicle Motors

The team will turn on the altimeter and wait for a successful continuity check in the energetics before attempting to insert the motor igniter. Once complete, an electrical motor igniter will be installed by the RSO. The number of people at the launch pad during this phase will be kept to a minimum.

8.3.1.5 Motor Ignition

The RSO will utilize a switch wired in series with the igniter to initiate the launch.

8.3.1.6 Misfire

If the team's launch vehicle does not launch when electrically triggered, the RSO will remove the launcher's safety interlock or disconnect its battery. The team will then wait 60 seconds after the last launch attempt before requesting permission from the RSO to approach the launch vehicle. Members will follow all directions given by the RSO.

8.3.1.7 Pre-Launch Checks

Team members will work in pairs to pack the parachutes and the rocket lead will check to ensure all systems are ready for flight. All energetics will be handled by the team mentor. The team will determine the launch vehicle's stability and thrust-to-weight ratio using

OpenRocket, a software tool for designing and simulating launch vehicles. An RSO will verify the launch vehicle is stable and has a thrust-to-weight ratio greater than 3:1 before allowing the launch vehicle on the launch pad. This ensures the launch vehicle will not succumb to weather cocking and will leave the launch rail at a speed great enough to make it aerodynamically stable.

8.3.1.8 Launch Procedures

The launch coordinator must use a 5 second countdown before launch. They will use a loudspeaker to broadcast the launch countdown and any problems to participants. The team will remain behind the safety tape while a launch vehicle is being launched to ensure their personal safety. The RSO will place the safety tape at a distance stated in the minimal distance table in the NAR High Power Safety Code. Further, the team will wait to launch the launch vehicle if the wind speed exceeds 20mph.

8.3.1.9 Launch Pad

The launch vehicle will be launched from a launch rail that provides rigid guidance until the launch vehicle has attained a speed of at least 52ft/s that ensures stable flight. It will be pointed to within 20 degrees of vertical and feature a blast deflector to prevent the motor's exhaust from hitting the ground. The RSO will ensure any flammable foliage has been removed from the surrounding area.

8.3.1.10 Launch Site

The launch site's smallest dimension must be at least one-half the maximum altitude on the FAA waiver or 1500ft, whichever is greater. In our case, this means the launch site must be at least 5,000ft by 5,000ft. The RSO will set up the launch rail at least 1500ft from any occupied building or public highway.

8.3.1.11 Flight

The team will not launch the launch vehicle at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site and will not put any flammable or explosive payload in the launch vehicle.

8.3.1.12 Recovery

Our launch vehicle will utilize a dual deployment recovery system, with a drogue parachute deploying at apogee and a main parachute deploying at 500ft. The drogue parachute allows the launch vehicle to descend quickly and avoid getting blown downrange by wind, and the main parachute slows the launch vehicle to a safe landing speed. The parachutes will be protected from the energetics by Nomex blankets tied to shock cord.

8.3.1.13 Recovery Safety

The team will not attempt to catch the launch vehicle as it's coming down or recover any part of the launch vehicle from power lines, tall trees, or other dangerous places

8.3.2 Launch Site

For subscale model launches, the team intends to launch with CMASS in Amesbury Massachusetts. CMASS is a NAR Section #464 site, where WPI USLI team members have launched from on multiple occasions, for individual NAR level one certifications. A backup location is White's Field, used by CATO Rocketry Club NAR #581 in Durham Connecticut. Both primary and backup sites have a FAA waiver for launches up to at least 2,000 ft., which will satisfy the requirements of our sub-scale test vehicle. Test launches of our competition vehicle will take place primarily at LWHPR Club on Lake Winnipesaukee in New Hampshire (NAR #834) which has an FAA waiver up to 16,000 ft. WPI has worked with the President, Jason Nadeau in the past, and test launched the 2019 competition rocket from this site. The launch site is limited by the weather, as it does not become operational until the ice on the lake has frozen sufficiently, usually opening in January. Since it would be beneficial for us to launch our full-scale rocket prior to January, additional launch sites were selected for earlier launches. Earlier launches may take place at CRMRC, BARC, or URRG. URRG (NAR #765) has an FAA waiver of 18,000 ft and is located in Youngstown, NY. CRMRC (NAR #635) has a FAA waiver of 10,000 ft and is located in St. Albans, VT. BARC (NAR #775) has a base FAA waiver of 5500ft with special clearance up to 8000ft and is located in Bridgeton NJ. URRG, CRMRC, and BARC will only be considered if all other sites are unavailable, as they are farthest from WPI.

8.4 Launch Briefings and Aerospace Compliance

The Safety Officer will conduct pre-launch safety briefings at the general body meeting immediately preceding each launch event. An additional pre-launch safety briefing will be given at the launch site before any team members handle the launch vehicle. Safety briefings will include recognition of hazards and effective procedures for the mitigation of associated risks. The briefing will also review Federal Aviation Regulations 14 CFR, Subchapter F, Part 101, Subpart C; Amateur Rockets and any other local laws regarding use of airspace. The Safety Officer will coordinate with the RSO and our team's NAR/TRA certified mentor to monitor launch procedures and ensure that all safety procedures are followed during preparation, launch, and recovery of the launch vehicle and payload.

8.5 Motor Safety and Handling

Rocket motors are classified as hazardous materials in the United States. Therefore, it is prohibited to ship or fly motors to the launch site for flight events. The team plans to purchase launch vehicle motors online and have hazmat shipping in order to comply with these regulations. Only our mentors, and/or NAR/TRA certified team members will be responsible for the purchase, storage, and handling of rocket motors and other energetics such as black powder. The Safety Officer will brief all individuals responsible for handling motors and energetics in compliance with the Code of Federal Regulation 27 Part 55: Commerce in Explosives; and fire prevention, National Fire Protection Association

(NFPA)1127 “Code for High Power Rocket Motors”, in addition to any local laws regarding launch vehicle motors or other energetics.

8.6 Covid-19 Precautions

WPI HPRC has implemented increased safety precautions in response to Covid-19 which are in alignment with guidance provided by local and state officials as well as the policies set forth by Worcester Polytechnic Institute. WPI has taken an active approach to preventing the spread of the virus by taking measures including the following: de-densifying housing, implementing enhanced cleaning protocols, making all non-mission critical events virtual, requiring all students to be tested regularly, and promoting safe practices of wearing masks, handwashing, and social distancing. The team has transitioned to holding all meetings virtually when possible and will continue to do so until it the WPI Student Activities Office deems it safe to begin meeting in person. Labs and workspaces on campus are currently open in a limited capacity with the addition of new guidelines and procedures to keep students safe. Hands on construction work will be performed by a limited number of students in accordance with WPI policy. Mask wearing and socially distancing will be required at any in person team activities, where hand sanitizer will be provided, and all surfaces and tools will be disinfected after use. WPI HPRC is confident that the team can successfully accomplish our objectives while complying with all COVID-19 guidelines to ensure the safety of all team members and the larger WPI community.

8.7 Member Safety Agreement

Safety is the highest priority of WPI HPRC and the primary consideration for all team events. In order to promote a culture of safety in all team activities, it is critical that each member understands their own personal responsibility in following all appropriate safety guidelines. There will be a general body meeting in where the safety officer will lead a safety presentation on all hazards outlined in this and NASA’s proposal outline document. In the interest of promoting personal responsibility for safety and minimizing the risks associated with high powered rocketry, all HPRC members are required to acknowledge and abide by the following written safety agreement.

WPI HPRC Written Safety Statement

- I recognize that fabrication and launch of High Power Rockets is a potentially dangerous activity, and that I have a responsibility to myself and to my teammates to actively ensure that best practice is used at all times to minimize risk associated with these activities.
- I will not use tools or perform operations for which I do not have an appropriate working knowledge and will complete all required training steps prior to using dangerous tools.
- In the event of uncertainty regarding safety or correct procedure, I will consult with the team’s Safety Officer before proceeding.

- I will employ appropriate PPE as required while performing machining operations, using hand/power tools, or handling hazardous materials.
- I will familiarize myself with the material safety data sheets relevant to any potentially hazardous materials I work with, along with the hazard mitigation techniques documented by our team.
- I understand that I have a responsibility to not just personally perform operations safely but also to actively contribute to a culture of safe practice within our team, and to actively intervene should I observe a team member failing to follow the terms of this safety agreement, reporting any violations to the team Safety Officer and WPI-appointed Lab Monitor on duty. Throughout my activities within the team, I will seek to continuously educate myself on hazard identification, mitigation, and safe practice, and to promote an environment where my teammates may learn from my example.
- I agree to follow all policies and procedures set forth by WPI regarding access and safe use of laboratory facilities. I understand that the team's Safety Officer and WPI Lab Monitors may intervene with any action judged to pose a potential safety hazard, and that failure to correct my actions to meet their standards will result in the loss of privileges to engage in fabrication or launch activities with the team.
- I understand that at NAR/TRA sanctioned events, instructions from or decisions made by the Range Safety Officer are final and must be followed, including in cases where such decisions run counter to information provided by USLI personnel or the team Safety Officer.
- I have read and understand the NAR High Power Rocket Safety code, and agree not to perform any launch activities in violation of the code, or in violation of FAA regulations, NFPA 1127, or any other applicable local, state, or federal laws and regulations.
- I have read and agree to the following safety regulations included in the 2020-2021 USLI Student Handbook:

    i. Range safety inspections will be conducted on each rocket before it is flown. Each team shall comply with the determination of the safety inspection or may be removed from the program.

    ii. The Range Safety Officer has the final say on all rocket safety issues. Therefore, the Range Safety Officer has the right to deny the launch of any rocket for safety reasons.

    iii. The team mentor is ultimately responsible for the safe flight and recovery of the team's rocket. There-fore, a team will not fly a rocket until the mentor has reviewed the design, examined the build and is satisfied the rocket meets established amateur rocketry design and safety guidelines.

    iv. Any team that does not comply with the safety requirements will not be allowed to launch their rocket.

By signing this document, I agree to all the above, and that failure to comply with the requirements may result in loss of shop privileges or membership standing within WPI HPRC.

9 Rocket Design

9.1 Overview

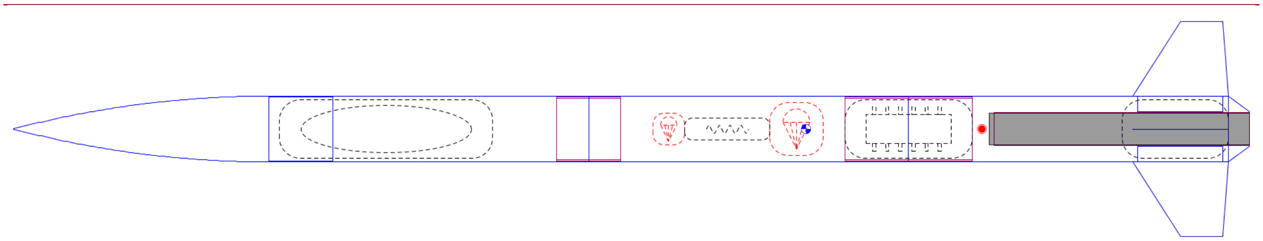

Figure 9.1 Rocket Design Overview

This year's rocket is planned to stand 116 in tall, with an outer diameter of 6.17 in, with a dry mass of 39.6 lbs, and a wet mass of 49.2 lbs. The rocket will split into 4 independent sections during descent, including the upper and lower airframe sections which will remain tethered, and the nosecone and payload which will each descend separately.

9.2 Airframe

9.2.1 Nose Cone

The design utilizes a filament wound fiberglass nose cone. This material was chosen for its high strength and flexibility, which attribute to its durability. The nose cone is 24 in long, tangent ogive (4:1 with a shape parameter of 1) in shape, and has a shoulder length of 6 in. In addition to having the durability we need to relaunch, fiberglass is radio transparent. Because the payload will be hosted in the upper airframe, a radio transparent material is needed to allow transmission of signals. Carbon fiber was also a material considered for the nose cone but was ultimately abandoned because it is more expensive and brittle than fiberglass.

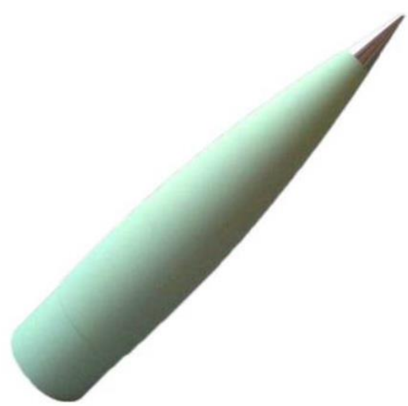

Figure 9.2 Madcow Rocketry Nose Cone

Over a 5:1 ratio, a 4:1 ogive provides a reduction in weight and skin friction drag. The nose cone also has an aluminum tip, which draws the center of gravity toward the front to achieve a more desirable stability. Furthermore, in the event of a nose-down landing, the metal tip will increase the strength of the nose cone and protect the fiberglass. To ensure compatibility between the parts, both the nose cone and airframe will be acquired from the same company, Madcow Rocketry.

The attachment method of the nose cone will be determined once there is an established deployment method for the payload. The primary options would be to connect with either shear pins or bolts. If the payload requires the ejection of the nose cone during flight, shear pins will most likely be used.

9.2.2 Main Airframe

The launch vehicle design process utilized OpenRocket version 15.03. The airframe of the vehicle will be separated into three sections, the upper airframe, middle airframe, and the lower airframe; each connected by fiberglass couplers. The coupler between the upper and middle airframe will be 1 airframe diameter in length (6 in) and the coupler between the middle and lower will be 12 in long and house the electronics bay. The section lengths will be 30 in, 30 in, and 30 in respectively, and will have an inner diameter of 6 in. This diameter was chosen to be 6 in to provide the payload team ample space to work with, as well as to allow for parachutes of an appropriate size to be packed less tightly. By packing the parachute less tightly, the recovery system will have the ability to act in a faster, smoother, and more reliable fashion.

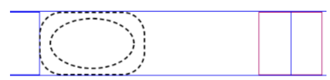

Figure 9.3 Upper Airframe

The middle airframe will house two parachutes that will deploy based on the recovery system. This placement allows for recovery of the rocket shortly after the UAV is released from the upper airframe. The electronics bay will be here, and will span into the lower airframe, thus acting as a coupler to hold the two sections together.

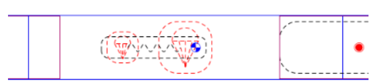

Figure 9.4 Middle Airframe

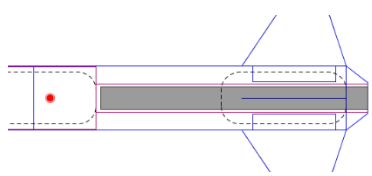

Figure 9.5 Lower Airframe

Fiberglass was selected as the airframe material due to its considerable strength, as well as its lower cost. The material proved to create a sturdy and resilient outer airframe covering for last year's rocket, though some difficulty with creating a smooth outer surface on top of Blue Tube was noted. Fiberglass is also transparent to radio waves and has good heat resistance.

Blue Tube and carbon fiber were considered as materials for the airframe as well. Though carbon fiber would be slightly stronger, with our limited budget we found it was best to use a cheaper material with similar strength. Carbon fiber will also block radio signals, potentially causing difficulty for the avionics team, so it was avoided. Blue Tube was not chosen because it is often warped. This causes problems related to the dimensional inaccuracy during assembly. It can also more zipper more easily than other materials, a problem the team has experienced in the past.

The fiberglass airframes are sold in 30 in and 60 in lengths and can be cut to length as needed. Slots will need to be cut for fins and air brakes. This will likely be done with a Dremel in a well-ventilated space, using respirator masks for protection against inhaling particles.

9.2.3 Fins

The fins extend through the airframe into the fin can. They will be a swept trapezoidal shape. The root length will be 9 in, the tip length will be 4 in, and they will have a height of 7 in. In addition, the fins have a sweep length of 4 in.

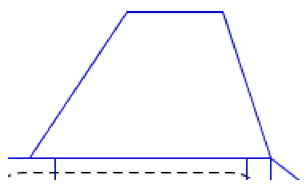

Figure 9.6 Fin Geometry

This design was chosen to provide an aerodynamic design and sufficient surface area to reach the desired stability. Although for our rocket an ideal fin shape would be elliptical, it would be difficult to manufacture. An elliptical fin is ideal because it produces the least amount of induced drag[1]. Induced drag is cause by air moving over the fins unevenly (with an angle of attack) creating a lift force. The lift force helps to right the rocket back to vertical but the induced drag causes vortices to form when the air moved from the high-pressure side to the low-pressure side.

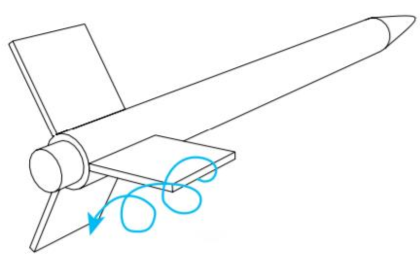

Figure 9.7 Apogee Rockets - Vortices on Fins[1]

An elliptical fin has less lift force created near the tip of the fin because of the smaller "tip length". This means that there is less induced drag and therefore smaller vortices. A

[1] Peak of Flight, issue 442, Apogee Rockets, May 2nd, 2017

trapezoidal fin shape is similar to elliptical in that it has a shorter fin tip chord to reduce the induced drag.

9.2.4 Tail Cone

The tail cone of a rocket is an important component that significantly reduces drag. The tail cone also needs to be designed to handle the impact of landing in the case that the airframe section lands on the tail, protecting the reloadable motor hardware. The tail cone for our rocket will be 3D printed from MatterHackers NylonX filament. It will have dimensions of 2 in long, with a fore diameter of 6 in, and aft diameter of 3 in. The tail cone will then be attached using bolts to the fin bracket.

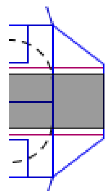

Figure 9.8 Tail Cone

Having the tail cone 3D printed allows the rocket to have a lighter overall weight, while being easier to manufacture than machined aluminum, another considered option. With all the intricacies with machining a part with complex geometry, like the tail cone, it takes a lot more time than a 3D print. This part needs be able to withstand a direct landing but is it does not require the strength of solid aluminum. Because we do not need the strength, a machined aluminum tail cone would add unnecessary weight to the aft end of the rocket, reducing the stability and apogee.

9.3 Propulsion Integration

9.3.1 Fin Can Design

The purpose of the fin can is to hold the fins securely in place within the airframe, while aiding in motor centering and retention. Our fin can design consists of two centering rings and a single mid-section divided into four 3D printed brackets as shown in Figure 9.9. Between these components, a total of five 1/4-20 bolts will secure each fin in place.

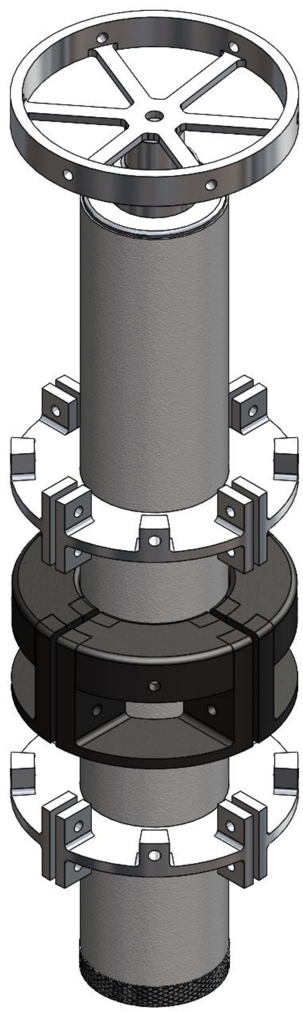

Figure 9.9 Fin Can and Motor Retention Partial Assembly

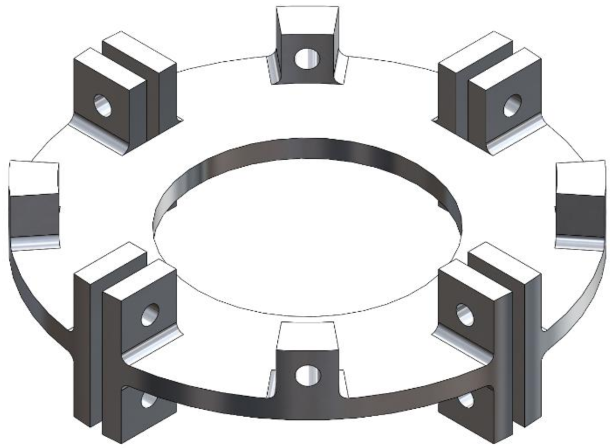

Figure 9.10 Centering Ring Design

Each fin will be secured with two 1/4-20 bolts through tabs extending above and below the upper and lower centering rings. These centering rings are responsible for four out of the five total bolts securing the fins in place. Each centering rings will be machined out of 6061-T6 aluminum alloy due to its good strength-to-weight ratio and high tensile strength. They will be attached to the airframe with four 1/4-20 bolts offset by 45 degrees from the tabs for bolting the fins, as shown in Figure 9.10.

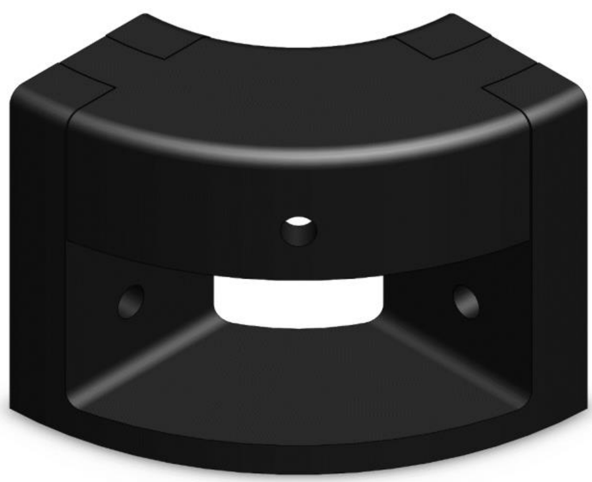

Figure 9.11 Mid-section Bracket Design

The mid-section bracket split into four sections provides additional support for each fin. Each of the four mid-section 3D printed brackets will be printed out of MatterHackers NylonX filament, a strong and lightweight carbon fiber reinforced nylon filament. To print this design, each bracket will be printed in two parts, an upper quarter ring that will be epoxied to a bottom section. The mid-section brackets will be located at the middle of each fin between the upper and lower centering rings and secured with a 1/4-20 bolt to fins on either side as shown in Figure 9.11. The addition of these four brackets is to ensure the prevention of fluttering that may occur to the fins during the launch vehicle's ascent. Each bracket will be bolted to the airframe with a 1/4-20 bolt securing through the top center of the bracket as shown in Figure 9.11.

9.3.2 Motor Retention Design

The motor retention system is composed of the two primary components responsible for securing the motor casing inside the launch vehicle and for thrust transfer to the vehicle. These components are the forward thrust plate and the motor tube shown in Figure 9.9.

A forward thrust plate will be secured to the forward end of the motor casing and lower airframe body tube as shown in Figure 9.12 to transfer the load produced by the motor directly into the remainder of the launch vehicle. The thrust plate will be machined from 6061-T6 aluminum due to the material's machinability, strength, and cost effectiveness of 6061-T6 aluminum. This component will withstand the thrust generated from the motor, keeping the lower airframe stable. The thrust plate will be attached to the body tube using six ¼-20 bolts and to the center of the forward closure of the motor casing with a 3/8 flat head socket cap screw. This aluminum forward thrust plate will allow for a relatively light weight and simple design to retain the fin can and motor under the forces produced during launch and recovery.

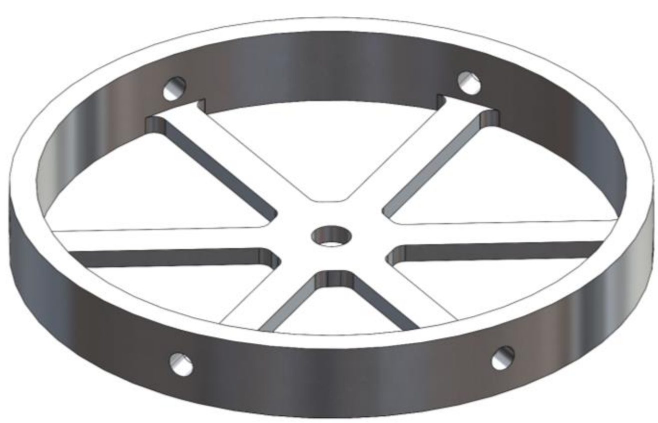

Figure 9.12 Forward Thrust Plate Design

9.3.3 Projected Motors

The primary motor chosen for the launch vehicle is the L1395-BS, a class L motor manufactured by Cesaroni Technology. It has a diameter of 2.95 in, length of 24.45 in, peak thrust of 1800 N, and a total impulse of 4895.40 Ns. The igniter used for this motor is an E-

Match. OpenRocket was used to simulate the best- and worst-case launch conditions for the launch vehicle's flight confirm this motor will allow us to get within range of our target apogee in either scenario. The thrust curve of this motor can be viewed in Figure 9.13.

4895L1395-BS Specifications	
Average Thrust	1418.86 N
Class	91% L
Delays	Plugged Seconds
Diameter	2.95 in
Igniter	E-Match
Length	24.45 in
Letter	L
Manufacturer	CTI
Name	L1395
Peak Thrust	1800 N
Propellant	APCP
Propellant Weight	2364.9 g
Thrust Duration	3.45s
Total Impulse	4895.40 Ns
Total Weight	4323g
Type	Reload

Table 9.1 L1395 Motor Specifications

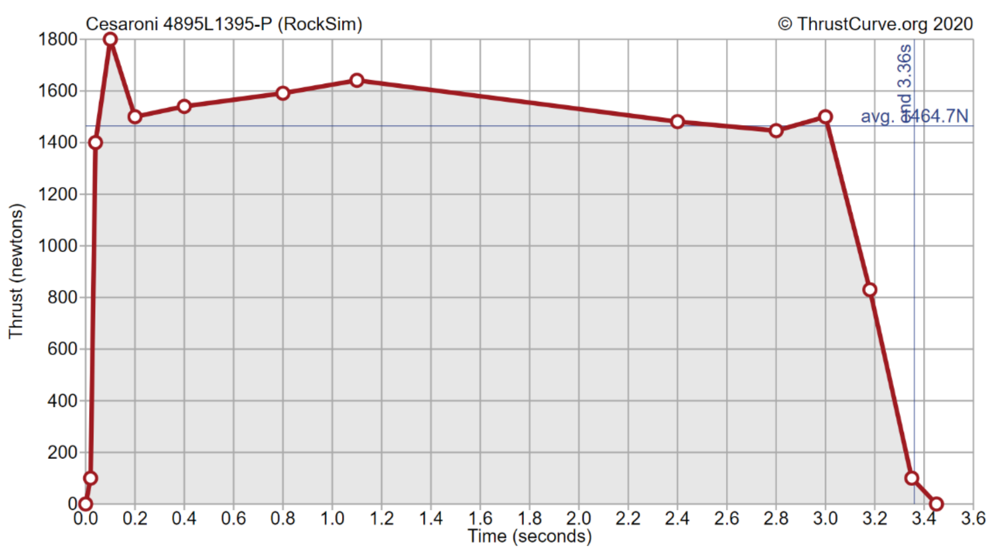

Figure 9.13 L1395 Thrust Over Time Graph

The backup motor selected for the launch vehicle is the L2375-P, which is also a L class motor manufactured by Cesaroni Technology. It has a diameter of 2.95 in, length of 24.45 in, peak thrust of 2608.3 N, and a total impulse of 4905.17 Ns. The igniter used is an E-Match. The average thrust is higher than the L1395 and the impulse is of a similar value, while the dimensions remain identical, allowing us to adopt this motor if the launch vehicle weighs more than expected. Using OpenRocket, this motor was tested in simulations of best- and worst-case scenario conditions for the launch vehicle's flight to confirm that we will be within range of our target apogee in either case. The thrust curve for this motor can be viewed in Figure 9.14.

4864L2375-P Specifications	
Average Thrust	2324.7 N
Class	92% L
Delays	Plugged Seconds
Diameter	2.95 in
Igniter	E-Match
Length	24.45 in
Letter	L
Manufacturer	CTI
Name	L2375
Peak Thrust	2608.3 N
Propellant	APCP
Propellant Weight	2322 g
Thrust Duration	2.11 S
Total Impulse	4905.2 Ns
Total Weight	4161 g
Type	Reload

Table 9.2 L2375 Motor Specifications

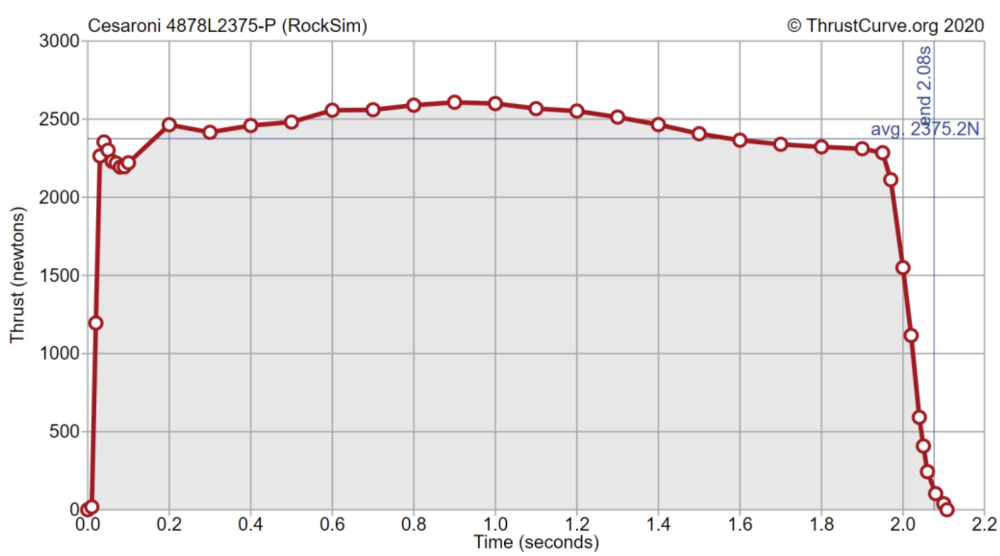

Figure 9.14 L2375 Thrust Over Time Graph

9.4 Recovery

9.4.1 Avionics Bay

The avionics bay will be housed in the coupler between the lower and middle airframes. It consists of forward and aft bulkheads, connected by a central T-shaped spine as shown in Figure 9.15. The purpose of the spine is to increase the structural integrity of the avionics bay. The spine will distribute tensile loads between the forward and aft bulkheads during the rocket recovery. This will lessen the loads on the forward bulkhead at the airframe connection. The spine will be split into two separate parts for better manufacturability. The main portion of the spine will be made of a 0.5 in aluminum hex bar, making it simpler to lock the rotation of the avionics sled and airbrake mechanism which will both be on the spine section of the avionics bay.

Figure 9.15 Avionics bay

A twist-lock mechanism will be utilized to lock the avionics bay into position. The aft bulkhead features a slot in its upper wall and within the body of the bulkhead is a rounded groove for the T-shaped spine. The spine will be inserted into the slot in the aft bulkhead and then rotated 90 degrees to lock it into place. This allows for simple launch assembly and maintenance. The coupler also ensures load distribution across the avionics bay due to the reaction of the spine and the aft bulkhead ceiling. The forward bulkhead, and therefore the avionics bay, will be permanently installed in the rocket by four bolts that rotationally constrain the spine.

9.4.2 Recovery Electronics

The electronics bay will house the two StratoLogger altimeters that will be wired to external switches on the main body of the launch vehicle. When switched to the on position, the altimeters will perform a specific set of beeps to communicate the continuity of the charges and confirm proper orientation within the launch vehicle. The StratoLogger is a versatile and an accurate altimeter with a simple cost-effective design that is sufficient for our purposes.

It is designed to provide control over firing a drogue and main parachute in a dual event deployment. The StratoLogger does not have an accelerometer, however it was deemed that lack of an accelerometer would not impede parachute deployment.

Rotary switches will be used to switch the altimeters on. A rotary switch is a 110/220V selector power switch that can be mounted on the inside of the airframe or through the wall of the avionics bay. It will be used to switch the common outputs of the two altimeters as a safe or arm switch.

A one or two cell lithium polymer (LiPo) battery will be used this year which was similarly used in previous years. These LiPo batteries have the highest energy density per weight and are very compact. They are also better at handling the forces of launch than some alternatives, such as 9-volt batteries, so they can be reliably reused. LiPos are much more resistant to the effects of cold temperatures and will be used since our test launches will be done in the northern winter months making the LiPos more reliable.

9.4.3 Parachute Selection

The recovery system will consist of two parachutes to slow down the launch vehicle. Both parachutes will be stored in the middle airframe. The drogue parachute is used to slow the descent of the launch vehicle until main parachute deployment, so the main parachute does not experience a high impulse when deployed.

Using the sizing guide provided by the University of Idaho[2] we can use weight and drag to solve for the proper radii for our two parachutes.

$$r = \sqrt{\frac{2mg}{\pi C_d A_p v^2}}$$

Using the following equation for weight with gravity as the only acceleration. Since the landing kinetic energy must not exceed 75 ft-lbf per independent section of the launch vehicle, the mass of the lower and middle airframes will be used in these calculations.

$$W = ma = mg$$

Using this weight, we can calculate the drag force with the coefficient of drag (C_d) of the parachute, the area of the parachute (A_p), density of the fluid (ρ), in this case air, and relative velocity of the fluid (v).

$$D = \frac{1}{2} C_d A_p \rho v^2$$

[2] Sizing a Parachute, Levi Westra, University of Idaho, https://www.webpages.uidaho.edu/dl2/on_target/tv.htm

Using this process, in addition to validation in by OpenRocket flight simulations, we have decided on the tentative radii for the two parachutes we will be using. They may change with the mass of the vehicle sections. The drogue parachute will have a diameter of 36 in and drag coefficient of 0.75. The main parachute will have a diameter for 144 in, drag coefficient of 2.20, and will be deployed at 500 ft to ensure the launch vehicle sections have a safe landing velocity and also minimize the descent time. Both parachutes will have canopies made of ripstop nylon. The parachutes will be attached to the airframe sections using 1 in tubular nylon shock cord with a total length of 400 in.

Additionally, the nosecone will be attached to its own smaller parachute, of a to be determined size. The nosecone will eject and its parachute will open at payload ejection, and the nosecone will descend separately from the rest of the rocket.

9.4.4 Parachute Retention & Release

The dual deployment recovery system will operate out of a single bay, with both parachutes housed in the middle airframe. The drogue parachute will be ejected from the rocket at apogee using black powder charges, which will be set off by signals from the altimeter, breaking the shear pins holding the upper and middle airframe together. During drogue ejection, the main will be retained inside the body of the rocket until the launch vehicle descends to 500 ft, at which point the main parachute will also deploy.

The retention and release method for the main parachute consists of two redundant devices - an Advanced Retention Release Device (ARRD) and a Tender Descender—which will keep the main parachute inside the body tube until the rocket reaches the main deployment altitude. The Rattworks ARRD, made by Aerocon Systems, will be bolted to the forward bulkhead of the avionics bay. The other end of the ARRD will be connect to the Tender Descender L3, made by Tinder Rocketry. The main parachute will be connected to the U-bolt on the forward bulkhead and place directly on top of the ARRD and Tender Descender, while still inside its deployment bag. The Tender Descender will be connected by a piece of shock cord to the top of the main parachute. The drogue will be connected to the main parachute with shock cord, with its other end tethered to the bulkhead in the upper airframe.

At 500 ft, the altimeter will ignite the black powder charges in both devices to release the main chute. The drag force of the drogue chute on the shock cord will pull the main parachute out of the body tube and allow it to fully inflate. The redundancy of the release devices will ensure that at least one of the devices will release the parachute, making the design reliable. Although this design is more mechanically complicated, these two redundant devices are much more reliable than alternative release devices and can help prevent tangling of shock cords. The single bay design also clears up more space in the lower airframe, which will be occupied by the motor, airbrake mechanism, and avionics bay.

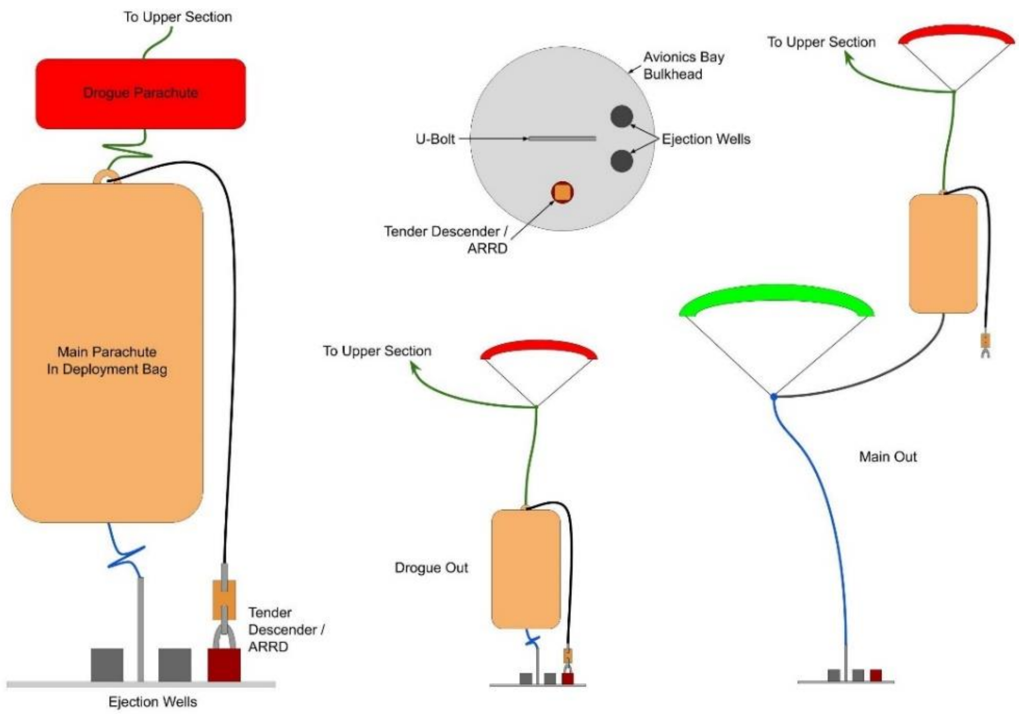

Figure 9.16 Recovery System Configuration and Parachute Deployment Stages

If the ARRD and Tender Descender design is not reliable when tested, we have a backup release method. Our design will remain a single bay dual deployment system, and the drogue will still be ejected the same way. In the backup design, the main parachute will not be held inside the body tube and will instead be ejected with the drogue parachute while remaining packed. Double or triple redundant Jolly Logic Chute Release devices will keep the main parachute packed and will allow it to release at the main deployment altitude. Jolly Logic devices have been previously used by the team and have been more complicated to use since they require monitoring multiple device batteries and altimeter settings.

9.4.5 Mission Performance Predictions

The projected flight plan of the launch vehicle was done using the flight simulation feature on OpenRocket, as shown in Figure 9.17. With the primary motor, the L1395 (section 9.3.3), the launch vehicle will reach an apogee of 4856 ft in 17.8 s, a maximum velocity of 613 ft/s at approximately 3 s, and a maximum acceleration of 231 ft/s^2 at approximately 3 s. The main parachute will be deployed at an altitude of 500 ft at approximately 70 s, while the launch vehicle will have a downward velocity of 345 ft/s. The descent time of the launch vehicle will be approximately 88 s, and the landing velocity is 12.1 ft/s.

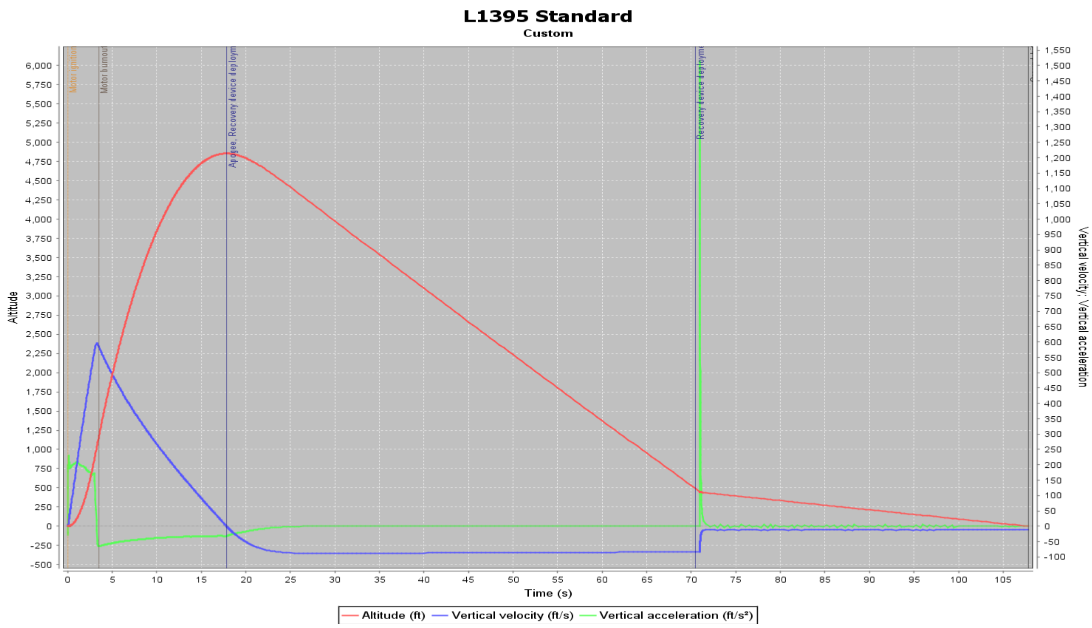

Figure 9.17 Vehicle Altitude, Vertical Velocity, and Vertical Acceleration Over Time.

Figure 9.18 Figure 9.18 shows the stability of the launch vehicle over time. The stability of the vehicle at rail exit is 2.69 cal and the maximum stability will be about 3.7 cal at approximately 3.5 s.

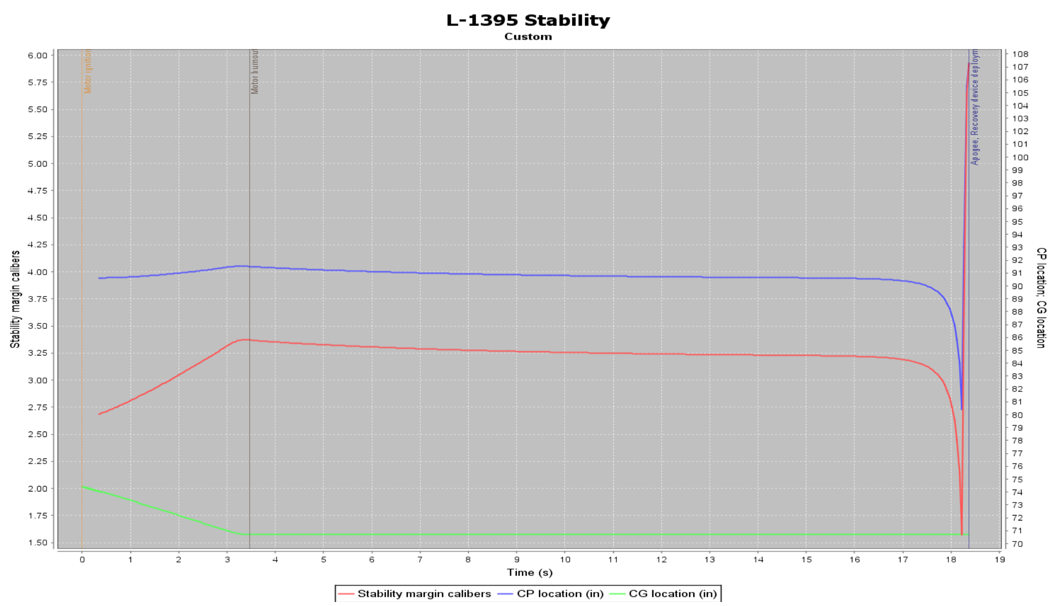

Figure 9.18 Vehicle Stability Over Time.

9.5 Mechanical Systems

9.5.1 Airbrakes

One goal of our team this year is to have an altitude control system. Our airbrake system accomplishes this by allowing us to control the amount of drag on our rocket as we head towards or target altitude. This is done through extending our airbrake fins from the rocket. This means the farther the airbrake fins are extended from the airframe of the rocket the larger the surface area of the fins that is exposed in turn increasing the drag. The fins can also be retracted easily with our control set up allowing us to vary the amount of drag during flight. This gives us the ability to control the drag on the rocket throughout flight by either increasing it or decreasing it.

9.5.2 Airbrake Mechanical Design

In order to have a small, effective, airbrake system, an important topic to consider is how to include the least amount of moving parts, as that will result in the fewest possible areas to break. To accomplish this, there will be five main components of the system. There will be the actuator plate, fins, a gear system, guide plate, and cover plate.

9.5.2.1 Actuator Plate

The actuator plate has four equiangular slots designed to apply constant torque to the dowel pins attached to the fins. This allows for our fins to extend and retract at the discretion of our control system allowing us to control the exposed surface area of the fins at any altitude to control the amount of drag on the rocket. The actuator plate spins independently of the spine this can be seen in section 9.4.1.

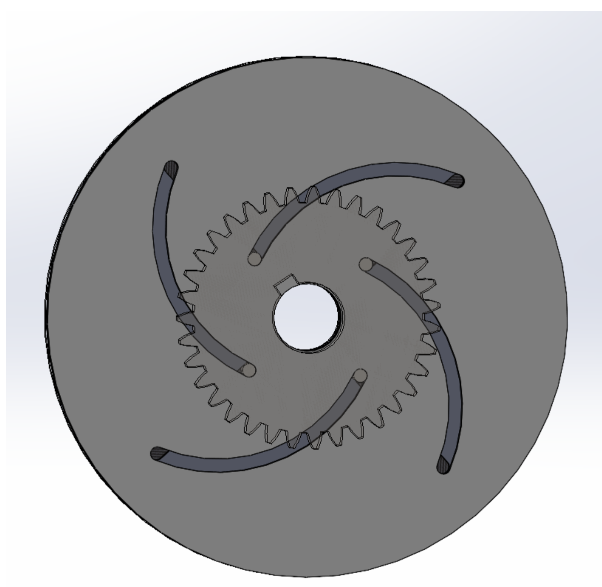

Figure 9.19 Actuator Plate Retracted

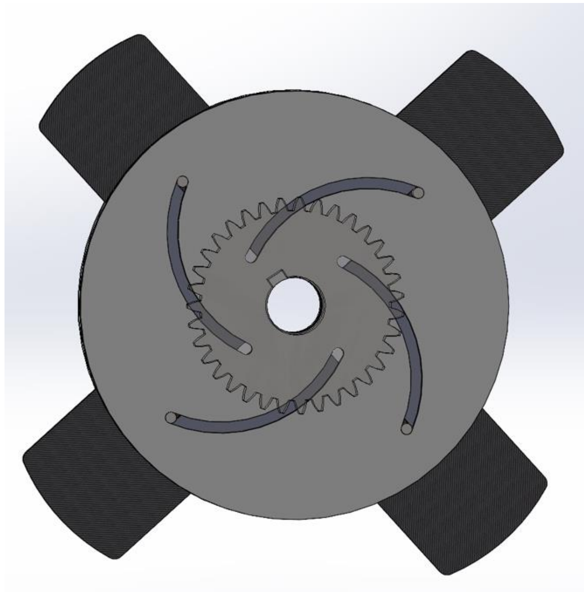

Figure 9.20 Actuator Plate Open

9.5.2.2 Fins

The fins have a rounded trapezoidal shape on one side, and a rectangular form on the other side to act as the actual fin. The fin pins will be connected through a hole on the trapezoidal side of the fins to the guide and actuator plates. These pins will allow for the spinning of the actuator plate, and thus the movement of the fins.

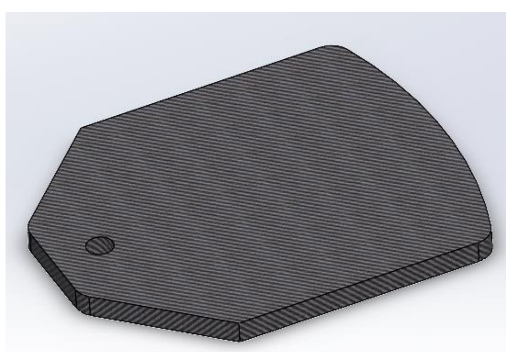

Figure 9.21 Carbon Fiber Fin

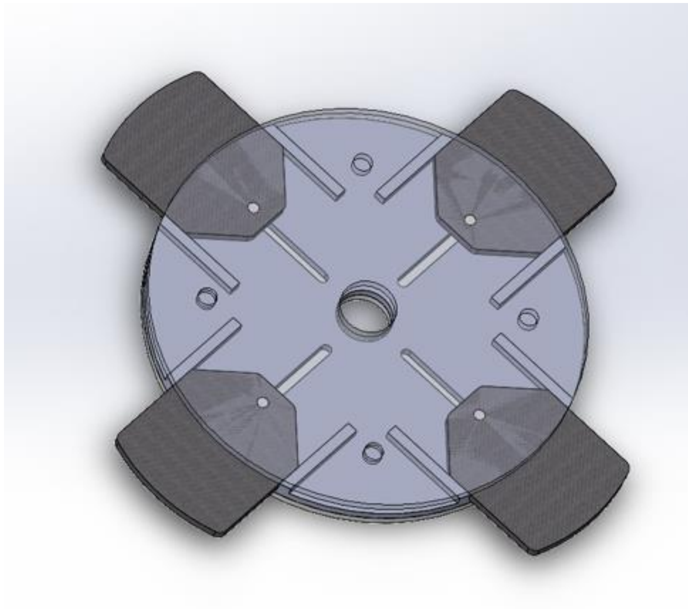

Figure 9.22 Fins Extended

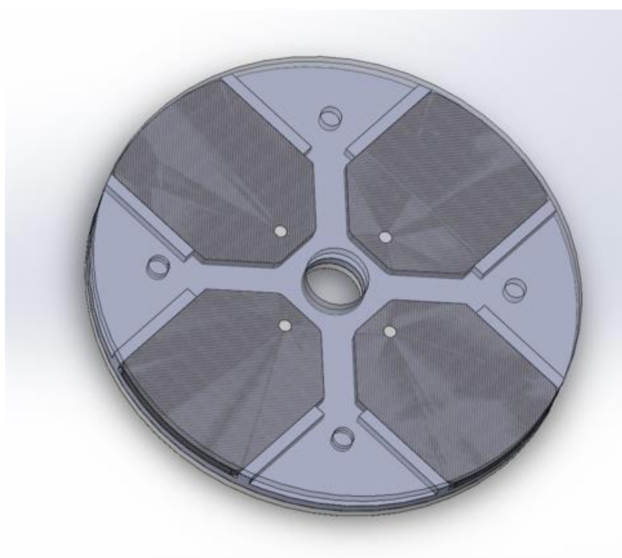

Figure 9.23 Fins Retracted

9.5.2.3 Gear System

The gear system consists of two gears, with one connected to the actuator plate and the other connected to a servo. The servo will spin the gears and cause the actuator plate to move the fins out. This system is designed such that the fins can be adjusted based on the desired drag. The gear system spins independently of the spine.

9.5.2.4 Guide Plate

The guide plate is a round plate with guides for the fins and slots for the fin pins. The guide plate is connected to the cover plate via bolts but separate from the actuator plate beneath it. The guide plate is dependent of the spine and is connected in the center hole.

9.5.2.5 Cover Plate

The cover plate is bolted into the guide plate and closes off the air brakes from the rest of the rocket. The cover plate is dependent of the spine and is connected in the center hole.

9.5.3 Material Selection and Justification

The twist plate of the air brake system will be constructed with a 1/8 in G10 Fiberglass plate for three main reasons. Its outstanding strength to weight ratio eliminates the need for a heavy chunk of aluminum that will weigh down the rocket and maintains the strength necessary to build a sturdy component. Additionally, fiberglass is used instead of carbon fiber because it is less rigid and therefore more durable, a necessary quality for a moving mechanism. Financially, fiberglass is preferred because of its lower cost compared to carbon fiber.

The four airbrake fins will be made from a 1/8in solid carbon fiber plate. Despite the high cost, the high stiffness of carbon fiber is necessary for an external part that will be under immense stress. This material is preferred because it is lightweight and strong.

The airbrake's guide plate and cover plate will be manufactured with 1/8 in Delrin plastic. In general, Delrin is high strength and has low coefficient of friction. There is also the added benefit that Delrin can be simulated in SolidWorks Simulation. Delrin's low coefficient of friction is essential to the guide plate's intended purpose; to allow for ease of movement across its surface. This material also eliminates the need for a low friction cover film. Since the cover plate is not a structural component but rather a design preference, it is unnecessary to allocate funds to carbon fiber or fiberglass. Delrin is also easy to machine and drill holes into, which is necessary to attach the cover plate to the airbrake system.

9.5.4 Construction Methods

The part above will be manufactured using either waterjet or laser cutting. These two processes were selected because they are precise and relatively quick. The fiberglass twist plate and the four carbon fiber fins will be produced via waterjet. These two materials are particularly compatible with a waterjet because they are made of multiple layers, which a laser cannot cut through. The lack heat produced by waterjet is ideal for fiberglass because it prevents heat related stress and thermal distortion. The clean cuts made through this process are imperative for the twist plate specifically because the arc slots need to be very smooth and precise. The Delrin guide plate and Delrin cover plate will be laser cut. Delrin is highly compatible with laser cutting, and team accessibility to laser cutting allows for more experimentation with the slots. Furthermore, water jetting is unnecessary for a non-structural component such as the cover plate.

9.5.5 Integration with Avionics Bay

The airbrakes are located in the Avionics Bay as depicted in the image below. This positioning allows for the airbrake system to be below the center of gravity in the rocket maintaining our stability throughout deployment of the airbrakes and flight with the airbrakes deployed. This positioning of the airbrakes is also ideal due to the fact that the airbrake system is located just above the electronics for the avionics system. This allows for us to easily house our servo motor in the avionics section along with the controllers for it, simplifying the wiring of the system. The complete Avionics Bay design is shown in Figure 9.15. The airbrake guide plate is secured in place onto the avionics bay spine by a ring attachment as seen in Figure 9.24 This way, most of the drag force burden is transmitted to the T-shaped spine instead of the electronics compartments.

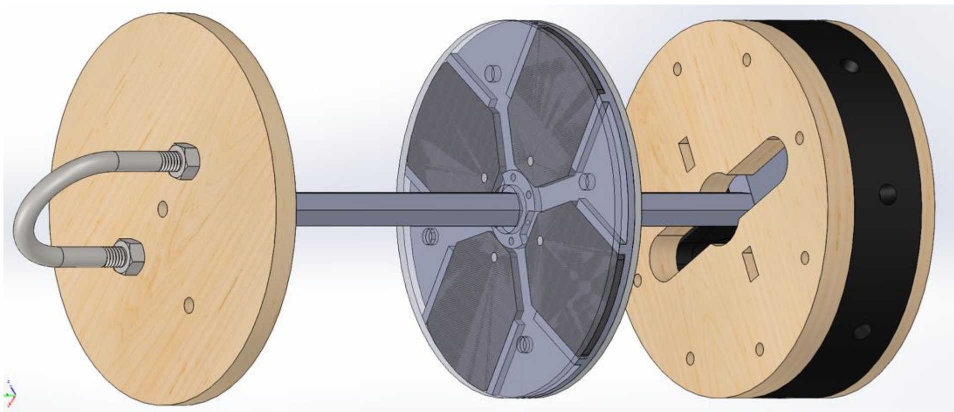

Figure 9.24 Avionics Bay

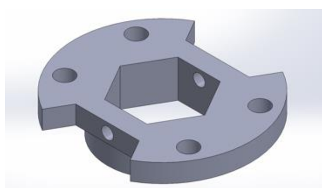

Figure 7 Ring Attachment

9.5.6 Airbrakes Electronics Designs

In order to provide both the necessary torque as well as a compact design, we have elected to choose a Hitec HS-755MG Servo. This motor provides a torque of 167oz-in at 4.8 V and 200 oz-in at 6.0 V, while only being 2.907 x 1.124 x 2.044 in. At this compact size, it will easily fit on one side of the rotating plate, and with the current gear size, will mesh nicely with the gear currently attached to the rotating bottom plate.

Figure 9.25 Hitec HS-755MG Servo

9.6 Avionics

9.6.1 Avionics Board

In addition to the commercial flight computers, the vehicle will have an additional avionics board. It will incorporate the functionality of the team's custom telemetry package from the previous year's rocket. That is, it will log and transmit live telemetry and serve as a GPS tracker. Additionally, this system will also control the airbrake mechanism (section 9.5.1). After developing prototypes using breadboard wiring, the team hopes to create a finalized single board design that will be more durable, compact, and lightweight compared to last year's design.

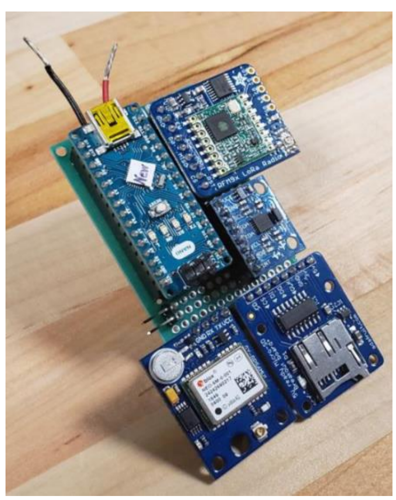

Figure 9.26 Last year's telemetry system.

The airbrake mechanism is actuated by a single servo controlled by a PWM signal. In order to determine the optimal time to deploy the air brakes such that the vehicle precisely hits the target apogee, the team will create a state space model of the vehicle's dynamics. The predictions of the model will be used be used by the controller to identify a time to actuate the servo.

9.6.2 Microcontroller

Arguably one of the most important electrical aspects of our design will be the microcontroller. In addition to connecting the other components as is further discussed, the flight computer we use will determine airbrake deployment (section 9.5.1). Differing from last year, the microcontroller will have a heavier computational load placed upon it for calculating airbrake deployment. Therefore, speed, feature set, and accessibility will be key factors in determining our final decision for a microcontroller.

As of now, multiple options, as well as their benefits and costs, are being discussed. Primary contenders for our choice of dev board, as well as their key benefits and features, are shown in the table below.

Processor	Dev Board	ROM	RAM	Supported IDEs	Features
STM32F3 (Cortex-M4)	STM32F3Discovery	256 kB	48 kB	STM32CubeIDE	Gyroscope Accelerometer
i.MX RT1060 (Cortex-M7)	Teensy 4.1	8192 kB	1024 kB	Arduino IDE	MicroSD slot I/O options
AM3358 (Cortex-A8 + 2x PRUs)	BeagleBone Black Rev C	4 GB	512 MB	Desktop Linux IDEs.	Performance
SAM3X8E (Cortex-M3)	Arduino Due	512 kB	96 kB	Arduino IDE	I/O options Documentation
ATSAMD21G18 (Cortex-M0+)	Arduino Zero	256 kB	32 kB	Arduino IDE	I/O options Documentation

Table 9.3 Processor Comparison

There are benefits and risks to each option. The STM32F3Discovery for example has many built features, such as the gyroscope and accelerometer. This could allow for easier prototyping. However, the use of more accurate and independent sensors is an option that may detract from the STM processor. The Teensy 4.1 has 8192 kB of flash memory, I/O options, and an included MicroSD card slot for data recording. While it is compatible with the well documented Arduino IDE, compatibility be an issue. The BeagleBone Black Rev C stands out among the others for performance. With three total processors, as well as accelerators, the BeagleBone Black will be able to quickly handle data from our rocket. A big downside is overhead, running an operating system such as Linux or Android. While this improves flexibility, it will increase complexity. Finally, the Arduino Due and Zero are a more basic option that are well documented and with 50+ I/O, but with limited specifications. Each could be a reliable choice.

9.6.3 Telemetry Design

Within the electronics bay, the chosen microcontroller board will transmit data collected from the other components to the radio transceiver. The transceivers we are considering include the Adafruit RFM95W LoRa (Long Range) 900 MHz and RFM95W LoRa 915 MHz.

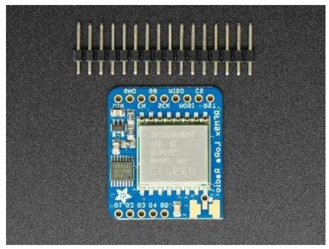

Figure 9.2 Adafruit RFM95W LoRa 915 MHz

An important distinction between these transceivers is their frequencies. Lower frequencies give longer ranges; however, this comes with a tradeoff of slower transmission speeds. Depending on the amount and type of data we transmit, the speed will have to be considered. Each option works well with Arduino boards. A LoRa external antenna will be connected to the radio transceiver to collect data. The Adafruit 900MHz Antenna Kit is a viable option since it can be used with all LoRa breakout boards. Long range capabilities make these radio transceivers very good options.

Figure 0.3 Adafruit 900MHz Antenna Kit

9.6.4 Accelerometer

Our rocket will have an accelerometer and gyroscope in order to measure its acceleration and rotation and provide the primary method to estimate velocity and position. This sensor will help our flight computer determine the best time to deploy our air brakes in order to reach our target altitude and log acceleration data. The accelerometer will be chosen based on its type, the maximum acceleration it can record, its operating voltage, and number of axes. The three main types of accelerometers are Capacitive MEMS, Piezoresistive, and Piezoelectric. Piezoelectric accelerometers cannot measure 0 Hz, or constant, accelerations and are mainly used for vibration measurement, so we will not be using them. MEMS and Piezoresistive accelerometers can measure constant accelerations like the one our rocket will produce, and they are good for tracking velocity and position. Piezoresistive accelerometers have a high sensitivity to temperature changes, so extra consideration must be taken.

Last year the team used the MPU6050 accelerometer/gyroscope. This is a three axis MEMS type accelerometer combined with a three-axis gyroscope, as well as a digital motion processor. The chip comes on a breakout board manufactured by Adafruit. It can measure up to 16 g acceleration and 2000 deg/sec rotation and runs on 3.3 V. This is a very popular gyroscope for all motion tracking purposes, and it would be a great choice for our rocket.

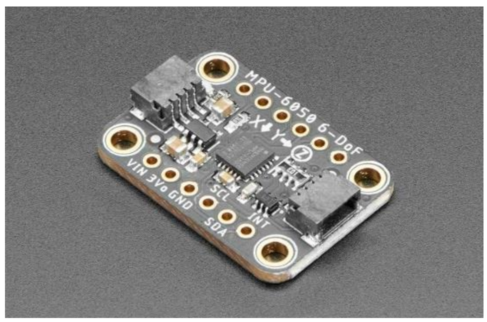

Figure 9.27 Adafruit MPU6050 accelerometer/gyro breakout board

A secondary option for the accelerometer is the LIS331HH, a three axis accelerometer that can measure up to 24 g on all three axes. This board can measure greater forces than the MPU6050, however it does not have an integrated gyroscope.

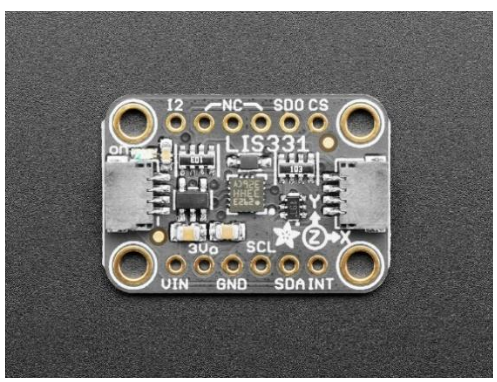

Figure 9.28 Adafruit LIS331HH 3-axis accelerometer

9.6.5 GPS

The rocket will include a GPS receiver that serves as the primary method to measure the position and velocity of the rocket. The GPS receiver would also aid in locating the rocket should it disappear from the sightline. One GPS receiver being considered is the MTK3339. This receiver can track 22 satellites simultaneously at a sensitivity of -165 dBm. The receiver can track its location within 10 feet of accuracy up to 10 times per second (10 Hz). The receiver can also track the velocity with an accuracy of 0.33 ft/s for velocities not exceeding 1690 ft/s. The MTK3339 is available on a breakout board manufactured by Adafruit which will make prototyping easier.

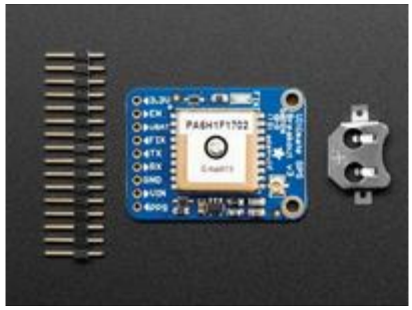

Figure 9.29 MTK3339 Breakout Board

Another option being considered is the u-blox NEO-M8M. The advantages to this board are a greater update rate at 18 Hz and a slightly better positional accuracy of 8 ft. Its velocity accuracy is also better at 0.16 ft/s for velocities not exceeding 1640 ft/s. Adafruit does not have a breakout board for the NEO-M8M.

Figure 9.30 u-blox NEO-M8M GPS Receiver

9.6.6 Barometer

The primary purpose of the barometer is to track the altitude of the rocket. The altitude can be used in conjunction with the other sensors data to estimate the trajectory of the rocket in real time. The MPL3115A2 and BMP280 are two options being considered. The MPL3115A2 has a resolution of 8 pascals (1 Foot). Additionally, it has a temperature sensor with an accuracy of ±5.4°F. One perk of the MPL3115A2 is that it has a built-in altitude calculator. The BMP280 has up to 100 pascals (10 feet) resolution. It also has a temperature sensor with ±1.8°F accuracy. The BMP280 does not have built in altitude calculation, so the main processor would compute that value.

Figure 9.31 MPL3115A2 Barometric/Temperature/Altitude Sensor

Figure 9.32 BMP280 Barometric Pressure/Temperature/Altitude Sensor

10 Payload Design

10.1 Concept of Operations

The payload will be deployed from the airframe at 800 feet AGL. The deployment will consist of a black powder charge going off in the coupler between the upper and middle airframe which will push off the nose cone which will descend separately and push the payload out of the tube. After which the parachute will deploy and the payload will descend under parachute until it reaches the ground where the parachute will release, and the orientation will begin. First the self-righting system will bring the payload close to the desired orientation after which the stabilization brings the payload with 5 degrees of level tolerance. The photo will be taken and transmitted back to the ground station. The approximate dimensions of the payload are 10 in long by 5.5in in diameter.

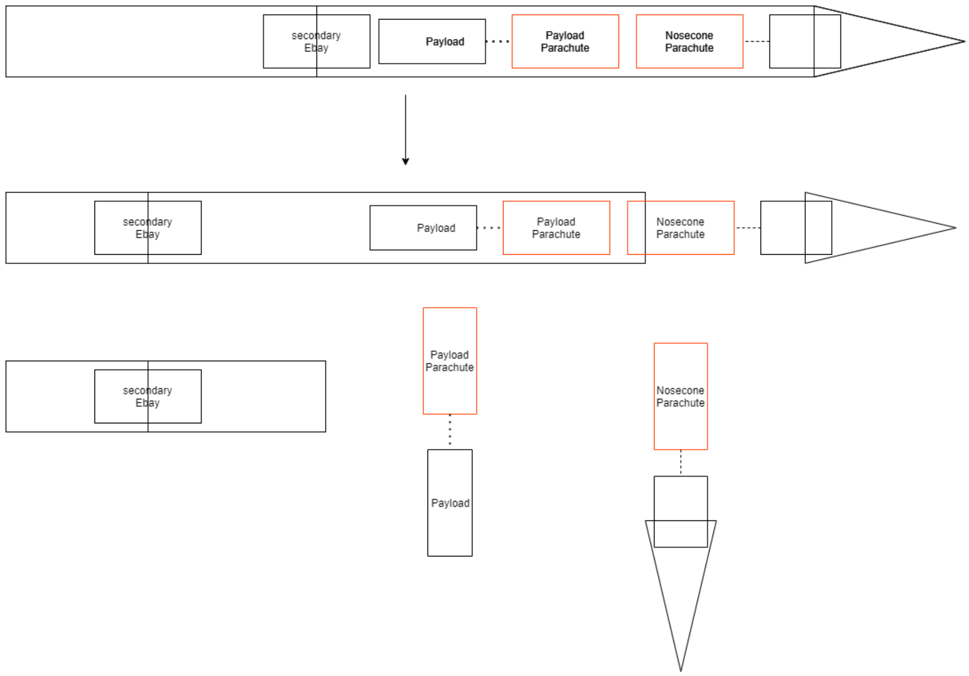

Figure 10.1 Payload Concept of Operations

10.2 Self-Righting

In order to provide the stabilization system a suitable starting point to get the lander within the specified tolerance of level, it first must right itself from whatever orientation it landed in. This will be achieved with a system of petals which rotate outwards to lever the entire lander to a suitable, close to upright position before the stabilization system levels the lander more precisely. The 6 petals will be grouped into pairs to create three larger "virtual" petals which act as if the petals were made from a larger angular cut while still reducing the size of the individual petals. Pairing the petals together will help stabilize the payload during the self-righting sequence by having two points of contact instead of just one if they were not to be paired. The three stabilization legs would then be located between the paired "virtual" petals.

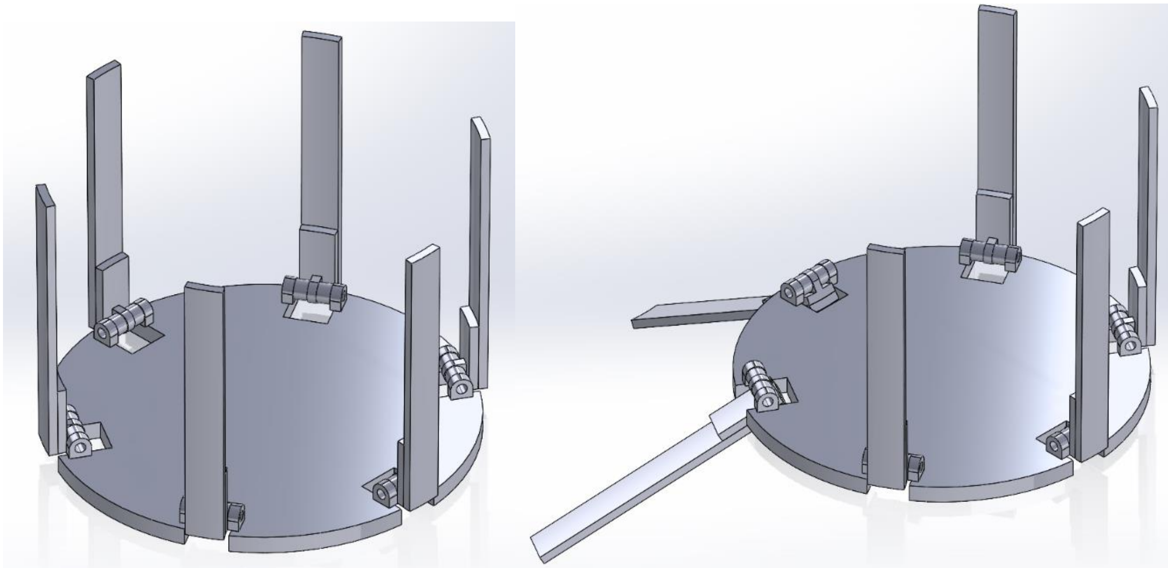

Figure 10.2 Petals in stowed positions and one pair being actuated.

The petals will most likely be 3D printed (with attention paid to layer direction and its effect on strength). There is also the option of cutting them from a material such as plate carbon fiber which would have the benefit of increased strength. The ability with 3D printing to create a curved surface allows for a maximized volume when stowed in the airframe versus the likely flat surfaces of the carbon fiber or metal petals, although the narrow width of the petals means that the volume loss would be relatively small and both options are entirely reasonable.

Rotation of the petals will be achieved by one of three methods which is yet to be chosen. One possibility is to have individual linear actuators for each petal which extend and torque the petals outwards. An issue with using linear actuators is that to maintain a compact footprint, they would have to be near-vertical and only be able to act on the lower portion of the petals which would provide less force on the ground as the lever arm from the hinge to the actuator would be relatively small. Another option for actuating the petals is to build gear teeth into the petals which would be driven by a servo. Using this method would allow for a more direct transfer of torque to the petals while easily achieving a small footprint to allow for stabilization mechanisms in the area. The final actuation method being considered is a wire-pulley system driven by servos. A wire would be attached near the end of each petal and to the pulley on the servo which would rotate to drive the petals outward. This method has the benefit of allowing the actuators to all be in the center of the payload to give more room to the stabilization system. However, because cables can only ever be in tension, there is the problem of not being able to provide more torque than the weight of the petals provide. The pulley system would therefore only be feasible with the addition of springs that act to push the petals outward, so the cables act only to hold the petals back from releasing early and limit the rate at which the petals extend. The rate limiting would ensure that the spring-driven legs do not deploy so rapidly that they flip the lander over. This method would also require a locking mechanism so that the possibility of early deployment (i.e. in the rocket) is near-zero, which would add mechanical complexity.

Figure 10.3 Petal Actuation Options (from left to right, linear actuator, geared servo, and servo with pulley).

10.3 Stabilization System

10.3.1 Deployment System

The stabilization system of the payload will consist of three parallel fourbar linkages radially spaced about the payload centerline. These linkages will be stored within the payload body (Figure 10.4) until it has been righted, at which point each will be deployed by a motor located at the intersection of the lower yellow and blue links (Figure 10.5). These motors will then coordinate with the payload's computer to bring the payload to within five degrees of vertical. This system was chosen because of the predictability of its motion, its reliability over the alternate designs, and the range of foot options this design will enable. This design also allows for the installation of torque-assist modules such as a constant-force spring about the crank shaft that reduce the load on the motor. Finally, this design can be modified with the inclusion of a worm gear in a transmission connecting the motor and the crank to prevent motor back drive.

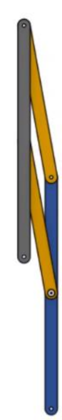

Figure 10.4 The Stabilization Linkage in its Stowed Configuration. This Model Does Not Include the Foot Design.

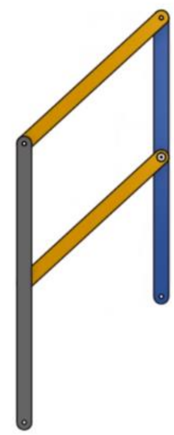

Figure 10.5 - Stabilization Linkage in its Deployed Configuration. The Blue Link is the Ground Link, and the Yellow Link is the Crank.

Alternate systems considered were a fixed or freely rotating linear actuator, both of which were rejected due to reliability issues with the linear actuators available to the team and restrictions the motors will place on foot design. A pulley-based design was also considered but was rejected due to the location requirements of a driver motor and the complexities of a pulley-based system.

10.3.2 Foot design

The foot design at the bottom of the stabilization system will be comprised of a ball joint that is restricted by two parallel springs on opposite sides of the foot. In order to account for variation in terrain, this system will be restricted in the yaw direction, but free to rotate in pitch and roll. This restriction will come from the two-spring system attached on a protruding horizontal bar above the foot and above the ball joint and will allow for more reliable connection with the ground while the stabilization system is activated. The bottom of the foot will be grooved radially with reference to the payload body in order to obtain lateral traction in various terrain, while also preventing friction in the radial direction, again referenced to the payload body. When combined with the other two legs, the payload will not slip around on the ground while also being able to adjust the stabilization system with the minimal amount of motor load. Before the payload is jettisoned, the feet will be stored as close to vertical as possible. During deployment, the forces from the springs will bring the foot to rest horizontally to ensure the foot hugs the ground on contact instead of being sub optimally loaded.

Alternative designs for the feet neglected the use of the dual-spring design pictured below, and mostly consisted of disks with knurled bottoms and hinged joints. These designs were rejected because they placed increased load on the motor and could either not fully adapt to uneven landing terrain as with the hinged joints or had too many degrees of freedom to adapt to the terrain as with the fully-free ball joint.

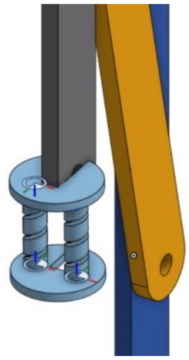

Figure 10.6 Closeup of the Foot as it is Mounted to the Linkage Coupler.

10.4 Photography

The recovery subteam has elected to construct a multiple camera array with fisheye (wide field of view) angle cameras in order to stitch together a 360-degree panoramic photo. We are looking at Raspberry Pi/Arduino cameras with approximately 120 or greater degree field of view. We decided to go with such a large field of view to minimize the number of pictures we will need to stitch together as well as the number of cameras we will need to take these pictures. This will enable us to easily stitch the pictures together on the payload vehicle or at the ground station. We considered using a pre-built 360-degree consumer camera as it would take one picture to suit our needs but strayed away from this as it may be too difficult to get the image off the camera's proprietary software. With our own personal camera array, we will be more in control of the image taking and processing operation. We decided to use an Arduino or Raspberry Pi to control the cameras as we will be able to use it to take the pictures and process the pictures without the need to transfer to another piece of hardware.

Figure 10.7 SainSmart Wide Angle Fish-Eye Camera Lenses for Raspberry Pi 3

Figure 10.8 Arducam Multi Camera Adapter Module V2.2

In terms of mounting the cameras, we will mount the cameras back to back in a triangular or square layout in the center of the payload vehicle. The cameras will be mounted close together so we can optimize the field of view of each camera.

Example of camera orientation

Video processing and stitching will take place at the ground station after each camera's photo has been taken and transmitted. This will be completed using a photo-stitching mode in popular video editing software. This postproduction will take place on a laptop. The final stitched image can then be inserted into our PLAR presentation. Alternatively, we may investigate image processing onboard the payload vehicle through the means of an Open CV and Python script. We are continuing to investigate the feasibility of this software as a means of combining the multiple pictures.

10.5 Electrical

To complete the required mission sequence, the payload lander will have an electrical system featuring a suite of necessary processors, sensors, and actuators for enabling it to sufficiently interact with its environment in a robust manner. Small actuators in the form of common servomotors will drive their respective mechanisms, as these devices are widely used for small-scale robotic applications. Exact motor specifications will be determined later through more in-depth system analysis for power, torque or force, and precision requirements. Accompanying these actuators will be the battery power and control system likely to consist of a small lithium polymer (LiPo) battery, Arduino Nano or similar microprocessor, and various sensors which communicate to the main processor information needed for the lander to complete its ground activities. This will include the same sensors present in section 9.6 so that, like the rocket, it will have information on its altitude, location, orientation, as well as the ability to communicate its state through telemetry. This custom system configuration has been used in prior team competition years and has remained consistently reliable. As for the camera sensors and communication of the panoramic photo, design criteria for this system is described in the section 10.4. With information from these sensors, appropriately powered actuators driving their respective subsystems, and an implemented digital control system on a main processor, the lander will be enabled to autonomously determine when it has landed, orient itself to within 5 degrees level of the horizon, and transmit a panoramic photo to the base station receiver for team viewing.

11 Educational Engagement

One of our team's core values is Engagement. Our engagement plan has two sections. The first being club engagement events for members and WPI students. These events are hosted by HPRC and are open to anyone on the team with some open to the whole campus and cover topics such as CAD, coding, and manufacturing. The purpose of our engagement events is to educate students on useful skills that can be used beyond college and to create a connection between HPRC and the WPI community as well as enable newer members to participate in technical development.

The team's second section is STEM engagement. STEM engagement is a major part of HPRC because it connects us to the Worcester community and helps to inspire the future generations. Our STEM engagement is done through k-12 outreach events. These outreach evens are held throughout the year in collaboration with organizations like Big Brothers Big Sisters, The Civil Air Patrol and WPI's own Precollegiate Outreach Program. Since the age difference between events is large, each of our events focus on different STEM topics catering to that specific age group. With COVID-19 still limiting in person events for both our engagement and outreach events, they will be held remotely through video call sources like

Zoom and Microsoft Teams. All HPRC events are also posted on the HPRC YouTube channel for an increased reach of our engagement.

12 Project Plan

As a Subcommittee of the WPI Student AIAA chapter, the WPI Student Launch team enjoys many benefits that increase the sustainability of the program. The WPI AIAA has a strong presence on campus, being the largest special interest club. It provides a large audience of students with experience and interest in robotics and aerospace, many of which join AIAA specifically for rocketry. This provides a reliably large recruitment source from which the majority of our members are recruited from. Additional recruitment is done this year through social media and via word of mouth, including WPI's club activities fair. AIAA also provides many opportunities that help members to more actively participate in the team. They provide funding and mentorship to students looking to get level 1 and 2 NAR HPR certifications and run a variety of workshops throughout the year.

Although many changes had to be made to the operating procedures and team structure, the team has a better idea of what to expect going into this year's competition. This has allowed the team's Operating Document to become much more refined. With the more solidified use of subteams, this is expected to improve the distribution of work throughout the team and allow for more members to be able to have a mentor who can pass on their knowledge. Every other week the team will host one General Team Meeting; these are for communication flow between divisions and will consist of both design presentations, division updates, and fun social interaction for team bonding. Every week there will be at least one meeting for each division. This is where subteams meet to discuss their designs that have to focus and integrate within their own division. Subteam meetings will range with the number of meetings being increased as necessary to meet deadlines and to construct. There is will also be a weekly meeting of the Officer Board open to all members. The team now has much more explicit operational procedures, along with a better flow of work, which will reduce ambiguity when making team decisions.

This year we hope to have increased member participation in STEM engagement activities with our partners at Friendly House, Big Brothers Big Sisters, the AIAA and educational engagement programs through WPI. Last year we were also able to partner with the Civil Air Patrol at Hanscom Air Base. These partnerships allow us as a team to engage with our community and help to inspire the next generation of scientists and engineers. We achieve this through mentorship programs, STEM presentations, events activities focused on core STEM topics and by creating lasting connections between our team and the next generation. Although it may look different this coming year, with more online events, each year we hope to continue and expand our STEM engagement activities so we can sustain a strong connection between our community, the next generation and our team.

Another benefit of being associated not only with the AIAA but the institution of Worcester Polytechnic Institute itself is the multiple resources for the funding of this club. We are the only rocket competition club on campus, and the funding from AIAA has expanded from that of the previous year. The Student Government Association (SGA) allows all clubs to apply for funding requests to make sure sufficient funds are provided for the club's operation. Funding requests applied for this year can also be requested to be included in the budget for next year. Sponsorship has also been another area the blub has grown in. Just as of proposal we have two of our sponsors from last year returning to continue to support our team. Ensign-Bickford Industries, Inc. (EBI) has also reached out to our club through our AIAA chapter and would like to mentor our team. This provides us with the valuable resource of real engineers evaluating and reviewing our designs with the added bonus of additional presentation practice. Between the given budget from the AIAA, help from the SGA, in addition with sponsorship and fundraising, we believe Worcester Polytechnic Institute's USLI team will be able to sustain this and future competition projects.

12.1 Budget

This section describes HPRC's budget for USLI Competition year of 2020 – 2021. HPRC Subcommittee was allocated a budget of $7,388.65 through its parent AIAA Chapter. Of the total budget, $2654.85 are allocated directly to components and $4733.80 are allocated to logistics. We have currently been given $1000.00 from sponsors for a total of $8,388.65. Due to WPI's, ongoing ban of student travel, we are not planning to attend the competition in person this competition year. As an officer board, we have transferred half of our logistics budget, $2466.90, towards additional components. The remaining $2366.90 of the logistics budget is reserved for potential launches once school affiliated travel is allowed. The combined budget remaining for components is now $6,021.75. We have allocated a target budget for each of the major constructions required in the competition based on their respective costs in previous years. These estimate costs are used as guidelines until the sub teams begin purchasing actual components. We understand that this budget may not be enough for all the components or logistics needed in the future. We plan to submit additional funding requests to our Student Government Association, gain more sponsors, and fundraise.

Purpose	Percentage of Component Budget	Amount Allocated
Full Scale Rocket	40%	$2408.70
Full Scale Payload	25%	$1505.43
Sub-Scale Rocket	15%	$903.27
Other	20%	$1204.35
		Total: $ 6021.75

Table 12.1 Budget Outline

12.2 Funding

A significant portion of this year's funding for 2020-2021 WPI HPRC will come from corporate sponsors. In addition to this, other modes of funding may come from on campus fundraisers the team holds throughout the year, organized by the sponsorship officer. The Sponsorship Officer is responsible for gathering funds from corporate sponsors and communicating with the Financial Services Department of WPI to ensure all proper transfer of funds is being done so appropriately.

A sponsorship package has been organized to present to companies primarily located in the local Worcester area. Each sponsor interested in funding our team will be provided with the selection of several packages. In order of increasing value, these sponsorship levels are Bronze, Silver, Gold and Platinum. Each package is aligned with the amount of money the sponsor decides to fund the team. The corporate sponsorship package is approved by the Division of University Advancement on WPI's campus before it is presented to our potential sponsors. One of the team's primary goals in funding this year is to create strong and lasting relationships with these sponsors so they will be interested in working with us again in the following competition years. Currently we have confirmed two returning sponsors from last year that will be continuing their support for our team into the coming year. If the team has any extra funding from corporate sponsors at the end of the competition season, the money will roll over to be used in the next competition year in 2021-2022.

In addition to gathering corporate sponsorships, WPI HPRC will also be receiving funds from the WPI AIAA chapter on campus. They receive their annual budget from the Student Government Association (SGA) on campus which is responsible for governing undergraduate organizations on campus. This year, HPRC will be the only competitive rocketry team in AIAA so all the funding for high powered rocketry competitions will be going to HPRC. Any additional funds will have a request submitted to the Student Government Association.

12.3 Gantt Chart

		Name	Duration	Start	Finish	Predecessors
1		**Proposal**	**31 days?**	**8/19/20 8:00 AM**	**10/1/20 8:00 AM**	
2		Proposal Announcement	0 days?	8/19/20 8:00 AM	8/19/20 8:00 AM	
3		Orientation	6 days?	9/8/20 8:00 AM	9/15/20 5:00 PM	
4		Recruting	17 days?	8/23/20 8:00 AM	9/15/20 5:00 PM	
5		Brainstorming	21 days?	8/19/20 8:00 AM	9/16/20 5:00 PM	
6		Presenting Ideas	2 days?	9/16/20 8:00 AM	9/17/20 5:00 PM	
7		Finalizing Ideas	2 days?	9/17/20 8:00 AM	9/18/20 5:00 PM	
8		Proposal Writing	2 days?	9/17/20 8:00 AM	9/18/20 5:00 PM	
9		Proposal Revision/Collection	0 days?	9/20/20 8:00 AM	9/21/20 5:00 PM	
10		Submission	1 day?	9/21/20 8:00 AM	9/21/20 5:00 PM	
11		Awarded Proposal	0 days?	10/1/20 8:00 AM	10/1/20 8:00 AM	
12		**PDR**	**60 days?**	**9/22/20 8:00 AM**	**12/14/20 5:00 PM**	
13		Rocket Design	17 days?	9/22/20 8:00 AM	10/14/20 5:00 PM	
14		Payload Design	17 days?	9/22/20 8:00 AM	10/14/20 5:00 PM	
15		Outreach Events	53 days?	9/22/20 8:00 AM	12/3/20 5:00 PM	
16		Workshops	60 days?	9/22/20 8:00 AM	12/14/20 5:00 PM	
17		Internal Design Presentations	3 days?	10/14/20 8:00 AM	10/16/20 5:00 PM	
18		Design Revisions	3 days?	10/17/20 8:00 AM	10/21/20 5:00 PM	
19		Safety Analysis	4 days?	10/21/20 8:00 AM	10/26/20 5:00 PM	
20		PDR Writing	7 days?	10/22/20 8:00 AM	10/30/20 5:00 PM	
21		PDR Revision/Collection	0 days?	11/1/20 9:00 AM	11/2/20 5:00 PM	
22		PDR Submission	0.875 days?	11/2/20 9:00 AM	11/2/20 5:00 PM	
23		PDR Presentation	14.875 days?	11/3/20 9:00 AM	11/23/20 5:00 PM	
24		**CDR**	**60.875 day...**	**11/3/20 9:00 AM**	**1/26/21 5:00 PM**	
25		Revisions Suggested by NASA	15.875 days?	11/4/20 9:00 AM	11/25/20 5:00 PM	
26		Subscale Design	1 day?	11/3/20 9:00 AM	11/4/20 9:00 AM	
27		Testing Components	5.875 days?	11/10/20 9:00 AM	11/17/20 5:00 PM	
28		Internal Design Presentations	2.875 days?	11/18/20 9:00 AM	11/20/20 5:00 PM	
29		Subscale Construction (Safely)	10 days?	11/21/20 9:00 AM	12/4/20 5:00 PM	
30		Subscale Flight	5.875 days?	12/4/20 9:00 AM	12/11/20 5:00 PM	
31		Flight Analysis	4.875 days?	12/14/20 9:00 AM	12/18/20 5:00 PM	
32		CDR Writing	14.875 days?	12/14/20 9:00 AM	1/1/21 5:00 PM	
33		Winter Break	21.875 days?	12/14/20 9:00 AM	1/12/21 5:00 PM	
34		CDR Revision/Collection	0 days?	1/2/21 9:00 AM	1/4/21 5:00 PM	
35		CDR Submission	0.875 days?	1/4/21 9:00 AM	1/4/21 5:00 PM	

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		Name	Duration	Start	Finish	Predecessors
36		CDR Presentation	13.875 days?	1/7/21 9:00 AM	1/26/21 5:00 PM	
37		**FRR**	**56.875 day...**	**1/8/21 9:00 AM**	**3/29/21 5:00 PM**	
38		Revisions Suggested by NASA	14.875 days?	1/8/21 9:00 AM	1/28/21 5:00 PM	
39		Testing Components	5.875 days?	1/13/21 9:00 AM	1/20/21 5:00 PM	
40		Full Scale Construction (Safely)	22.875 days?	1/20/21 9:00 AM	2/19/21 5:00 PM	
41		Full Scale Flight	5 days?	2/20/21 9:00 AM	2/26/21 5:00 PM	
42		Flight Analysis	6 days?	2/20/21 9:00 AM	3/1/21 5:00 PM	
43		FRR Writing	11.875 days?	3/1/21 9:00 AM	3/16/21 5:00 PM	
44		FRR Revision/Collection	0 days?	3/6/21 9:00 AM	3/8/21 5:00 PM	
45		FRR Submission	0.875 days?	3/8/21 9:00 AM	3/8/21 5:00 PM	
46		FRR Presentation	12.875 days?	3/11/21 9:00 AM	3/29/21 5:00 PM	
47		**FRR Addendum**	**15.875 day...**	**3/8/21 9:00 AM**	**3/29/21 5:00 PM**	
48		Full Scale Flight	9.875 days?	3/8/21 9:00 AM	3/19/21 5:00 PM	
49		Flight Analysis	3 days?	3/20/21 8:00 AM	3/24/21 5:00 PM	
50		FRR Addendum Writing	3 days?	3/24/21 8:00 AM	3/26/21 5:00 PM	
51		FRR Addendum Revision/Collection	1 day?	3/27/21 8:00 AM	3/29/21 5:00 PM	
52		FRR Addendum Submission	1 day?	3/29/21 8:00 AM	3/29/21 5:00 PM	
53		**PLAR**	**20 days?**	**3/30/21 8:00 AM**	**4/26/21 5:00 PM**	
54		Full Scale Competition Flight	11 days?	3/30/21 8:00 AM	4/13/21 5:00 PM	
55		Flight Analysis	4 days?	4/9/21 8:00 AM	4/14/21 5:00 PM	
56		PLAR Writing	7 days?	4/15/21 8:00 AM	4/23/21 5:00 PM	
57		PLAR Revision/Collection	1 day?	4/24/21 8:00 AM	4/26/21 5:00 PM	
58		PLAR Submission	1 day?	4/26/21 8:00 AM	4/26/21 5:00 PM	

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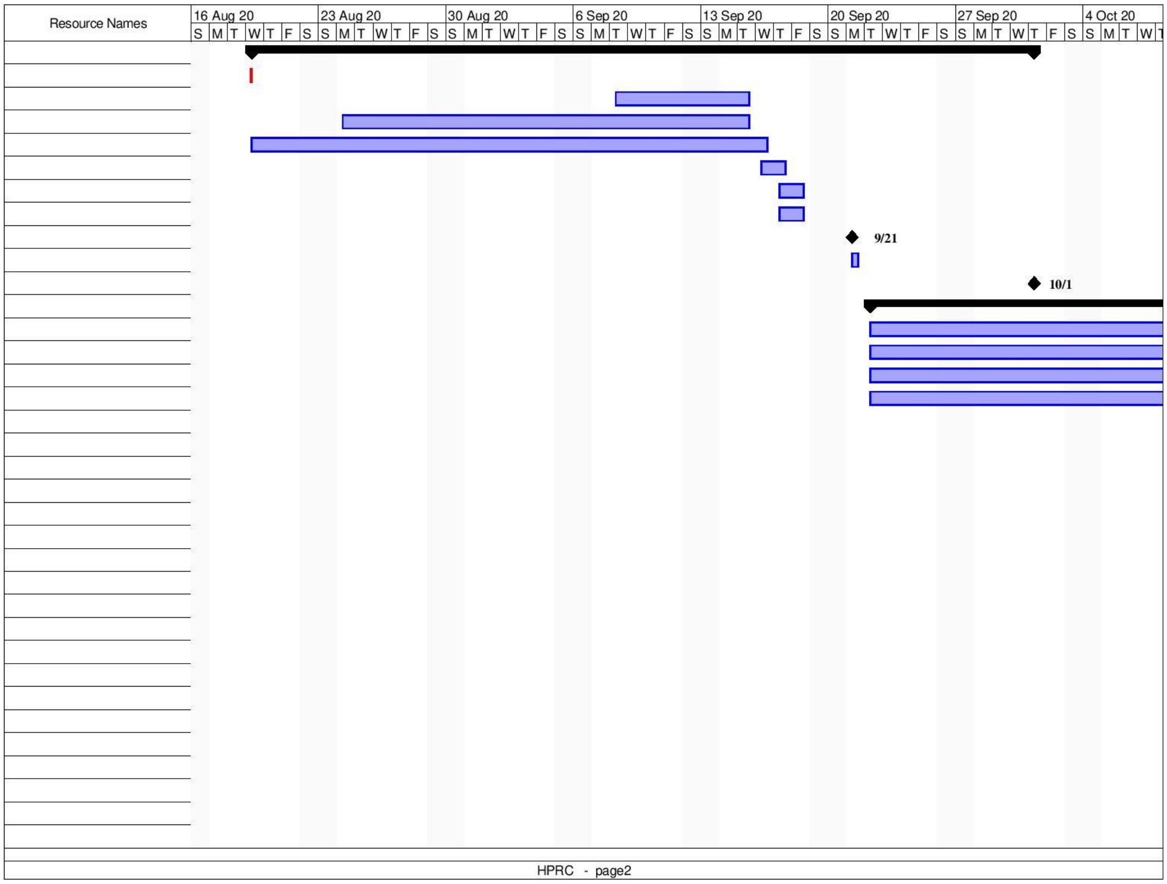
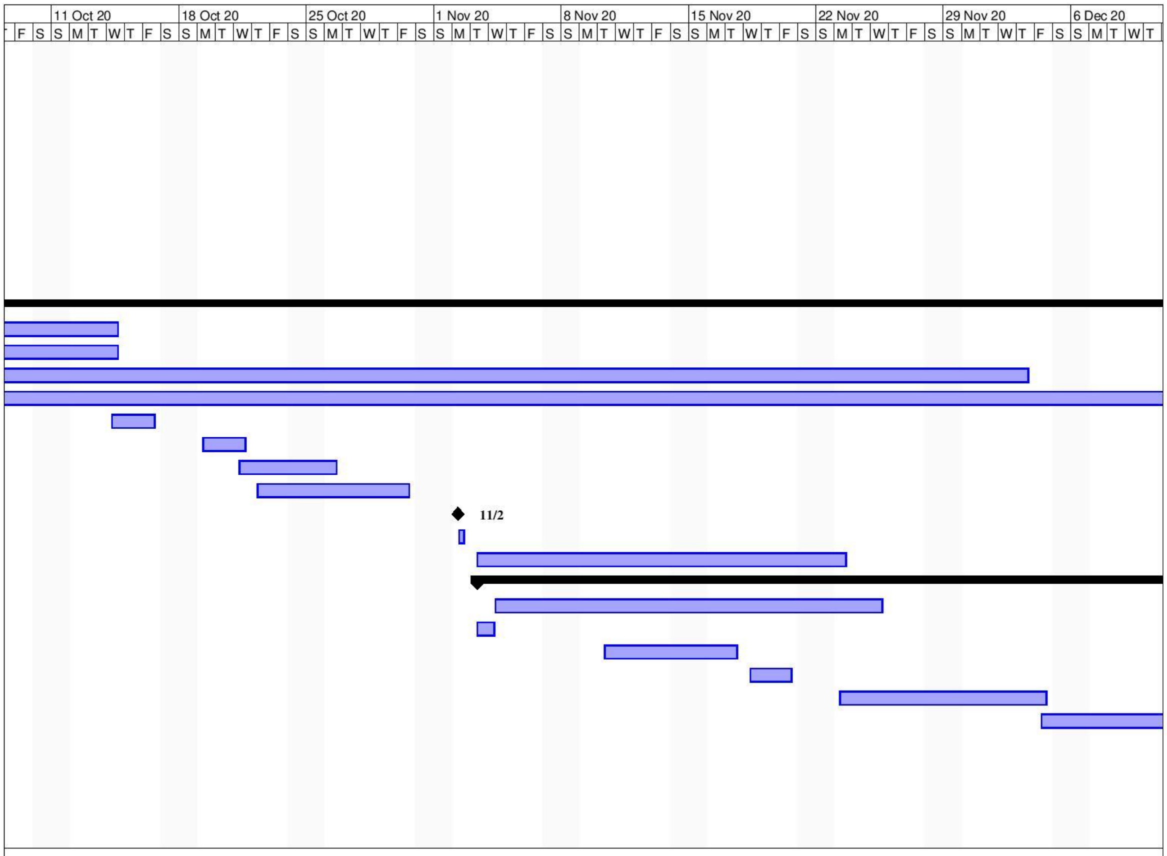

Resource Names
16 Aug 20
23 Aug 20
30 Aug 20
6 Sep 20
13 Sep 20
20 Sep 20
27 Sep 20
4 Oct 20
9/21
10/1
HPRC - page2



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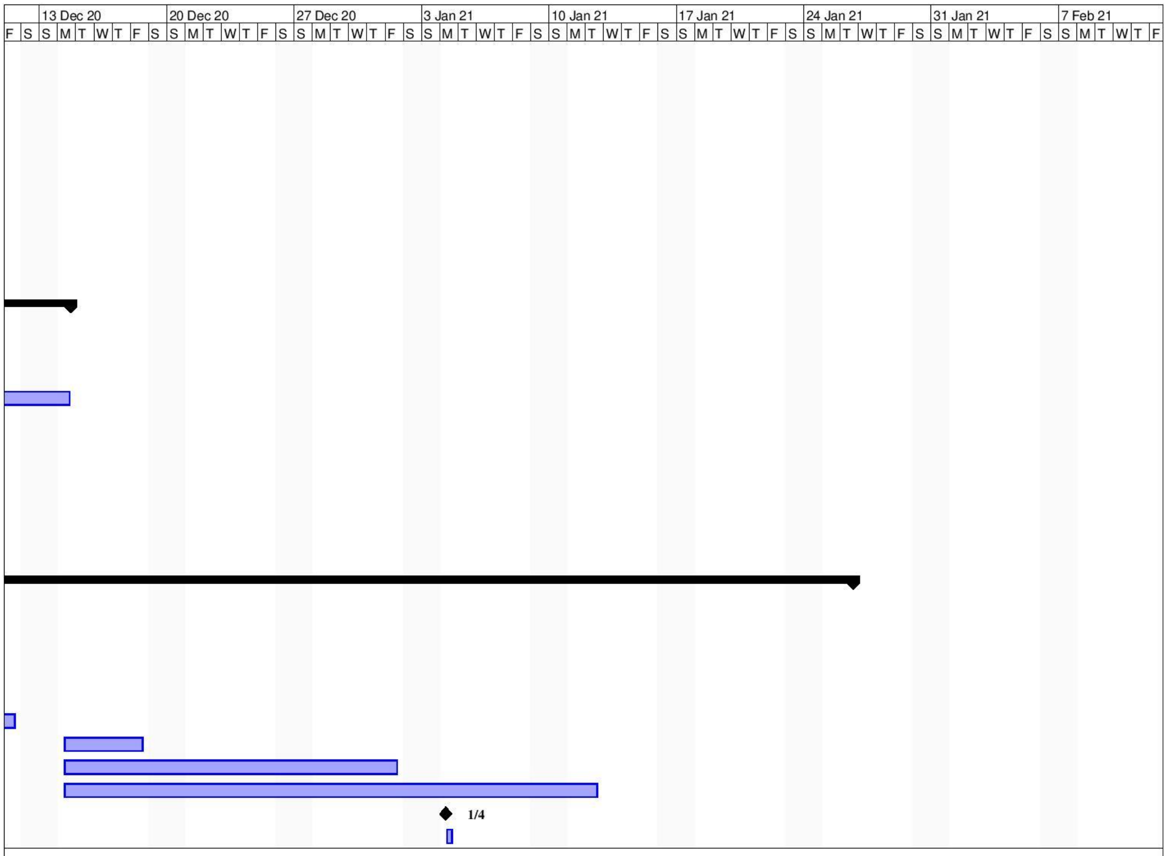
25 Oct 20
1 Nov 20
8 Nov 20
15 Nov 20
22 Nov 20
29 Nov 20
6 Dec 20
11/2

HPRC - page3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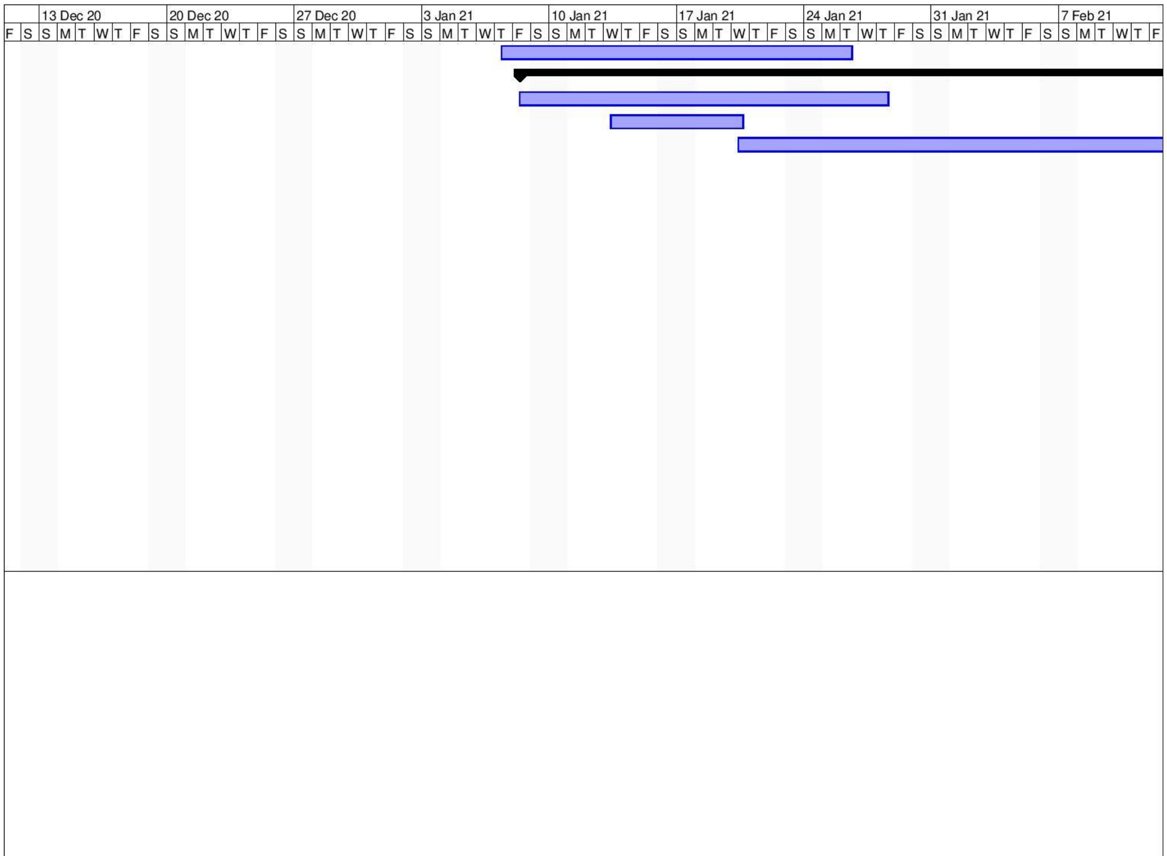
17 Jan 21
24 Jan 21
31 Jan 21
7 Feb 21
1/4

HPRC - page4


13 Dec 20
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3 Jan 21
10 Jan 21
17 Jan 21
24 Jan 21
31 Jan 21
7 Feb 21
F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F S S M T W T F

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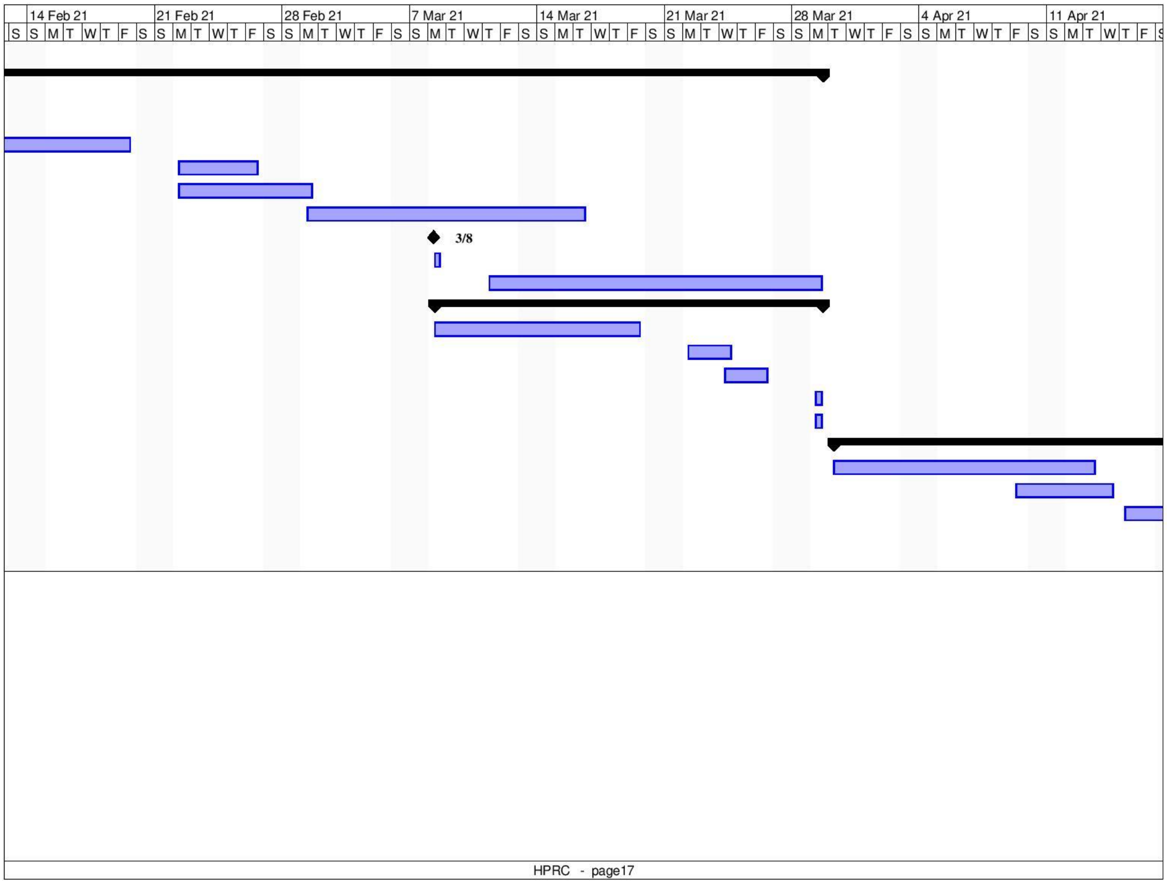
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7 Mar 21
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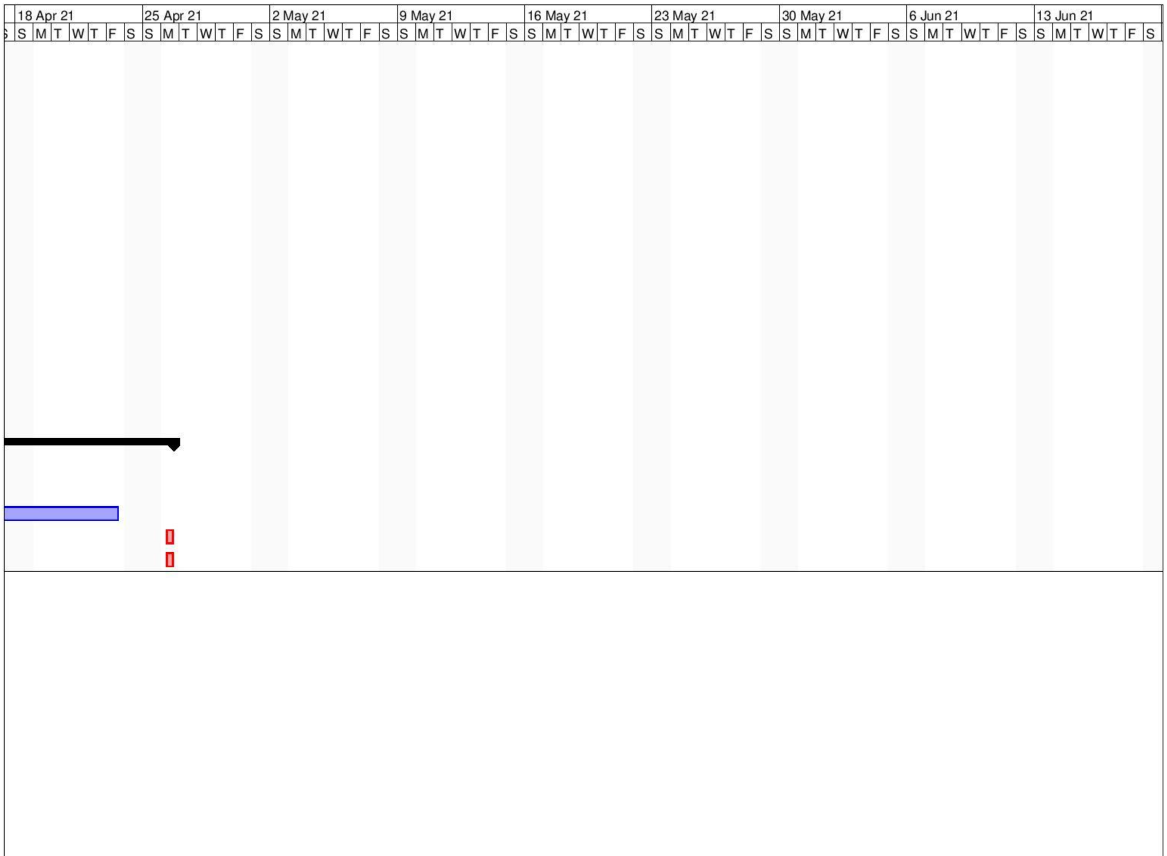
21 Mar 21
28 Mar 21
4 Apr 21
11 Apr 21
3/8
HPRC - page17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16 May 21
23 May 21
30 May 21
6 Jun 21
13 Jun 21