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Team 501: NASA Student Launch

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# Abstract

As space exploration expands, so does the design and technology of modern high-power rocketry. The Zenith Program is a student rocket club at the FAMU-FSU College of Engineering. The program is led by Senior Design Team 501 competing in the NASA University Student Launch. This year’s program is set out to fly a high-power solid-fuel rocket to an altitude between 4,600 feet aboveground level. The rocket will carry a payload with a camera that will perform a series of tasks after landing. The rocket’s nose cone, fins, and tail cone are all made of 3D printed material. Store bought parts makeup most of the motor, avionics system, and parachutes. The flight computer is wired to batteries, kill switches, and ejection charges in a specific way to lessen failure points in flight controls. An Arduino Mega will control the movement of a servo motor that guides the camera device for the payload. The team will complete a series of design reviews that mirrors NASA’s industry standards. NASA Student Launch is one of eight Artemis Student Challenges. Their mission is to build knowledge and introduce students to topics, techniques, and technologies critical to the success of the agency’s Artemis program. This year the team has asked itself two main questions: how closely can we match the rocket’s flight profile to preflight computer models? Also, can we design a failure tolerant recovery system? Since this is a competition, our team will be scored at how close our predictions are to the actual flight data. Our work will support NASA’s research on reusable high-power rockets and the advancing journey of modern spaceflight. In addition, we will create a foundation for future Zenith members who would like to participate in student aerospace projects.

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# Acknowledgement

These remarks thanks those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

* Paragraph 1 thank sponsor!
* Paragraph 2 thank advisors.
* Paragraph 3 thank those that provided you materials and resources.
* Paragraph 4 thank anyone else who helped you.

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# List of Acronyms

|  |  |
| --- | --- |
| AIAA | American Institute of Aeronautics and Astronautics |
| AME | Aero-Propulsion, Mechatronics and Energy Center |
| BPWC | Binary Pairwise Comparison |
| CDR | Critical Design Review |
| COE | College of Engineering |
| CRT | Cross Reference Table |
| DAQ | Data Acquisition |
| FAMU | Florida Agricultural & Mechanical University |
| FCAAP | Florida Center for Advanced Aero-Propulsion |
| FMEA | Failure Mode & Effect Analysis |
| FOV | Field of view |
| FRR | Flight Readiness Review |
| FSU | Florida State University |
| GNC | Guidance, Navigation, and Control |
| HOQ | House of Quality |
| IWF | Integrated Weight Factors |
| ME | Mechanical Engineering |
| MSFC | Marshall Space Flight Center |
| NAR | National Association of Rocketry |
| NASA | National Aeronautics and Space Administration |
| PDR | Preliminary Design Review |
| ROAR | Regional Orlando Applied Rocketry |
| RSO | Range Safety Officer |
| SD | Senior Design |
| SFSS | Santa Fe Soaring Saints |
| SRA | Space Rocketry Association |
| STEM | Science, Technology, Engineering, and Math |
| TRA | Tripoli Rocketry Association |
| TWR | Thrust to weight ratio |
| CAD | Computer Aided Design |

# Chapter One: EML 4551C

## 1.1 Project Scope

**Project Description**

The motive of this project is to design a solid-propellant rocket that will compete in the 2023 National Aeronautics and Space Administration (NASA) Student Launch competition held at the NASA Marshall Space Flight Center (MSFC).

The intent of this program is to design, manufacture, and launch a solid-fueled rocket, in conjunction with AIAA junior members, to an altitude between 4,000 and 6,000 feet before using a dual-deployment recovery system to recover the vehicle intact within 2500ft of the launch site. A 3D printed payload is to be deployed on descent, housing a camera system to execute a RAFCO (radio frequency command) sequence transmitted by the NASA ground team after landing

The design of the rocket’s aerodynamics, airframe, recovery system, and avionics, as well as the payload’s deployment, recovery, and RF operation, must all abide by and stay within the limitations and regulations set forth in the 2023 NASA Student Launch Handbook.

**Key Goals**

The following information outlines the key goals that Senior Design team 501 has selected to achieve based on the milestones and performance requirements set out for the student competition:

* Simulate a successful and accurate flight test to reach within 100 ft of the team’s proposed apogee
* Maintain a mid-flight stability margin between 3 and 4 calibers
* From apogee the vehicle should reach touchdown in under 80 seconds
* Payload is to complete an autonomous task with a scientific purpose
* Be awarded for at least one of the competition categories

**Market**

The primary market for this particular project is defined as the company hosting the event that will showcase the performance of the product. The secondary markets are the companies and organizations that would benefit from the success of the product designed.

**Primary Markets**

* Office of STEM Engagement at NASA MSFC

**Secondary Markets**

* FAMU-FSU College of Engineering
* AIAA Chapter at FAMU-FSU College of Engineering
* Small satellite launch companies

**Assumptions**

Although many objectives of the project are clearly mentioned in the Student Launch handbook, there were still assumptions to be made that are intended to control the scope. The following is a list of assumptions for our project:

* The rocket is to reach an altitude between the minimum and maximum of 4000 ft and 6000 ft
* The launch site will be on a plain crop field with slightly uneven terrain
* The weather conditions on launch day will have no severe impact on flight
  + Wind speeds no greater than 20 mph
  + No rain, and/or thunderstorms
* 8ft 1010-rails and 12ft 1515-rails will be in operational condition
* The launch rails will be canted between 5 - 10 deg from the vertical direction

**Stakeholders**

Project stakeholders are anyone with investment, interest, or control over the project. Below is a list of stakeholders sorted by organization followed by a table sorting these stakeholders by type and purpose.

* Marshall Spaceflight Center
  + NASA Office of STEM Engagement
    - Proposal Review Panel
    - PDR Review Panel
    - CDR Review Panel
    - FRR Review Panel
  + NASA Range Safety Officer
* Spaceport Rocketry Association (NAR #342 / TRA #73)
  + Mr. Tom McKeown
  + SRA Range Safety Officer
* Regional Orlando Applied Rocketry (NAR #795)
  + Mr. Adam Nehr
  + ROAR Range Safety Officer
* Santa Fe Soaring Saints (NAR #904)
  + Mr. Jimmy Yawn
  + SFSS Range Safety Officer
* Aero-Propulsion, Mechatronics, and Energy Center
  + Dr. Chiang Shih
* Florida Center for Advanced Aero-Propulsion
  + Dr. Rajan Kumar
* FAMU-FSU College of Engineering Mechanical Department
  + Dr. William Oates

Dr. Shayne McConomy

Table 1: Project Stakeholders

|  |  |  |
| --- | --- | --- |
| **Investment**  **(Funding)** | **Interest**  **(Technical Advising and Assistance)** | **Control**  **(Dictates Goals and Operations)** |
| 1. Dr. William Oates – ME Dept 2. Dr. Chiang Shih – AME | 1. Tom McKeown – SRA 2. Adam Nehr – ROAR 3. Jimmy Yawn – SFSS 4. Dr. Rajan Kumar – FCAAP 5. Dr. Chiang Shih – AME 6. Marshall Spaceflight Center 7. NASA Office of STEM Engagement 8. Proposal Review Panel 9. PDR Review Panel 10. CDR Review Panel 11. FRR Review Panel | 1. Dr. Shayne McConomy – Project Sponsor 2. Dr. Chiang Shih – Project Advisor and Investor 3. NASA Range Safety Officer(s) (RSO’s) 4. NAR/TRA test launch facility RSO’s |

## 1.2 Customer Needs

For this project we have identified five customers who will have an impact on our final design as the following:

1. NASA Student Launch Panel
2. Dr. William Oates (beneficiary)
3. Dr. Shayne McConomy (beneficiary)
4. Dr. Chiang Shih (beneficiary)
5. Future FAMU-FSU College of Engineering AIAA Student Teams (end users)

It is important to note that customer statements which include “**must**” are a non-negotiable requirement by NASA to gain launch approval. These requirements are not open to interpretation and will be physically verified by the range safety officer (RSO) before launch. Other firm design requirements exist but cannot be physically verified by the RSO and will not be listed as a “must”. The table below consists of the questions posed to our customers, their responses, and the subsequent interpreted needs.

Table 2: Interpreted Customer Needs

|  |  |  |
| --- | --- | --- |
| **Question/Prompt** | **Customer Statement** | **Interpreted Need** |
| Why should we go to this student launch competition? | I would like publicity for the college and a year-over-year goal for aerospace inclined students | The vehicle can fly during launch week and excel in certain areas of the competition scoring scheme |
| How long should the descent time of the flight vehicle be? | The launch vehicle can have a maximum descent time of 90 seconds. Teams that land in under 80 seconds are awarded bonus points. | The vehicle can be recovered in under 85 seconds |
| May we design our own avionics unit and flight control programs? | No, all flight computers and avionic units **must** be commercial off the shelf, or the vehicle will not be cleared by range safety for flight. Also, all recovery electronics and pyrotechnic initiators should be powered by commercially available batteries. | The flight computer and power sources are sourced commercially |
| In the past, what systems have given teams the most difficulty? | Previous years have struggled with recovery. This is usually due to poor chute material and sourcing a good vendor. | The recovery system can reliably deploy the drogue and main chutes |
| What kind of performance outcomes would you like out of the competition? | Given the project’s budget, I would suggest excelling in one, or maybe even two, categories at the least. | The flight vehicle can place top 3 in one or two of the award categories |
| Will the rocket design be used/referenced for future AIAA teams? | Yes, I would like it to be reusable for later years for ease of design iteration and cost savings. | The design will feature robust parts and modular features for replaceability |
| What altitude should we aim for? | The given altitude range is 4,000 – 6,000 ft. You may choose a target altitude in this range and design for it. | The rocket can achieve apogee between 4,000 – 6,000 ft |
| **Question/Prompt** | **Customer Statement** | **Interpreted Need** |
| Are there any limitations to propulsion system options? | The launch vehicle **must** have a single motor propulsion system with an engine that **must** not exceed a total impulse of 5,120 Newton-seconds. | The rocket is powered by one solid propellant motor system with impulse under 5,120 Newton-seconds. |
| What are your recommendations for the payload? Any Specifics? | Previous teams have all done rovers. Do your best to stay away from drones. | The payload can be a rover or other device, but not a UAS (unmanned aerial system) |
| How will the ignition of the rocket be handled? | The launch vehicle **must** be capable of being launched by a standard 12-volt direct current firing system. E-matches and igniters for recovery should also be commercially bought off the shelf. | The launch vehicle can be ignited by a 12V DC igniter and will not use external circuitry or ground service (other than what is provided by NASA). |
| Is there a maximum amount of body sections the vehicle can have? | The launch vehicle islimited to four (4) independent sections. Each section **must** be either tethered to the main vehicle or recovered separately from the main vehicle using its own parachute. | The vehicle can have a maximum of 4 independently recoverable or shock cord tethered sections |
| How much area do we have to recover the rocket? | Vehicles recovered outside a 2,500-foot radius from the launch pad will be awarded no recovery points. | The recovery system staging limits the ability of the rocket to drift on descent. |
| Are there any TWR requirements? | The launch vehicle should have a thrust to weight ratio (TWR) of 5.0:1.0 on the pad | Rocket mass is controlled to allow for a TWR between 5:1 and 7:1 |
| **Question/Prompt** | **Customer Statement** | **Interpreted Need** |
| Does the flight vehicle require a camera? | The launch vehicle should contain an automated camera system with a FOV between 100 and 180 degrees and the capability to swivel 360 degrees. | The vehicle can capture 360-degree video about the Z-axis |
| Is there a maximum Mach number the flight vehicle cannot exceed? | The launch vehicle should not exceed Mach 1 at any point during flight. | The vehicle’s maximum speed will be limited through motor selection based on rocket mass and aerodynamics |
| Is there anything we should know about telemetry transmission and receiving? | On board transmitters are limited to 250 mW (each) and will broadcast on unique frequencies for each team to limit interference | The vehicle can transmit telemetry with low power transmitters on team-specific frequencies |
| Do we have stability constraints? | The launch vehicle should have a minimum static stability margin of 2.0 at the point of rail exit. | The vehicle’s stability remains between 2.0 and 5.0 cal |
| What can and can’t we do to improve stability? | Ballast should remain under 10% of the total unballasted weight of the rocket. Use of light-weight metal is permitted but limited to the amount necessary to ensure structural integrity of the airframe under operating stresses. | The design will use as little metal as possible (for safety) and apply ballast mass sparingly |
| Is there a minimum parachute deployment height? | The main parachute should deploy no lower than 500 ft. | The main parachute can reliably deploy above 550 ft |
| Are there any additional requirements for the onboard camera? | The camera system should execute a string of transmitted commands quickly, with a maximum of 30 seconds between photos taken. | The camera system can receive and execute commands in rapid succession. The camera can take photos in rapid succession |
| Are we allowed to delay our chute deployment at apogee? | The apogee event may be delayed up to 2.0 seconds | The recovery system can reliably deploy the drogue chute within 2 seconds of apogee |

**Explanation of Results**

Customer questions could not be posed to NASA prior to acceptance of the team’s proposal and formal entry to the competition. With the proposal now accepted, we can pose customer questions at the Preliminary Design Review (PDR) question and answer session in mid-October. At present, NASA customer needs were gathered entirely from the 2023 NASA Student Launch Handbook, which outlines both firm design requirements necessary for launch approval and soft requirements which dictate vehicle performance but only affect scoring in the competition.

Non-negotiables from NASA are the use of commercial off-the-shelf flight computer(s), pyrotechnic initiators, parachutes, and batteries, as well as the ability to ignite the motor with a standard 12V DC ignition system provided by NASA on launch day and no external circuitry or other ground support equipment. Major competition (soft) requirements include achieving altitude between 4-6k feet AGL, limiting cross range to 2,500 ft from the launch rail, recovering the vehicle in under 90 seconds, and limiting motor impulse to below 5,120 N-s (L-class).

Customer questions were posed to Dr. McConomy and Dr. Shih in separate meetings, one in-person in Dr. McConomy’s office and the other remotely with Dr. Shih from the AIAA fabrication shop. Arguably the most important need brought forth by Dr. McConomy was for the vehicle to not become a jack of all trades, but rather to specialize and excel in one or two scoring categories, as completing the competition, and winning a category is the most likely route to placing ranked in this competition. Another need from Dr. McConomy include robust validation of the recovery system, as previous teams had trouble with nosecone separation and chute deployment.

Dr. Shih’s primary needs were in the long-term viability of the project and vehicle. The team interpreted this to mean a desire for reusability and interchangeability in parts, so that future teams can use and improve the previous design without having to purchase or manufacture the entire vehicle over again. Ultimately, these required and interpreted needs will further dictate the functional breakdown of our design.

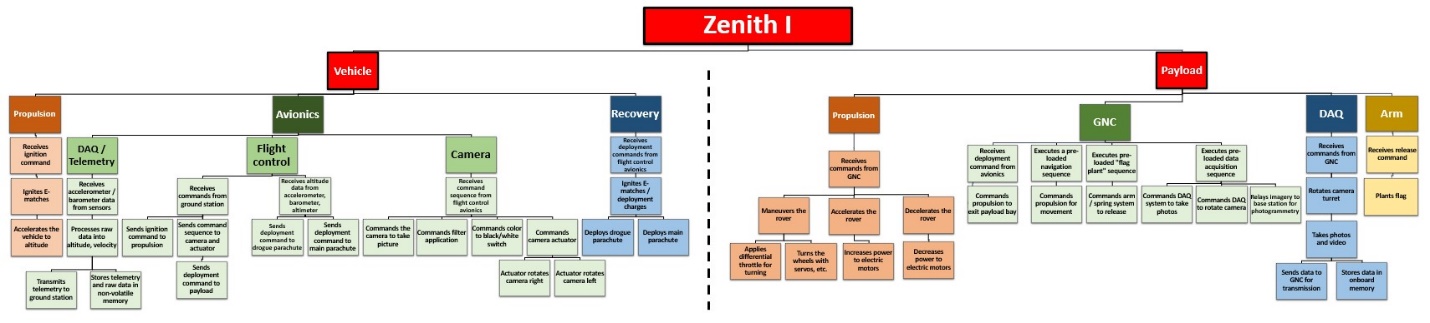
## 1.3 Functional Decomposition

**Introduction**

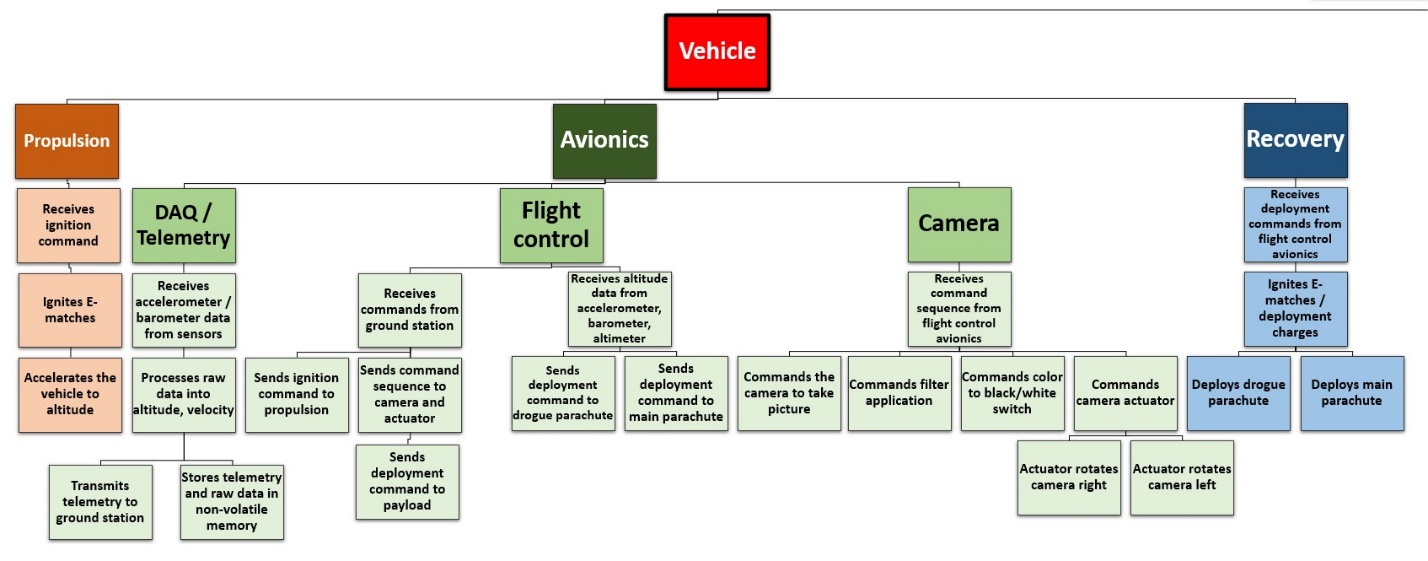
Functional decomposition is the development of the design’s necessary systems based on the information given from our customers. It aims to translate the customer needs into major systems of the design, with each subsequently having sub-systems performing minor functions. Following our discussions with our project sponsor and advisor, we managed to decompose our system into two major systems: the flight vehicle and the payload. Each design was then further broken down into functional sub, and sub-sub systems responsible for performing tasks.

**Hierarchy Chart**

Given the scale of the hierarchy chart, the text outlining the minor functions is unreadable. The takeaway from the full chart is that our system was subdivided into two major systems, the vehicle and payload, as shown in red with their division denoted by the vertical dashed line. Subsystems for each are color coded for ease of viewing. Sub-sub systems branch from the main subsystem and are denoted by a slightly lighter shade of the main subsystem color. Functions are denoted by light shading of the subsystem color.

Figure 1: Full Functional Decomposition

For ease of reading and presentation, the two major system decompositions will be presented and discussed separately, since the subsystems of each are for the most part independent of each other (exceptions discussed later).

Figure 2: Flight Vehicle Functional Hierarchy Chart

The vehicle is comprised of three major subsystem, propulsion, avionics, and recovery. The propulsion and recovery systems are comparatively simple, as these only receive commands from the avionics unit and perform the task commanded. In the case of propulsion, this task is to light the main engine. The recovery system’s functions are to deploy the drogue and main parachutes.

The avionics unit is a more complicated sub-system, and can be subdivided into three sub-sub systems, those being data acquisition and telemetry (DAQ/TEL), flight control, and camera. DAQ/TEL is responsible for reading information from the vehicle sensors, processing relevant quantities such as position, velocity, and altitude, and handling this data. Data is stored in onboard non-volatile memory and simultaneously remotely transmitted to the flight monitoring ground station.

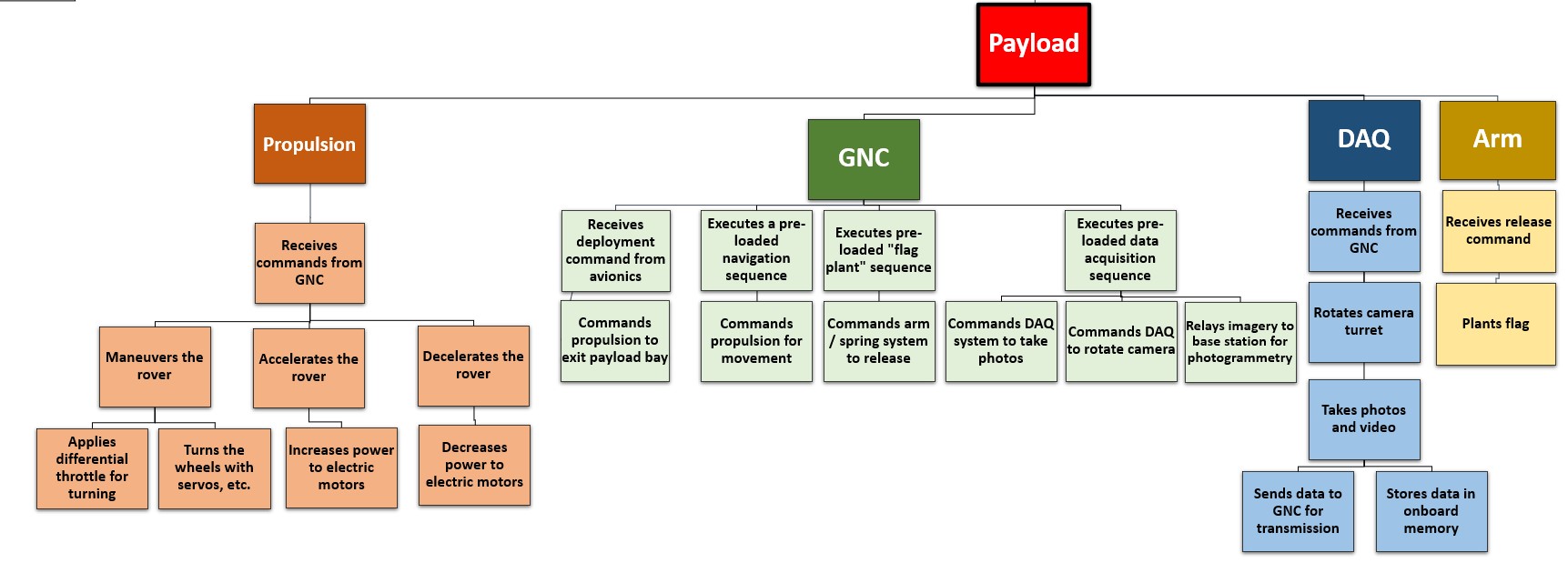
Flight control refers to the portion of the avionics unit that receives and issues commands to the vehicle. Commands received from ground station include main engine ignition and payload deployment, with payload deployment being the only crossover between the two major systems. The vehicle avionics is responsible for commanding the activation of the payload guidance, navigation, and control (GNC) unit, and for activating the deployment system within the vehicle payload bay. Commands issued by avionics are sent automatically during flight to the recovery system. These commands operate on altitude or velocity triggers and call for drogue or main parachute deployment.

The camera system refers to the onboard camera and actuator that rotates the camera about the vehicle Z-axis. The avionics unit will receive a randomized command sequence issued to the flight control team by NASA immediately before flight. The unit will then issue commands to the camera system, which is responsible for commanding the camera and actuator to do any of the following:

* + A1—Turn camera 60º to the right
  + B2—Turn camera 60º to the left
  + C3—Take picture
  + D4—Change camera mode from color to grayscale
  + E5—Change camera mode back from grayscale to color
  + F6—Rotate image 180º (upside down).
  + G7—Special effects filter (Apply any filter or image distortion you want and state what filter or distortion was used).
  + H8—Remove all filters.

The command sequence will be uploaded to the vehicle mid-flight in the (example) form:

“XX4XXX C3 A1 D4 C3 F6 C3 F6 B2 B2 C3.”

Figure 3:Payload Functional Hierarchy Chart

The payload system is a rover that may operate autonomously, remotely controlled, or some combination of the two. The system is to be mobile, capable of transmitting data to the flight control ground station and must perform a scientific task upon landing. Our chosen task is to capture 360-degree photo/video of a survey area to be post-processed with photogrammetry software to generate 3D terrain models for use in scouting landing sites for future propulsive landed craft and payloads.

The rover propulsion system is responsible for receiving commands, sent by ground control our pre-uploaded and autonomously executed, and actuating the motors, brakes, etc which will drive the rover. The design decision regarding the inclusion of brakes, wheels vs. treads, and/or actively steered wheels have not been made yet, so the team has stated a function of the system is to command some actuator to pivot the wheels or apply differential throttle to the motors in the even the wheels are fixed, or treads are used.

The guidance, navigation, and control system (GNC) is responsible for receiving commands from ground control or ordering the execution of a pre-loaded command sequence. GNC is the only point of crossover between the vehicle and payload systems, as the vehicle avionics unit will command the activation of the GNC unit and issue the deployment command, which may require the GNC unit to command movement from propulsion in conjunction with the vehicle payload deployment system. In post-deployment operation, the GNC unit will command propulsion for all movements. The team has chosen for the payload manipulator arm to deploy a small American flag, so the GNC unit will issue the command to the arm system to release springs, or command actuators to make the arm move. The GNC system is also responsible for command of the data acquisition (DAQ) system, or the photo/video camera responsible for photogrammetric imagery collection. Design decisions regarding the use of a 360-degree fisheye lens or a camera on a rotating turret have not yet been made, so a function of GNC is to command DAQ camera rotation. GNC is also responsible for the transmission of data back to ground.

As described above, the DAQ system is comprised of a camera and a potentially rotating turret. The system is passive and serves only to execute the functions commanded by GNC that have been discussed above. The DAQ system will store collected data in onboard memory and replay duplicate data to GNC for transmission back to flight control for post-processing in photogrammetry software. Similarly, the concept for the arm system has been described above, and it acts as a passive system which executes the “flag plant” command issued by GNC.

**Connection to Systems**

With the major tasks of the flight profile identified and sub-system functions in service of said tasks mapped, an analysis of subsystem interconnectivity can be performed. To that end, two cross-reference tables were generated that map the subsystems involved in completing each function discussed. As previously discussed, the vehicle and payload are major systems which are essentially insulated, thus the tables were generated separately. There is, however, a single task that requires crossover between sub-systems of each major system, which are donated with the unique marker [X\*].

Table 3: Flight Vehicle CRT

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Vehicle Sub-system Cross Reference** | | | | | | | |
| **Function** | **Propulsion** | **Avionics** | | | **Recovery** | | |
|  |  | | DAQ | | Flight | Cam |  |
| Ignite the main engine | X |  | X |  |  | | |
| Capture/store/transmit flight data |  | | X | | X |  |  |
| Camera image capture sequence |  |  | X | X |  | | |
| Parachute deployment (drogue and main) |  | X | X |  | X | | |
| Deploy rover from payload bay |  |  | X\* |  |  | | |

## Table 4: Payload CRT

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Payload Sub-system Cross Reference** | | | | |
| **Function** | **Propulsion** | **GNC** | **DAQ** | **Arm** |
| Deploy from payload bay | X\* | X\* |  |  |
| Movement: acceleration/deceleration/steering | X | X |  |  |
| Collect photogrammetric images |  | X | X |  |
| Transmit/store collected data |  | X | X |  |
| Plant flag and claim launch site for the COE |  | X |  | X |

**Smart Integration**

From the cross-reference tables, the most involved sub-system in either major system is the avionics (AV) or GNC unit. These units act as the brain of each system and are the only system which can both send and receive commands. AV and GNC are integrated with all other subsystems to send commands and to receive data back from certain sub-systems.

In the vehicle, the table shows the propulsion and recovery systems are insulated from each other. These systems have a single one-way connection from avionics and wait for a command to execute their task with no output sent back. In the case of propulsion, the flight control sub-sub system of avionics commands the firing of the main engine. For recovery, the DAQ unit reports velocity and altitude data to flight control, which triggers the recovery system’s parachute deployments. The same control path is used for the gathering, storage, and transmission of flight data, although the process occurs internally to the avionics sub-system with the external connection being a transmission to the ground unit. The image capture sequence also occurs internal to avionics, where flight control receives the command string and sends it to the camera sub-sub system for execution. The data from the camera system is then stored and returned to flight control for transmission to ground, with ground being the only connection external to avionics during the process.

The rover deployment after landing is the only cross-over point between the major vehicle and payload systems, as the rover deploy command is received by vehicle avionics flight control and is then passed to the rover GNC unit. The rover GNC unit receives the command and dictates inputs to the rover propulsion sub-system to facilitate exit from the payload bay. In the event the design is finalized with a vehicle-side system for payload deployment, the flight control sub-sub system would command both the rover GNC unit, and a payload deployment-subsystem added to the vehicle.

Once deployed from the payload bay, the rover major system is effectively insulated from the vehicle. As mentioned previously, the GNC unit is integrated with all sub-systems as this acts as the command center for the rover. The propulsion, DAQ, and arm systems are insulated from each other, all with only a connection to GNC for receiving commands and, in the case of DAQ, returning data. The propulsion sub-system has a one-way link, with movement commands sent from GNC. The arm sub-system has a one-way link, with the “flag plant” command sent from GNC, which either releases a spring or commands actuators; method to be determined. The GNC connection to the DAQ system is a two-way connection, with image/video capture and potential camera rotation commands being sent to DAQ, with data returned to GNC for transmission back to the ground station.

**Action and Outcome**

To relate the required action items to a physical outcome, excluding discussion of the method for achieving the outcome, the following table was generated.

Table 5: Mission Actions and Nominal Outcomes

|  |  |
| --- | --- |
| **Mission Actions and Nominal Outcomes** | |
| **Action** | **Outcome** |
| Ignition command sent | E-matches electrically ignite,  solid fuel begins combustion |
| Motor ignition | Vehicle is accelerated off launch rails to proper rail exit speed and launch angle |
| Motor burnout | Loss of thrust causes no significant perturbations to vehicle stability |
| Camera command sequence sent | Camera captures photos, applies/removes filters, changes image orientation. Camera actuator rotates camera about Z-axis properly |
| Apogee reached | Flight computer DAQ systems reads zero velocity and commands drogue deploy |
| Drogue chute deployment | Ejection charges fire, drogue chute deploys without entanglement or loss of vehicle stability before apogee + 2s |
| Vehicle reaches 600 ft AGL | Barometer/accelerometer data allow for calculation of altitude, flight control orders main deployment |
| Main chute deployment | Ejection charges fire, main chute deploys without entanglement above 550 ft, descent rate reduces to 17 ft/s |
| Ground impact | Vehicle integrity is not compromised after ground impact. Payload bay lands in configuration suitable for rover deployment |
| Payload deploy command sent | Avionics commands rover GNC “wake up”. GNC commands propulsion to exit payload bay. Rover can exit bay without issue. |
| Payload movement commands sent | Rover can move over terrain without becoming immobilized by outside factors |
| DAQ photogrammetry capture sequence commands sent | DAQ system is able to capture and transmit photo and video. Camera turret can rotate if commanded. |
| “Flag plant” command sent | Manipulator arm can deploy from rover without issue. Flag is planted firmly without tipping over or manipulator losing grip before or during deployment. |

## 1.4 Target Summary

The targets of our project are discussed around the needs of the customer. The customer desired a launch vehicle that can be recovered in under 90 seconds. To address this need, our vehicle-design and propulsion lead worked with the recovery systems lead to target a descent time of 80 seconds. As required by the customer, the launch vehicle must be powered by one single motor propulsion system and this motor cannot be capable of exceeding 1,150 lb-s of total impulse. The team approached this need by targeting high powered propulsions systems with a total impulse 5% under the maximum. The customer requested the flight vehicle be recovered within a 2,500-foot radius from where the vehicle is launched. The team addressed this need by targeting the vehicle’s flight stability margin between 2.2 and 5 calibers until apogee. The customer stated that the vehicle is limited to having 4 independent sections that must be tethered to the vehicle or recovered separately from the main vehicle using its own parachute. Our vehicle-design lead and avionics lead worked together to target the vehicles sections to contain 4 independent sections including the upper payload bay, payload rover, lower payload bay, and avionics bay. The customer requested the main recovery system to deploy no lower than 500 feet, to which we applied a target of 550 feet for the main parachute to deploy. For the vehicle’s speed, the customer requested keeping the vehicle’s Mach number under 1 at any point during flight. For this request our team targeted a 0.75 Mach Number as the maximum for the vehicle during flight. Table 6 expands further into our targets made from our customer needs and how our team will measure them.

The targets of the project are also based on the project’s functions. The functions are listed above in section 1.3. Please note that there are no functions based on the payload arm system as this system has been removed from the final design. Table 6 and 7 below are a list of our mission critical targets and metrics. The additional targets and metrics for the design can be viewed in Appendix C.

Table 6: Customer Needs based Targets and Metrics

|  |  |  |  |
| --- | --- | --- | --- |
| **Need** | **Target** | **Metric** | |
| Loiter on pad in flight-ready condition | 2.5 hours | | Test avionics system in pre-flight mode against battery drain. Verify 2.5 hour loiter |
| Thrust to weight of better than 5:1 | 20:1 | | Thrust taken from motor manufacturer specs. Weight of final vehicle measured. TWR calculated. |
| Rail exit velocity above 52 ft/s | 124 ft/s | | Flight computer telemetry downlink and onboard memory backup copy of data |
| Vehicle apogee within 4-6k feet | 4,600 ft AGL | | Flight computer telemetry downlink and onboard memory backup copy of data |
| Descent time to ground in under 90s | 78 s | | 1. Flight computer telemetry downlink and onboard memory backup copy of data 2. Time descent with stopwatch |
| Vehicle and stability on pad between 2 and 5 cal | 2.2 cal | | OpenRocket simulation gives CG, CP, and stability. SolidWorks gives CP and CG. Can calculate stability to verify ORK sim. |
| Flight stability between 2 and 5 cal across profile | 2.2 – 5 cal across profile | | OpenRocket simulation gives CG, CP, and stability plot vs. flight time. Verify margins not exceeded. |
| Rover deployment by parachute shock cord | No damage to rover or housing | Visual inspection post-flight | |
| Vehicle ground impact velocity | 20 ft/s | OpenRocket simulation verified practically by accelerometer data from flight computer | |
| Rover ground impact | No damage to rover or housing | Visual inspection post-flight | |
| Rocket should be made launch ready in | 2 hrs | Stopwatch team from pre-flight to install on pad. Verify less than 2 hours. | |
|  |  |  | |
| **Need** | **Target** | **Metric** | |
| Recover vehicle within specified area (2500 ft radius) | *Ambient Wind* | *Recovery Target* | Surveyor’s wheel used to determine distance of recovered vehicle from launch pad |
| 0mph  5 mph  10 mph  15 mph  20 mph | 150 ft  585 ft  1200 ft  1700 ft  2350 ft |
| Competition team should place in award category | Best Rookie Team (#1)  Altitude (#1-3) | Placements announced at launch week award ceremony | |

Table 7: Functions based Targets and Metrics

|  |  |  |
| --- | --- | --- |
| **Function** | **Target** | **Metric** |
| Executes a pre-loaded navigation sequence | Executes 4x 90 degree turns | Visual inspection |
| Executes pre-loaded data acquisition sequence | 120 seconds of video taken | Inspect the length of video stored on the hard drive |
| Drogue deploy within 2s of apogee | Apogee + 1.5s | Flight computer telemetry downlink and onboard memory backup copy of data |
| Main parachute deployment | 550 ft AGL | Flight computer telemetry downlink and onboard memory backup copy of data |

## 1.5 Concept Generation

**Introduction**

Concept generation involved the team conducting a brainstorming session to derive as many design solutions as possible. The team utilized a variety of concept generation tools to produce 100 concepts that are listed in Appendix D. After discussions with our advisor and sponsor, the team determined it would be best to split the 100 concepts into 50 ideas for the launch vehicle and the remaining 50 for the payload. Narrowing down these concepts and the selection of the most viable designs are later discussed in the concept selection phase.

**Generation Tools**

In order to generate 100 concepts multiple concept generation tools were used. Two morphological charts were used first to generate a combined 32 ideas for both the launch vehicle and payload designs. Both morphological charts consist of design solutions that are based on our functional decomposition.

Table 8: Launch Vehicle Morphological Chart

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Launch Vehicle Components** | **Solutions** | | | | |
| **Propulsion System** | Solid Propellant | Liquid Propellant | Hybrid Propellant | Mentos-Coke | Compressed Air |
| **Stability Method** | Fins | Arms | Thrusters | Actuating Nosecone | Ballast Mass |
| **Recovery Method** | Dual Deployment (Drogue/Main) | Thrusters | Single Deployment Method | Dual Deployment (Streamer/Main) | Bounce house positioned under landing vehicle |
| **Nosecone Type** | Elliptical | Ogive | LD-Haack Series | LV-Haack Series | Conical |

Table 9: Payload Morphological Chart

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Payload Component** | **Solutions** | | | | |
| **Propulsion Type** | Single-motor drivetrain | Front/rear axle drive | Unpropelled/Dumb | Glider | All-wheel/rotor drive |
| **Motion Generator** | Wheels | Robotic legs | Tank treads | Propeller | Static structure |
| **Microcontroller** | Arduino Mega | Raspberry Pi | ESP32 | Beagle-Bone Black | Arduino Mini |
| **Purpose (Function)** | Plant Flag | Soil Sample Collection | Terrain Image Processing | Sow Crops | Barometric Data |
| **Stability** | Line Tether to Flight Vehicle | Sled | Ballast mass | Outriggers | Large wheelbase/treads |

Following the morphological chart, a mix of biomimicry and general brainstorming was used to generate 42 more concepts for the payload. Since the payload must do something with a scientific purpose, a descent amount of our ideas about the payload’s motion were nature inspired. The remaining 26 ideas were produced by just ordinary brainstorming for launch vehicle concepts. All 100 concepts are presented in Appendix C, with 50 launch vehicle and 50 payload concepts presented in separate tables.

**High Fidelity Concepts**

The three high fidelity concepts for both the launch vehicle and payload are the ideas that the team deems most viable and will be further analyzed in the selection phase. Each of these concepts best addresses the targets and functions of both of our systems. The high-fidelity concepts for both the launch vehicle and payload can be viewed in the tables below.

Table 10: High Fidelity Concepts for Launch Vehicle

|  |  |
| --- | --- |
| **Concept #** | **Concept** |
| 1 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, 3-D printed fins (clipped delta geometry), removable fins, LD-Haack series 3-D printed nose |
| 2 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, fixed trapezoidal plywood fins, ogive 3-D printed nose |
| 3 | Solid motor, dual deployment, streamer + main chute, black powder ejection system, fixed 3-D printed fins (delta geometry), LV-Haack series 3-D printed nose |

Table 11: High Fidelity Concepts for Payload

|  |  |
| --- | --- |
| **Concept #** | **Concept** |
| 1 | Independent motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing |
| 2 | Single motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing |
| 3 | Dual motor drive to short-span treads, Arduino mega controlled, terrain image processing |

As previously mentioned, each of the high-fidelity and some of the medium-fidelity concepts shown above will be analyzed in depth for concept selection. The concept analysis will be based off of the desired attributes and performance outcomes that directly meet our selection criteria.

**Medium Fidelity Concepts**

The five medium fidelity concepts for both the launch vehicle and payload were chosen as ideas that are favored by the team but will not be fully analyzed in the selection phase. These concepts show feasible characteristics and could possibly do well at meeting the needs of our customer. These ideas are shown in the tables below.

Table 12: Medium Fidelity Concepts for Launch Vehicle

|  |  |
| --- | --- |
| **Concept #** | **Concept** |
| 4 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, fixed plywood delta fins, LV-Haack series 3-D printed nose |
| 5 | Solid motor, dual deployment, drogue + main chute, black powder ejection system, fixed 3-D printed fins (clipped delta geometry) ogive 3-D printed nose |
| 6 | Solid motor, dual deployment, streamer + main chute, CO2 ejection system, 3-D printed fins (clipped delta geometry), removable fins, conical commercial bought nose |
| 7 | Solid motor, dual deployment, streamer + main chute, black powder ejection system, plywood trapezoidal fins, removable fins, elliptical commercial bought nose |
| 8 | Solid motor, dual deployment, streamer + main chute, CO2 ejection system, plywood fixed delta fins, LV Haack 3-d print nose |

Table 13: Medium Fidelity Concepts for Payload

|  |  |
| --- | --- |
| **Concept #** | **Concept** |
| 4 | 1-12V DC Motor, tank tread, Raspberry Pi and Soil Sample Collection |
| 5 | independent motor drive, 4 tires, Arduino Mega and flag plant |
| 6 | independent motor drive, Spiked 2-Wheel, Arduino Mega, Sow Crops, and a tether |
| 7 | 1-12V DC Motor, Spiked 2-Wheel, Arduino Mega, Terrain Image Processing |
| 8 | independent motor drive, Spiked 2-Wheel, Raspberry Pi, Terrain Image Processing, flag plant |

## 1.6 Concept Selection

Concepts for the launch vehicle were assessed first using a Binary Pairwise Comparison, which compared the importance of each customer need against the others to determine the importance weight factor of each for use in the House of Quality.

Table 14: Launch Vehicle BPWC Chart

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Customer Needs** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **Total** |
| **1** | Reusable vehicle | **-** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2** | Stability across flight profile | 1 | **-** | 1 | 1 | 1 | 1 | 1 | 1 | 7 |
| **3** | Controlled descent | 1 | 0 | **-** | 1 | 0 | 1 | 1 | 1 | 5 |
| **4** | Successful recovery | 1 | 0 | 0 | **-** | 0 | 1 | 1 | 0 | 3 |
| **5** | Body sections successfully separate | 1 | 0 | 1 | 1 | **-** | 1 | 1 | 1 | 6 |
| **6** | Acceptable TWR | 1 | 0 | 0 | 0 | 0 | **-** | 1 | 0 | 2 |
| **7** | Minimal drift on descent | 1 | 0 | 0 | 0 | 0 | 0 | **-** | 0 | 1 |
| **8** | Achieves target altitude | 1 | 0 | 0 | 1 | 0 | 1 | 1 | **-** | 4 |
| **Total** | | 7 | 0 | 2 | 4 | 1 | 5 | 6 | 3 | **n-1 = 7** |

In Table 14 customer needs were compared against each other to help determine weight factors and importance.

Table 15: Launch Vehicle Customer Need Importance Weight Factors

|  |  |
| --- | --- |
| **Importance Weight Factors** | |
| **7** | Stable across flight profile |
| **6** | Body sections successfully separate |
| **5** | Controlled descent |
| **4** | Achieves target altitude |
| **3** | Successful landing |
| **2** | Acceptable TWR |
| **1** | Minimal drift on descent |
| **0** | Reusable vehicle |

With the weight factors for each customer needs determined; engineering characteristics were devised for the vehicle across the flight profile. These characteristics were then compared by relative impact to each customer need to determine their rank order.

Table 16: Launch Vehicle House of Quality

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Engineering Characteristics** | | | | | | | | | | | | | | | | | |
| **Improvement Direction** | | **↓** | **↑** | **↓** | **↑** | **↑** | **↓** | **↑** | **↓** | **↓** | **↑** | **↓** | **↑** | **↓** | **↓** | **↓** | **↓** | **↑** | **↓** |
| **Units** | | in | in | lb | s | in | lb |  |  |  | ft | ft |  |  | s |  |  | lb | °F |
| **Customer Requirements** | **Importance  Weight Factor** | Cg Location from base | Cp Location from base | Thrust | Burn time | Body Length | Mass | Velocity off Rod | Acceleration | Max Velocity | Apogee | Lateral Drift | Descent Rate | Impact Energy | Descent Time | Drag Coef. | Spin Rate | Ejection Force | Ejection Gas Temp |
| Stability across flight profile | **7** | 9 | 9 |  | 3 | 3 | 3 |  | 1 | 3 |  |  |  |  |  |  | 3 |  |  |
| Body sections successfully separate | **6** |  |  |  |  |  |  |  | 3 | 3 |  |  |  |  |  |  |  | 9 |  |
| Controlled descent | **5** |  |  |  |  |  |  |  |  |  |  |  | 9 |  | 3 |  |  |  |  |
| Achieves target altitude | **4** |  |  | 9 |  |  | 9 | 1 |  |  | 9 |  |  |  |  | 9 |  |  | 9 |
| Successful recovery | **3** |  |  |  |  |  |  |  | 1 |  | 3 | 3 | 9 | 9 | 3 |  |  | 9 |  |
| Acceptable TWR | **2** |  |  | 9 |  |  | 9 |  |  |  |  |  |  |  |  |  |  |  |  |
| Minimal drift on descent | **1** |  |  |  |  | 9 |  |  |  |  |  | 9 |  |  |  | 3 | 1 |  |  |
| Reusable vehicle | **0** |  |  |  |  |  |  |  | 3 |  |  |  |  | 9 |  |  |  |  | 9 |
| **Raw Score** | **683** | 63 | 63 | 54 | 21 | 21 | 75 | 4 | 28 | 39 | 45 | 9 | 72 | 27 | 24 | 36 | 21 | 81 | 36 |
| **Relative Weight %** | | 9.2 | 9.2 | 7.9 | 3.1 | 3.1 | 11.0 | 0.6 | 4.1 | 5.7 | 6.6 | 1.3 | 10.5 | 4.0 | 3.5 | 5.3 | 3.1 | 11.9 | 5.3 |
| **Rank Order** | | 4 | 4 | 5 | 12 | 12 | 2 | 14 | 9 | 7 | 6 | 13 | 3 | 10 | 11 | 8 | 12 | 1 | 8 |

Table 17: Launch Vehicle Engineering Characteristics Rank Order

|  |  |
| --- | --- |
| **Engineering Characteristic Rank Order** | |
| 1 | Ejection Force |
| 2 | Mass |
| 3 | Descent Rate |
| 4 | Cp Location from base |
| 4 | Cg Location from base |
| 5 | Thrust |
| 6 | Apogee |
| 7 | Max Velocity |
| 8 | Ejection Gas Temp. |
| 8 | Drag Coef. |
| 9 | Acceleration |
| 10 | Impact Energy |
| 11 | Descent Time |
| 12 | Burn time |
| 12 | Body Length |
| 12 | Spin Rate |
| 13 | Lateral Drift |
| 14 | Velocity off Rod |

From the table above, characteristics were selected to remove items which saw little to no variance between concepts to streamline concept comparison. A modularity category was also added as this was a feature with variation between concepts that was not compared as an engineering characteristic in the House of Quality. To compare the medium and high-fidelity vehicle concepts, Pugh charts were implemented, as shown below:

Table 18: Launch Vehicle High and Medium Fidelity Concept Summary

|  |  |
| --- | --- |
| **Concepts** | |
| **High Fidelity** | |
| 1 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, 3-D printed fins (clipped delta geometry), removable fins, LD-Haack series 3-D printed nose |
| 2 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, fixed trapezoidal plywood fins, ogive 3-D printed nose |
| 3 | Solid motor, dual deployment, streamer + main chute, black powder ejection system, fixed 3-D printed fins (delta geometry), LV-Haack series 3-D printed nose |
| **Medium Fidelity** | |
| 4 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, fixed plywood delta fins, LV-Haack series 3-D printed nose |
| 5 | Solid motor, dual deployment, drogue + main chute, black powder ejection system, fixed 3-D printed fins (clipped delta geometry) ogive 3-D printed nose |
| 6 | Solid motor, dual deployment, streamer + main chute, CO2 ejection system, 3-D printed fins (clipped delta geometry), removable fins, conical commercial bought nose |
| 7 | Solid motor, dual deployment, streamer + main chute, black powder ejection system, plywood trapezoidal fins, removable fins, elliptical commercial bought nose |
| 8 | Solid motor, dual deployment, streamer + main chute, CO2 ejection system, plywood fixed delta fins, LV Haack 3-d print nose |

Table 19: Launch Vehicle Pugh Chart 1

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Selection Criteria** | **Concepts** | | | | | | | |
| 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Low Mass | Datum | + | s | + | s | + | + | s |
| Mild Descent Rate | + | + | s | + | + | s | s |
| Low Ejection Gas Temp. | s | s | - | s | - | s | - |
| Drag Coefficient | + | + | s | + | + | + | - |
| Low Impact Energy | + | s | s | s | + | s | - |
| Stability | + | + | s | s | + | + | - |
| Modularity | + | s | s | + | - | + | s |
|  | # Of Plus(+) | 6 | 4 | 1 | 3 | 5 | 4 | 0 |
|  | # Of Minus(-) | 0 | 0 | 1 | 0 | 1 | 0 | 4 |

The first Pugh Chart table above shows that concept 8 was chosen as the initial comparison datum. Concepts 7 and 3 were easily eliminated after comparison, as concept 7 generated a net negative comparison score, while concept 3 generated a net zero score. Concept 4 generated a net positive 3 score but was also eliminated. Despite concept 3’s score demonstrating it was no better nor worse than the datum, and concept 4’s score showing it was better than the datum, these were eliminated because of the disparity in improvement between these and concepts 1, 2, 5 and 6, which all showed net positive scores of between 4 and 6. Having the highest net positive score, concept 1 was chosen as the next datum for comparison.

Table 20: Launch Vehicle Pugh Chart 2

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Selection Criteria** | **Concepts** | | | |
| 1 | 2 | 5 | 6 |
| Low Mass | Datum | - | s | s |
| Mild Descent Rate | - | s | - |
| Low Ejection Gas Temp. | s | - | s |
| Drag Coefficient | + | + | + |
| Low Impact Energy | - | s | - |
| Stability | - | - | s |
| Modularity | - | - | s |
|  | # Of Plus(+) | 1 | 1 | 2 |
|  | # Of Minus(-) | 5 | 2 | 3 |

The second Pugh Chart table above shows that concepts 2, 5, and 6 all received net negative scores when compared to the new datum. This made selection exceedingly easy, as all contenders were eliminated and the datum, concept 1, was selected. The final vehicle design selected will incorporate a solid propellant motor, dual deployment recovery system utilizing a drogue and main parachute, a CO2 ejection system, removable 3-D printed clipped delta fins, and a 3-D printed LD Haack series nosecone.

AHP analysis for the vehicle was excluded, as this analysis seeks to identify bias in the selection process, which this team will readily admit to up front. Unlike a typical open ended design project where a superior design can be objectively chosen, this project began from a highly constrained space. NASA’s extensive vehicle requirements almost entirely dictate from the start how the vehicle will look and perform, with the only real design freedom afforded to the team being minor component selections such as altimeter selection, body material, motor selection, fin geometry, etc. The team is also budget constrained and must therefore bias the concept selection in favor of what can reasonably be afforded for commercial purchase or cheap and rapid manufacture at the College of Engineering. None of this is to say that the vehicle design selected is inferior or that the performance and safety will be sub-standard, but it is in the best interest of the team and project to identify the heavy bias present in our design and selection process. Due to our team working on an accelerated schedule, a preliminary design concept has been modeled and serves as our leading design. The figures below show the leading design.

Figure 4: Selected Launch Vehicle Concept #1 Solid Sketch

Text

Description automatically generated with low confidence

Figure 5: Selected Launch Vehicle Concept #1 Transparent Sketch

Diagram

Description automatically generated with medium confidence

Following the concept selection for the launch vehicle is the payload. The payload concept selection was analyzed and determined using the same selection tools that were used for the launch vehicle.

Table 21: Payload BPWC Chart

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Customer Needs** | | **1** | **2** | **3** | **4** | **5** | **Total** |
| **1** | Payload remains immobile in during flight | **-** | 0 | 0 | 1 | 1 | 2 |
| **2** | Payload is deployed intact | 1 | **-** | 0 | 1 | 1 | 3 |
| **3** | Payload fits inside launch vehicle | 1 | 1 | **-** | 1 | 1 | 4 |
| **4** | Payload has a scientific task | 0 | 0 | 0 | **-** | 0 | 0 |
| **5** | Payload can move through terrain | 0 | 0 | 0 | 1 | **-** | 1 |
| **Total** | | 2 | 1 | 0 | 4 | 3 | **n-1 = 7** |

Table 22: Payload Customer Need Importance Weight Factors

|  |  |
| --- | --- |
| **Importance Weight Factors** | |
| 4 | Payload fits inside launch vehicle |
| 3 | Payload is deployed intact |
| 2 | Payload remains immobile in during flight |
| 1 | Payload can move through terrain |
| 0 | Payload has a scientific task |

After the weight factors for each customer need were determined, engineering characteristics were created for the payload rover across its geometry and transportation functionality. These characteristics were compared to each customer need in order to rank their importance.

Table 23: Payload House of Quality Chart

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | **Engineering Characteristics** | | | |
| **Improvement Direction** | | **↓** | **↑** | **↓** | **↑** |
| **Units** | | in | in | lb | s |
| **Customer Requirements** | **Importance  Weight Factor** | Volume | Weight | Traction | Propulsion |
| Payload remains immobile in during flight | **2** | 1 | 3 |  |  |
| Payload is deployed intact | **3** |  | 9 |  |  |
| Payload fits inside launch vehicle | **4** | 9 |  |  |  |
| Payload has a scientific task | **0** |  |  |  |  |
| Payload can move through terrain | **1** |  | 9 | 9 | 9 |
| **Raw Score** | **98** | 38 | 42 | 9 | 9 |
| **Relative Weight %** | | 38.8 | 42.9 | 9.2 | 9.2 |
| **Rank Order** | | 2 | 1 | 3 | 3 |

Table 24: Payload Engineering Characteristics Rank Order

|  |  |
| --- | --- |
| **Engineering Characteristic Rank Order** | |
| 1 | Weight |
| 2 | Volume |
| 3 | Traction |
| 3 | Propulsion |

From the table above, all characteristics were chosen and ranked in order. The following Pugh Charts were created to compare the medium and high-fidelity payload concepts.

Table 25: Payload High and Medium Fidelity Concepts Summary

|  |  |
| --- | --- |
| **Concept #** | **Concept** |
| **High Fidelity** | |
| 1 | Independent motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing, and a tether for stability |
| 2 | Single motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing |
| 3 | Dual motor drive to short-span treads, Arduino mega controlled, terrain image processing |
| **Medium Fidelity** | |
| 4 | 1-12V DC Motor, tank tread, Raspberry Pi, and Soil Sample Collection |
| 5 | independent motor drive, 4 tires, Arduino Mega and flag plant |
| 6 | independent motor drive, Spiked 2-Wheel, Arduino Mega, Sow Crops, and a tether |
| 7 | 1-12V DC Motor, Spiked 2-Wheel, Arduino Mega, Terrain Image Processing |
| 8 | independent motor drive, Spiked 2-Wheel, Raspberry Pi, flag plant, and sled for stability |

Table 26: Payload Pugh Chart 1

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Selection Criteria** | **Concepts** | | | | | | | |
| 5 | 1 | 2 | 3 | 4 | 6 | 7 | 8 |
| Volume | Datum | + | + | - | - | - | + | + |
| Weight | + | + | - | - | + | + | + |
| Traction | + | + | + | + | + | + | + |
| Propulsion | s | - | + | - | s | - | s |
|  | # Of Plus(+) | 3 | 3 | 1 | 1 | 2 | 3 | 3 |
|  | # Of Minus(-) | 0 | 1 | 2 | 3 | 1 | 1 | 0 |

The first Pugh Chart table above shows that concept 5 was chosen as the initial comparison datum. Concepts 3 and 4 were eliminated because their weight and volume characteristics were trumped by concept 5’s. Additionally, concept 4’s propulsion system did not exceed the standards of concept 5’s. Although concept 6 had a few attributes that were more desirable than concept 5’s, it was eliminated due to its volume characteristics and similar propulsion system, pushing it below the standards of concept 5. Concepts 1 and 8 have the highest scores. Concept 5 was eventually eliminated in correspondence to the high scoring concepts 1, 2, 7, and 8. The team chose concept 8 to be chosen for the next datum because the scientific task (Flag Plant) for concept 8 was a favorite during the early stages of this project.

Table 27: Payload Pugh Chart 2

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Selection Criteria** | **Concepts** | | | |
| 8 | 1 | 2 | 7 |
| Volume | Datum | s | + | - |
| Weight | + | s | + |
| Traction | + | s | - |
| Propulsion | s | - | - |
|  | # Of Plus(+) | 2 | 1 | 0 |
|  | # Of Minus(-) | 0 | 1 | 1 |

The second Pugh Chart table above shows Concepts 1, 2, and 7 in comparison to the datum, concept 8. Concepts 7 was easily eliminated due to it negative score and concept 2 was eliminated because the only valuable feature in comparison to concept 8 was its volume. Lastly, concept 8 was eliminated due concept 1’s weight and traction features, which were very important engineering characteristics as shown in table 23.

Similar to the launch vehicle, the AHP analysis for the payload was excluded for some of the same reasons. As previously mentioned, a typical open ended design project has little constraints that allows the design’s characteristics to be unbiasedly chosen. With the extensive number of constraints for the vehicle implemented by NASA, the launch vehicle was designed in accommodation to those requirements. These vehicle constraints combined with our budget constraints prevent our team from designing too far out of the “box.” The vehicle’s body diameter and length for the leading design caused major limitations to the payload’s dimensions and storage method. The housing for the payload serves as the method of storage during flight. This housing must be designed to tightly fit in the vehicles airframe. The payload and housing material was chosen based on the budgetary constraints, using ABS filament was one of the cheapest ways to design a payload rover that is low in manufacturing cost but has attractive material characteristics to prevent any damage during or after flight.

Figure 6: Selected Payload Concept #1 SketchDiagram

Description automatically generated

Figure 7: Selected Payload Concept #1 Sketch with Housing StorageLogo

Description automatically generated with low confidence

## 1.8 Spring Project Plan

# Chapter Two: EML 4552C

## Spring Plan

### Project Plan.

### Build Plan.

# Appendices

# Appendix A: Code of Conduct

**Overview**

This document provides an overview of the policies and expectations governing Senior Design Group 501. This document may be further updated throughout the semester to provide better clarity on the expectations or on how to handle new procedures required for course completion. Each member of the group was given input on all the following procedures and agreed upon these terms as recognized by the Statement of Understanding.

**Mission Statement**

The intent of this program is to design, manufacture, and launch a solid-fueled rocket, in conjunction with AIAA junior members, to an altitude between 4,000 and 6,000 feet before using a dual-deployment recovery system to recover the vehicle intact within 2500ft of the launch site. A 3D printed payload is to be deployed on descent, housing a camera system to execute a RAFCO (radio frequency command) sequence transmitted by the NASA ground team after landing

**Team Roles**

The following roles have been created to align with the goals of our project and the specialization of the group members. Each member has considered their strength and chosen their role accordingly.

Should any work outside of the duties listed below be required of any team member, they are expected to coordinate and collaborate with other 501 team members and supporting AIAA members to accomplish the task.

**Jedreck Acquissa – Ground Systems Lead**

Primarily responsible for the design, development, and testing of the dual deployment recovery system, containing two sets of two, redundant, black powder initiated CO2 ejection charges deploying a drogue and main parachute. Primarily responsible for launch-day charge assembly and wiring, and launch day parachute packing. Controls and data acquisition to be handled by Avionics Team. Responsible for liaising with Avionics Lead as design and programming changes are made.

**Peyton C. Breland – Propulsion and Vehicle Design Lead**

Primarily responsible for all design, simulation, and integration of the flight vehicle and engine configuration. Maintains up to date OpenRocket model of sub- and full-scale flight vehicles, reflecting updated component masses and locations, and updated flight modeling for each vehicle for varied launch angle and wind conditions. Responsible for developing engineering drawings, assemblies,and implementing these while overseeing the manufacturing of vehicle sections and internal structures. Responsible for liaising with avionics and recovery system leads in assembly of sub-scale and full-scale launch vehicle.

**Dylan A. Gardner – STEM Engagement Lead**

Primary point of contact for the scheduling and planning of all STEM engagement activities. Responsible for the development of entertaining, relevant, and educational hour-long presentations or workshops tailored for both middle and high-school level students. Responsible for developing connections with local educational institutions, teachers, and administrators to facilitate multiple engagement events per institution and continuity of event planning across program leadership transition. Responsible for development of post-event feedback collection mechanisms and implementation of critiques to future events. Responsible for liaising with the Senior Design professor and Program Director in event scheduling.

**Zachary L. Isriel – Program Director**

Primary point of contact for the project. Responsible for liaising with faculty and technical advisors to provide knowledge, resources, solutions, etc. to Department Heads. Primarily responsible for budget development, tracking, and component ordering. Responsible for managing and assisting Leads to ensure development is on schedule and budget. Responsible for organizing SD-501 and Zenith Program meetings in and out of the fabrication shop to communicate updates, delegate work, and facilitate inter-department cooperation during design and development.

**Mark A. Ioffredo – Payload Design Lead**

Responsible for the design and development of the 3D printed payload system and all related software. Responsible for liaising with Avionics team for assistance with development of RAFCO sequence decoder and camera turret control program, as well as RF receiver component selection and integration. Responsible for the testing of payload software by executing RF transmission, receiving, and command string decoding tests using various, randomly generated, command strings. Primarily responsible for the printing of rover housing and assembly/wiring of all internal components..

**Strike System**

The strike system is intended as a deterrent against frequent or intentional violations of the Code of Conduct and defines the point at which the team can no longer manage the behavior of a member or members on its own. Strikes will be tracked in a spreadsheet found in the Microsoft Teams workspace utilized by this design group. The strike spreadsheet will include a tally of all strikes for each member and will be a locked document administered by one team member unanimously elected by the team. Strikes will be recorded with a description of the incident as well as the date and time of the infraction.

A record of edits to the spreadsheet will be made available to any member within 24 hours of any request made during the work week, and by 11:59 PM on Monday for requests made over the weekend (after 5PM Friday, all of Saturday and Sunday).

Individual strikes carry no penalty for team members. Cumulative total is the driving factor for action taken. A team member having three strikes will be referred to the professor of record, Dr. McConomy, with records of the infractions to be discussed. Handling of the team member and their infraction(s) is at Dr. McConomy’s discretion after referral.

Violations of the Code of Conduct carrying a strike as penalty will be discussed in the relevant section below. Note that cases of grossly inappropriate conduct which are well-defined in their relevant sections carry an immediate three strikes and referral to the instructor.

**Communication**

**Zero-Tolerance Policy**

Across all forms of contact used by this team communications are expected to be professional, non-derogatory, and non-defamatory regarding other persons, especially fellow team members, and organizations. A zero-tolerance policy is in effect for disrespect towards other persons or groups based on race, religion, gender, gender identity, sexual orientation, and/or political ideology. Failure to adhere to this policy will result in immediate issuance of three strikes to all members involved in the hateful or inappropriate speech or conduct. Team members are free to discuss any of the above at their own discretion and in an appropriate manner, although these discussions are discouraged for their lack of relevance to the work required and potential for ideological conflict to arise.

**Email**

Email may be used to communicate at any time. Group members are free to utilize both school and personal email addresses as they see fit while communicating amongst each other. It is expected that team members will check their work emails daily. Maximum reply time to an email is limited to 24 hours from the moment of delivery during the work week. Emails delivered between 5 PM on Friday and 12 AM on Monday must be replied to by 11:59 PM on Monday at the latest. Team members are encouraged but not required to be active through email communication over the weekend and on holidays.

Team members are expected to CC the entire team on project-related emails. All communication with College of Engineering employees or personnel, to include other students acting as teaching assistants or project mentors, will be conducted through school email accounts. Use of personal emails for such communications is prohibited.

**Texting**

A text group chat exists for the purpose of rapid communication between team members in which all team members may participate or view. There will be no explicit hours for use of the group chat. Members are expected to respectfully self-regulate the use of the chat. All members are free to text in the group message at any time, so long as the communication is not superfluous and respect for the time of day or night is maintained.

Members are free to adjust notification preferences as they see fit. Muting the group chat notifications is not prohibited, although group members with muted notifications are required to appraise themselves of the discussion in the group chat at least once a day. Response times to direct (one-to-one) text messages, or text messages in the group chat directed at a single team member, are limited to 24 hours from the time of receipt during the work week. Text messages before 10 AM on weekends are prohibited. Texts delivered between 5 PM on Friday and 12 AM on Monday must be replied to by 11:59 PM on Monday at the latest. Team members are encouraged but not required to be active on their phones over the weekend and on holidays.

**Phone calls**

Phone calls are to be used sparingly, as they entail communication with no record between only two parties, except in the case of scheduled group calls. Communication relevant to the entire group should be made through other channels available for review by the whole team. If the team elects to meet by phone, all members will take notes to keep a record of the call. Phone calls may be utilized between 8 AM and 8 PM during the work week. Phone calls before 10 AM on weekends are prohibited. Exceptions to these rules can be made if all team members involved agree to the time of the call.

**ZOOM and In-Person Meetings**

ZOOM meetings are the preferred method of meeting if in-person is not convenient or feasible. Just as in the case of group phone calls, all members are expected to document meetings with notes. Recordings of each ZOOM and/or in-person meeting will be taken and posted to the corresponding folder in Microsoft Teams for team records. Members that are not present at meetings will be expected to watch the recording to appraise themselves of the discussion during the meeting.

Meetings are to be scheduled during the work week at convenient times to maximize team attendance. Apart from valid excuses, attendance is mandatory at all meetings during the work week. Weekend meetings may be approved by unanimous consent. Although attendance for weekend meetings is not required, it is highly encouraged. Team members are expected to review the recording of any weekend meetings they are not present for.

**Protocol for Delayed Response**

In the event of a team member not replying within the required 24 hours during the week, or by 11:59 PM on Monday for communication delivered outside the work week, direct text messages and phone calls are authorized outside the pre-determined timeframes if the matter is time sensitive. Team members are expected to notify the entire team of the lack of response and seek assistance from the other members with the matter until communication can be established. In the event of the non-responsive team member not making contact within 12 hours of the missed response deadline, a strike will be issued against them. Strikes will be issued every subsequent 12 hours without contact.

**Dress Code**

The Zero-Tolerance Policy outlined in the Communication section of the Code of Conduct extends to clothing and accessories worn by team members. Discriminatory or hateful words or images on any article worn by a team member is prohibited and will result in an immediate issuance of three strikes. Clothing and accessories advertising political or other ideologies are permitted to be worn in casual settings, although these items are discouraged for their lack of relevance to the work required and potential for incitement of conflict.

Team members are expected to dress to the level of the occasion. Day-to-day class attendance at the College of Engineering warrants casual or business-casual attire. Business-casual attire is expected when formally meeting with the project sponsor or other related parties.

Virtual Design Reviews and any other professional presentations require formal attire. Formal attire is defined as a dress shoe, slacks, belt, button down shirt, blazer, tie, and neutral accessories as desired by individual team members. Any item expressing a political or other ideology is expressly prohibited during VDR’s, and other presentations or formal meetings. Female formal wear will not be defined on account of our all-male design team. Failure to appear in formal wear or wearing ideological attire or accessories to VDR’s or other presentations and meetings will result in a strike.

**Attendance Policy**

**Attendance**

Attendance at any meeting during the work week is mandatory unless absence is pre-approved and necessary. Attendance at weekend meetings is optional. A team member who misses a meeting is responsible for reviewing the recording of said meeting posted to the Microsoft Teams workspace.

**Process for Excusal**

In the event of minor illness or injury not requiring the attention of a medical professional, team members are expected to keep in contact and continue work as usual. In cases requiring medical attention, communication of a notification of leave is to be submitted in a team-wide channel. Immediately following the end of leave, the team member must report their return in a team-wide channel and send supporting documentation. The documentation provided must justify the need for and length of the leave taken.

For non-medical absences, advanced notice and evidence of need must be demonstrated to the entire team. For regularly occurring absences (example: traveling sports, band, etc.), a season schedule must be presented to the team in advance.

Absences taken without notification of leave will incur a strike. Absences announced but not supported by documentation incur a strike.

**Emergencies**

In the event of a medical or family emergency, it is understood that a team member may not be able to make contact immediately. Once able, any team member affected by an emergency is to make contact through a team-wide channel and give a brief explanation. If possible, the affected team member ought to give an estimate of how long they will be out of contact.

The process for excusal holds even for emergency situations. Evidence of need or documentation excusing the leave must be shown upon return to the group. Documentation is encouraged, when possible, to excuse emergencies, although the team may jointly accept a reasonable explanation. In the same vein, multiple instances of emergency absence without documentation are subject to scrutiny by the group, and strikes may be issued by consensus if the group feels the emergency clause is being abused.

**Process for Amendment**

The Code of Conduct may be amended at the discretion of the design team. To amend the document, a request for amendment must be proposed at least two weeks prior to meeting for the vote. A request for amendment is a written draft of the amendment and proposed meeting date and time, which is to be provided to the entire team for comments on and/or editing in the two-week period prior to the voting meeting. 100% attendance in-person and/or virtually is required to proceed with an amendment vote.

Amendments shall only pass by unanimous consent. Approved amendments will be uploaded to Appendix A. Amendments in the Code of Conduct immediately upon passing.

Amendments may be repealed by the same process outlined above. Repealed amendments will remain in Appendix A but will appear ~~stricken-through~~. The strike-through will be applied to an amendment immediately upon its repeal.

**AIAA Coordination**

The FAMU-FSU American Institute of Aeronautics and Astronautics rocket propulsion team is acting in support of this multi-year senior design project. Students on the project are divided among teams managed by appointed engineering leads. SD 501 members hold lead and team member positions on the project. The SD 501 seniors in team member positions are expected to act as a deputy team lead within their department. Senior design team members retain final say over all design decisions and responsibility for the correctness and quality of items submitted for grading.

The engineering leads will draft a breakdown of their team and systems, which will be reviewed and subject to approval by the project director. Attendance and performance of underclassmen will be monitored by the engineering leads. All points of contention with underclassmen will be handled professionally and objectively. Any problems or points of contention which cannot be resolved by discussion with the individual will be brought to the attention of the project director for resolution.

Any components designed by AIAA members not acting on the senior design team will be recorded as COTS (Commercial Off the Shelf) components with credit given to the designer. All AIAA members working in support of the project will be credited for their specific contributions in the project acknowledgements.

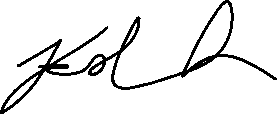
Students assuming responsibility for the continuation of the senior design project in subsequent years will be appointed at the discretion of the project sponsor, Dr. Shih, and professor of record, Dr. McConomy. Performance reviews and recommendations from the current design team will be submitted to both parties for consideration at the conclusion of the spring semester.

**Statement of Understanding**

I am aware that the Liquid Propellant Rocket project policies are available to me through the shared files under the Microsoft Teams page. It is my duty to familiarize myself with these policies throughout the entire duration of the project. I confirm that I have read and understood all the policies stated in this document. I hereby agree to adhere to the policies stated in this code of conduct, and any major violations may result in disciplinary actions decided upon by the rest of the group.



**Signatures**  **Date**



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x Jedreck Acquissa



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x Peyton Breland



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x Dylan Gardner



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x Mark Ioffredo



**\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ ­­­\_\_\_\_\_\_\_\_\_\_\_\_**

x Zachary Isriel

# Appendix B: Functional Decomposition

# Appendix C: Target Catalog

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Recovery System Derived Targets** | | | | |
| **Number** | **Target Description** | **Justification** | **Success Criteria** | **Metric** |
| 1 | New batteries shall be used for the altimeters before every flight | Insufficient voltage supply can lead to the altimeter powering off | New batteries will be chosen and verified to be full before being placed on the AV sled | Inspection/Analysis |
| 2 | U-bolts shall be used for all shock cord connections | U-bolts provide two points where shock can go through the bulkhead to increase stability | U-bolts are installed on the bulkheads as anchor points for the recovery harness | Inspection |
| 3 | All electronic components in the launch vehicle shall be removable. | Removable electronics allow for easier changes and adjustments to design | None of the electronic components in the launch vehicle are permanently fixed in place | Inspection/Test |
| 4 | There shall be no more than 4 sections of the vehicle recovered | NASA gives a requirement that there can be no more than 4 for the vehicle | The vehicle will be designed to have only 4 sections | Inspection/Test |
| 5 | The secondary ejection charges shall be based off a configured time set on the redundant altimeter | This will guarantee proper parachute deployments, if the primary altimeter fails | Both altimeters are completely independent of each other | Analysis/Test |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Safety Derived Targets** | | | | |
| **Number** | **Target Description** | **Justification** | **Success Criteria** | **Metric** |
| 1 | Proper safety equipment shall be provided to all personnel | The use of PPE helps to reduce the likelihood of injury while working | Entrances to all team shops are stocked with all necessary PPE | Inspection |
| 2 | Launch day attendees shall keep a reasonable pace during all aspects of activities | Maintaining a steady pace reduces the likelihood of falling or tripping | Team members are to walk, meaning having one foot on the ground at a time | inspection |
| 3 | All major hazards identified in the risk assessment matrix shall be decreased to yellow or green by CDR through mitigations | Mitigating potentially dangerous/frequent hazards creates a more robust system | All hazards identified in the CDR document fall in the yellow or green zones after the mitigation. | inspection |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Launch Vehicle Derived Targets** | | | | |
| **Number** | **Target Description** | **Justification** | **Success Criteria** | **Metric** |
| 1 | The launch vehicle shall not exceed 16Gs of acceleration during ascent | Acceleration higher than 16Gs could cause problems for the payload or vehicle structure | Simulations are done in OpenRocket | Analysis |
| 2 | The launch vehicle shall have symmetrical fins | This ensures that the launch vehicle is aerodynamic and ensures the CG is on center by causing equal aerodynamics on both sides and equal weight distribution | The launch vehicle has four fins equally spaced from each other around the airframe along with one camera positioned at the center of the nosecone | Inspection |
| 3 | The lower payload bay shall have at least 6 inches of interior length | This is to give the payload team enough space for any lower payload electronics | The lower payload bay is designed to have 6 inches of interior length | Inspection |
| 4 | The airframe shall be capable of launching in temperatures between 20- and 100-degrees Fahrenheit | The launch vehicle is planned to operate in a variety of launch fields and seasons | The airframe material is rated to not be damaged or deformed under these temperatures | Inspection/Analysis |
| 5 | The launch vehicle shall not go above Mach 0.7 | Higher speeds and accelerations are not necessary they endanger the payload and other structural components | Simulations are done is OpenRocket to confirm the launch vehicles maximum velocity | Analysis |
| 6 | The launch vehicle shall use at least 2 centering rings to support the motor tube | This ensures that the motor tube has the adequate support to experience the high force caused by the motor | Two centering rings along with the engine block will be used to support the motor tube | Inspection |
| 7 | The launch vehicle shall have a stability margin between 2.5 and 3.5 calibers | Stability margins lower than 2 are prohibited by NASA. Margins of stability greater than 2.2 are more stable | The aerodynamics lead designs the launch vehicle such that minimum stability margin of 2.5 calibers. | Analysis/Inspection |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Payload Derived Target** | | | | |
| **Number** | **Target Description** | **Justification** | **Success Criteria** | **Metric** |
| 1 | The payload vehicle SHALL have a diameter of less than 4.5 inches. | The Inner diameter of the launch vehicle is already limited to 6 inches. The extra space is needed for the rover housing | The Payload fits inside of its housing. | Inspection |
| 2 | The payload shall resist getting stuck during its motion | The rover will be subjected to rough terrain at Bragg Farm. It is important that the rover can work in many different conditions | The payload maintains traveling over rough terrain | Test |
| 3 | The payload shall be supported within the launch vehicle | The rover is subjected to the different forces during the launch. To limit the movement during the launch it must be supported from all sides. | The payload integration system supports the payload so that it is not dislodged before deployment | Inspection |
| 4 | The payload integration system shall be a maximum of 7 inches long | Limiting the length of the integration system also limits the payload length. This all lends to a more favorable static stability margin | The payload integration system is less than 7 inches | Test |

# Appendix D: Concept Generation

Table 28: Payload Concepts

|  |  |  |
| --- | --- | --- |
| **Concept #** | **Concept** | |
| **High Fidelity** | | |
| 1 | Independent motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing, and a tether for stability | |
| 2 | Single motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing | |
| 3 | Dual motor drive to short-span treads, Arduino mega controlled, terrain image processing | |
| **Medium Fidelity** | | |
| 4 | 1-12V DC Motor, tank tread, Raspberry Pi and Soil Sample Collection | |
| 5 | independent motor drive, 4 tires, Arduino Mega and flag plant | |
| 6 | independent motor drive, Spiked 2-Wheel, Arduino Mega, Sow Crops, and a tether | |
| 7 | 1-12V DC Motor, Spiked 2-Wheel, Arduino Mega, Terrain Image Processing | |
| 8 | independent motor drive, Spiked 2-Wheel, Raspberry Pi, flag plant, and sled for stability | |
| **Concept #** | **Concept** | |
| 9 | Independent motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing | **Morphological** |
| 10 | Single motor drive to 2 spiked wheels, Arduino Mega controlled, Terrain Image Processing |
| 11 | Dual motor drive to short-span treads, Arduino mega controlled, terrain image processing |
| 12 | 1-12V DC Motor, tank tread, Raspberry Pi and Soil Sample Collection |
| 13 | independent motor drive, 4 tires, Arduino Mega and flag plant |
| 14 | independent motor drive, Spiked 2-Wheel, Arduino Mega, Sow Crops, and a tether |
| 15 | 1-12V DC Motor, Spiked 2-Wheel, Arduino Mega, Terrain Image Processing |
| 16 | independent motor drive, Spiked 2-Wheel, Raspberry Pi, Terrain Image Processing, flag plant |
| 17 | 3-D printed body | **Brainstorming** |
| 18 | injection molded body |
| 19 | machined aluminum body |
| 20 | 2-wheeled car style |
| 21 | 6-wheel car/truck style |
| 22 | tank treads |
| 23 | outriggers for stability |
| 24 | tethered to launch vehicle for stability |
| 25 | Integrated winch to launch vehicle for recovery |
| 26 | payload includes detachable recovery section for independent parachute system |
| 27 | moving ballast mass to flip rover if turned upside down |
| 28 | payload on lazy-Susan inside rocket to act as vehicle camera |
| 29 | crawler robot, no wheels |
| 30 | cockroach like robot, 6legs flat body |
| 31 | dog like robot. 4 legs, tall or short. Cylinder body |
| 32 | bee like drone, Bean shaped body under 2 flapping wings |
| 33 | snake rover, interlocking cylinders which wiggle with motors |
| 34 | catapult payload out of launch vehicle tube. Rolling ball shaped |
| 35 | Internal reaction wheels flip flat sided payload |
| 36 | interchangeable payload(s) |
| 37 | tail on rover for stability |
| 38 | balloon/floating based payload |
| 39 | Dumb payload…. Non mobile, only transmits back data |
| 40 | Micro-payloads… many small "chips" that transmit data |
| 41 | liquid fueled rover (car) |
| 42 | Water based rover (floating boat or raft) |
| 43 | Hovering rover (drone) |
| 44 | rover with detachable wings |
| 45 | detachable payload sections. Rover leaves behind data stations |
| 46 | Cold gas thruster propulsion |
| 47 | Static "launcher" payload. Launcher lands and throws data collection devices |
| 48 | sling shot data chip launcher |
| 49 | Rotary data chip launcher |
| 50 | inflatable payload… blow up bouncing ball |

Table 29: Launch Vehicle Concepts

|  |  |  |
| --- | --- | --- |
| **Concept #** | **Concept** | |
| **High Fidelity** | | |
| 1 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, 3-D printed fins (clipped delta geometry), removable fins, LD-Haack series 3-D printed nose | |
| 2 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, fixed trapezoidal plywood fins, ogive 3-D printed nose | |
| 3 | Solid motor, dual deployment, streamer + main chute, black powder ejection system, fixed 3-D printed fins (delta geometry), LV-Haack series 3-D printed nose | |
| **Medium Fidelity** | | |
| 4 | Solid motor, dual deployment, drogue + main chute, CO2 ejection system, fixed plywood delta fins, LV-Haack series 3-D printed nose | |
| 5 | Solid motor, dual deployment, drogue + main chute, black powder ejection system, fixed 3-D printed fins (clipped delta geometry) ogive 3-D printed nose | |
| 6 | Solid motor, dual deployment, streamer + main chute, CO2 ejection system, 3-D printed fins (clipped delta geometry), removable fins, conical commercial bought nose | |
| 7 | Solid motor, dual deployment, streamer + main chute, black powder ejection system, plywood trapezoidal fins, removable fins, elliptical commercial bought nose | |
| 8 | Solid motor, dual deployment, streamer + main chute, CO2 ejection system, plywood fixed delta fins, LV Haack 3-d print nose | |
| **Concept #** | **Concept** | |
| 9 | A mentos and coke powered launch vehicle with a nosecone and fin configuration for optimizing stability | **Morphological** |
| 10 | A hybrid propellant powered launch vehicle with an actuating nosecone |
| 11 | A hybrid propellant powered launch vehicle with a arms for fins |
| 12 | A launch vehicle with a four-bar linkage mechanism ejects parachutes |
| 13 | A launch vehicle with compressed CO2 cartridge ejects parachutes |
| 14 | A solid propellant launch vehicle with a single deployment system (main), arms for stability, and a conical nosecone |
| 15 | A single deployment (main) launch vehicle with a liquid propellant motor, and actuating ogive nosecone for stability |
| 16 | A dual deployment (drogue/main) launch vehicle with a liquid propellant motor, fins for stability, and LV-Haack nosecone |
| 17 | A single deployment (main) launch vehicle with a solid propellant motor, fins for stability, and LD-Haack nosecone |
| 18 | A dual deployment (streamer/main) launch vehicle with a liquid propellant motor, arms for stability, and ogive nosecone |
| 19 | A dual deployment (streamer/main) launch vehicle with a hybrid propellant motor, thrusters for stability, and conical nosecone |
| 20 | A dual deployment (streamer/main) launch vehicle with a liquid propellant motor, arms for stability, and ogive nosecone |
| 21 | A single deployment (main) launch vehicle with a liquid propellant motor, and actuating ogive nosecone for stability |
| 22 | A dual deployment (drogue/main) launch vehicle with a liquid propellant motor, and actuating conical nosecone for stability |
| 23 | A dual deployment (streamer/main) launch vehicle with a hybrid propellant motor, and actuating LD-Haack nosecone for stability |
| 24 | A single deployment (main) launch vehicle with a solid propellant motor, thrusters for stability, and LV-Haack nosecone |
| 25 | A launch vehicle with a black powder charge to eject parachutes | **Brainstorming** |
| 26 | A launch vehicle with a payload ejected along with a main parachute and has its own parachute for recovery |
| 27 | A launch vehicle with a payload ejected along with a drogue parachute and has its own parachute for recovery |
| 28 | A launch vehicle with a payload that has a mechanical arm which pushes apart the vehicle sections for parachute deployment |
| 29 | A launch vehicle with a piston ejection system for payload deployment |
| 30 | A launch vehicle with only one parachute for recovery system |
| 31 | A launch vehicle that has an electronic latch that unhinges the vehicle sections at apogee to deploy drogue chute |
| 32 | A launch vehicle with a sling-shot propulsion system |
| 33 | A launch vehicle with the avionics bay located in the nosecone |
| 34 | A launch vehicle with feathered fins for slow descent |
| 35 | A launch vehicle with electronically maneuverable fins |
| 36 | A launch vehicle with retractable fins |
| 37 | A launch vehicle that ejects the motor at apogee |
| 38 | A launch vehicle that ejects the motor directly after burn time |
| 39 | A launch vehicle with a three-parachute system deployment |
| 40 | A launch vehicle with thrusted recovery and retractable legs for vehicle self-recovery |
| 41 | A launch vehicle with airbrakes to increase descent time |
| 42 | A launch vehicle with a robotic nosecone that substitutes for the payload |
| 43 | A launch vehicle with doors on each section of the vehicle for ease of access to recovery and avionics components |
| 44 | Launch vehicle has hatch doors on the airframe body for parachute deployment |
| 45 | Launch vehicle with camera sitting flush against outer airframe surface |
| 46 | A launch vehicle with a spherical nosecone |
| 47 | A launch vehicle with an actuating nosecone |
| 48 | A launch vehicle with flat surface serving as nosecone |
| 49 | A launch vehicle with booster staged separations |
| 50 | A launch vehicle with removable fin attachments |

# Appendix E: Risk Assessment

To conduct a Failure Mode and Effects Analysis for each vehicle system, environmental risk assessment, and personnel risk assessment, the risk classification matrix in the table below was used. The two tables on the following page define each severity and likelihood class.

Table 30: Risk Classification Matrix

Table

Description automatically generated

Table 31: Severity Classification Definitions

Table

Description automatically generated

Table 32: Likelihood Classification Definitions

Table

Description automatically generated

Table 33: Avionics and Power Systems FMEA

|  |  |  |
| --- | --- | --- |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PS.1)** Power loss on pad | * Dead battery * Disconnection of leads | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of power to flight computer | * Vehicle launch cannot be commanded * Battery replacement required * Personnel must approach cold vehicle – minimal risk | * Ensure battery is charged pre-flight * Have flight computer transmit battery condition * Firm lead attachment * Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PS.2)** Power loss in flight | * Dead battery * Disconnection of leads | 4A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of power to flight computer | * Loss of vehicle control * No control authority over recovery system * Unable to measure altitude * Unable to command deployment events * Unarrested descent * Risk to personnel | * Ensure battery is charged pre-flight * Have flight computer transmit battery condition * Firm lead attachment * Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PS.3)** Power loss after recovery | * Dead battery * Disconnection of leads | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of power to flight computer | * Loss of control authority over payload deployment mechanism * Unable to deploy payload | * Ensure battery is charged pre-flight * Have flight computer transmit battery condition * Firm lead attachment * Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.1)** In-flight barometer failure | * Bad component * Poor component calibration * Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Altitude cannot be determined from atmospheric pressure | * Vehicle relies on double integration of accelerometer data for altitude * Large compounding errors in integration may cause off-nominal main deployment * Nominal drogue deployment using accelerometer | * Purchase components from reputable dealer * Test components extensively before flight * Firm electrical lead attachments * Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.2)** In-flight accelerometer failure | * Bad component * Poor component calibration * Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Altitude and velocity cannot be determined by integration of acceleration data | * Vehicle relies on inflection of barometric data to determine apogee (pressure begins increasing) * Potential off-nominal drogue deploy * Nominal main chute deployment using barometer | * Purchase components from reputable dealer * Test components extensively before flight * Firm electrical lead attachments * Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.3)** Simultaneous in-flight accelerometer/barometer failure | * Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Altitude and velocity cannot be determined | * Recovery events reliant on time-commanded backup charges * Off-nominal drogue deploy * Off-nominal main deploy | * Purchase components from reputable dealer * Test components extensively before flight * Firm electrical lead attachments * Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.4)** In-flight/post-flight GPS unit failure | * Bad component * Poor component calibration * Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Vehicle landing site cannot be precisely determined | * Sonic beacon becomes primary locator * Visual tracking to ground aids in recovery | * Purchase components from reputable dealer * Test components extensively before flight * Firm electrical lead attachments * Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.5)** Flight computer failure (pre-flight) | * Bad component * Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of control authority over vehicle | * Vehicle launch cannot be commanded * Personnel must approach cold vehicle – minimal risk | * Same as previous |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.6)** Flight computer failure (in-flight) | * Bad component * Power loss | 4A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of control authority over vehicle | * No control authority over recovery system * Unable to measure altitude * Unable to command deployment events * Unarrested descent * Risk to personnel | * Same as previous |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.7)** Flight computer failure (post-flight) | * Bad component * Power loss | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of control authority over vehicle | * Loss of control authority over payload deployment mechanism * Unable to deploy payload | * Same as previous |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.8)** Wire leads disconnect | * Excessive vehicle vibration * Poor terminal connections | 4D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Any combination of AV.1 – AV.4, AV.6, and AV.7 failure modes | * Loss of control authority over vehicle * No control authority over recovery system * Unable to measure altitude * Unable to command deployment events * Unarrested descent * Risk to personnel * Loss of control authority over payload deployment mechanism * Unable to deploy payload | * Ensure proper soldering of terminal leads * Extensively test robustness of connections to tension and vibration * Implement vibration damping measures for electrical components * Redundant power/avionics |

Table 34: Energetics and Pyrotechnics FMEA

|  |  |  |
| --- | --- | --- |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PRO.1)** Failed motor igniter | * E-match fails to ignite * Black powder pellet fails to ignite after E-match | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Vehicle remains on launchpad in unknown state | * E-match/igniter replacement required * Personnel must approach warm vehicle – significant risk * Dud ignition converts vehicle cold * Random ignition in time following dud – significant risk to personnel approaching | * Redundant e-matches * E-match close proximity to black powder pellet |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PRO.2)** Ejection charge itiation failure | * E-match fails to ignite | 2B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Body sections do not separate | * Separation dependent on backup charge (time initiated) * Off-nominal parachute deployment | * Redundant e-matches |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PRO.3)** Ejection charge fails to separate sections | * Insufficient black powder load * Excessive friction in coupler * Shock cord entanglement | 2B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Body sections do not fully separate | * Structural damage between colliding body sections * Separation dependent on backup charge (time initiated) * Off-nominal parachute deployment | * Redundant ejection charges: * Time-commanded backup charge |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.1)** Unintentional motor ignition | * Static Discharge * Human Error | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Launch vehicle departs launch rails unexpectedly | * Flight computer not prepared to execute profile * Unable to command recovery sequence * Burns and hearing damage to personnel in immediate vicinity of vehicle | * Ensure vehicle is grounded in prep area and on pad * Ensure proper communication during count sequence |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.2)** Unintentional ejection charge initiation (pre-flight) | * Static Discharge * Human Error | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Unexpected black powder detonation | * Creation of large audible signature and expulsion of hot exhaust gasses * Great injury to personnel standing in line with and near charge. Medical emergency * Burns and hearing damage to personnel in immediate vicinity of vehicle * Body section(s) are ejected * Body sections impact nearby personnel. Minor to significant injuries | * Ensure vehicle is grounded in prep area and on pad * Ensure proper communication during count sequence * Implement CO2 ejection system |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.3)** Uneven combustion in solid fuel | * Poor mixing of fuel and oxidizer * Poor distribution of propellant in case | 4C |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Asymmetric thrust about vehicle z-axis | * Deviation from expected flight path * Loss of vehicle stability * In-flight break up of vehicle. Loss of vehicle * Unarrested descent. Risk to personnel | * Purchase motor from reputable dealer (Cesaroni is the current selection) |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.4)** Motor exhaust in body tube | * Motor case rupture * Nozzle foreword of thrust plate | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Damage to body tube * Loss of vehicle integrity | * Mid-flight fin detachment * Catastrophic body rupture * Vehicle in-flight breakup * Loss of vehicle | * Aluminum motor case, thrust plate, and motor retainer * Extensive sealing in motor compartment |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.5)** Motor jettison | * Thrust plate or motor retainer failure | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Motor and casing separate from launch vehicle after burnout | * Changes to stability margin as Cg shifts towards nose * Deviation from projected flight profile * Risk to personnel from uncontrolled, unarrested descent of metal motor casing | * Aluminum thrust plate and motor retainer to ensure dynamic loading margins are not exceeded |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.6)** Avionics damage | * Hot/corrosive ejection charge exhaust gasses | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Development of any AV.1 – AV.4 and AV.6 Failure Modes | * No control authority over recovery system * Unable to measure altitude * Unable to command deployment events * Unarrested descent * Risk to personnel | * Insulate void space in body * Implement CO2 ejection system |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.7)** Burned parachute(s) | * Hot/corrosive ejection charge exhaust gasses | 4D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Drogue and/or main parachute unable to provide sufficient drag to slow descent | * Partially or fully unarrested descent * Fire inside body tube * Fire in canopy on descent | * Kevlar blankets to retain chutes * Insulate void space * Implement CO2 ejection system |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.8)** Chain detonation of ejection charges | * Hot/corrosive ejection charge exhaust gasses | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Multiple separation event at apogee * Simultaneous deployment of drogue and main chute | * Deviation from intended flight profile * Risk to personnel from (4) and (5) * structural damage to colliding body sections * Parachute entanglement. Increased descent rate Uncontrolled descent. * Decreased descent rate. Increased wind drift. Vehicle exits recovery zone | * Insulate void space in body * Implement CO2 cooling system to black powder ejection charges |

Table 35: Recovery System FMEA

|  |  |  |
| --- | --- | --- |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.1)** Drogue parachute entanglement | * Poor shock cord stowage in body * Snag hazards in deployment path | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * High descent rate after apogee * Main parachute deployment at higher speed | * Main parachute canopy damaged in high-speed deployment * Main parachute cords tear or rupture * Partially or fully unarrested vehicle descent * Over tensioning of vehicle shock cord. Cord tearing or rupture * Unarrested descent of body sections * Risk to personnel * Major repair needed | * Design for no snag hazards in deployment path of parachute * Reeve loose shock cord * Implement cord routing solutions |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.2)** Main parachute entanglement | * Poor shock cord stowage in body * Snag hazards in deployment path | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * High descent rate after main deployment * High ground impact velocity | * Partially arrested descent * Damage to vehicle structures * Damage to internal components * Major repair required | * Design for no snag hazards in deployment path of parachute * Reeve loose shock cord * Implement cord routing solutions |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.3)** Single electronic chute release failure | * Bad component * Power loss * Debris in latch mechanism | 2B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Parachute remains retained in body | * Chute deployment contingent upon second release (timed event) * Off-nominal chute deployment | * Cross connection of retaining cord ends between two chute releases * Reputable distributor |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.4)** Double electronic chute release failure | * Power loss | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Parachute deployment rendered impossible | * Unarrested descent * Loss of vehicle * Risk to personnel | * Cross connection of retaining cord ends between two chute releases * Reputable distributor |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.5)** Shock cord rupture | * Excessive tension on cord | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Tether between body sections compromised | * Unarrested descent of body section(s) | * Extensive simulation pre-flight * Select shock cord with large factor of safety |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.6)** Shock cord entanglement | * Poor shock cord stowage in body * Snag hazards in deployment path | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Shock cord unable to extend to full length | * Collision of body sections on descent * Very minor damage to structure | * Reeve loose shock cord * Implement cord routing solutions |

Table 36: Vehicle Structures FMEA

|  |  |  |
| --- | --- | --- |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.1)** Melting of fin assembly during motor burn | * Heat transfer from motor case * Lack of heat resistance in fin material | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of flight stability | * Vehicle breakup in-flight * Loss of vehicle * Unarrested descent of body sections * Risk to personnel | * Use heat resistant print material * Treat for heat resistance * Minimize heat transfer |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.2)** Fins shear off | * Fin flutter * Aerodynamic loading | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of flight stability | * Vehicle breakup in-flight * Loss of vehicle * Unarrested descent of body sections * Risk to personnel | * Extensive simulation pre-flight * Ensure flutter speed >> max vehicle velocity |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.3)** Body tube zippering | * Shock cord contact with body on deployment | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of vehicle integrity | * Vehicle damage on descent * Major repair needed | * Implement “bumpers” to avoid cord contact * Implement cord routing |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.4)** Damaged motor retainer | * Defect in part * Excessive dynamic loading | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Potential motor jettison after burnout | * Unarrested descent of motor casing * Risk to personnel * Minor repair required | * Aluminum motor retainer to absorb far larger loads than necessary |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.5)** Bulkhead or U-bolt torn loose | * Excessive loading during chute deployment * Late chute deployment | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Body section(s) disconnected from parachute | * Unarrested descent of body section(s) * Risk to personnel * Major repairs required | * Extensive pre-flight simulation * Extra thick bolts and wide bracing on bulkheads |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.6)** Dislodged centering ring(s) | * Defect in part(s) * Excessive dynamic loading * Poor connection to threaded rods | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Motor long axis no longer colinear with vehicle z-axis | * Deviation from flight profile * Minor loss of stability * Risk to personnel | * Fix centering rings to threaded rods with hex nuts * Use thread lock to fix nuts |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.7)** Damaged rover retainer | * Defect in part(s) * Poor 3D print * Excessive dynamic loading * Excessive ground impact velocity | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Rover sits loose in payload bay | * Minor decrease in vehicle stability * Minor rover damage * Improper or impossible rover deployment | * Extensive pre-flight testing * Minimize ground impact velocity * Cushion landing |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.8)** Damaged avionics sled retainer(s) | * Defect in part(s) * Poor 3D print * Excessive dynamic loading * Excessive ground impact velocity | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Avionics sleds sit loose in av bay | * Potential for AV.8 failure mode * Loss of control authority over vehicle | * Extensive pre-flight testing * Minimize ground impact velocity * Cushion landing |

Table 37: Payload FMEA

|  |  |  |
| --- | --- | --- |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.1)** 3-D printed rover body damaged | * High ground impact velocity * Defects in 3D print | 1C |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Structure of rover compromised | * Loose components dig into terrain * Loss of propulsion * Internal wiring shifted. Leads torn from Arduino | * Extensive pre-flight testing * Minimize ground impact velocity * Cushion landing |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.2)** 3-D printed rover wheels damaged | * High ground impact velocity * Defects in 3D print | 1C |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Traction and/or propulsion negatively impacted * Physical immobilization | * None | * Extensive pre-flight testing * Minimize ground impact velocity * Cushion landing |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.3)** Electronic latch fails to release quick link on shock cord | * Power loss * Debris in latch mechanism | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Payload remains tethered to recovered flight vehicle | * Rover can only move as far from vehicle as slack in shock cord will allow | * Ensure firm lead connections * Clean latch mechanism |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.4)** Wheels become entrenched in loose terrain | * Insufficient wheel diameter * Insufficient tread on tires | 1D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Physical immobilization | * None | * Extensive pre-flight testing |
|  | | |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.5)** Rover becomes stuck in furrow of plowed field | * Cylindrical rover geometry | 1D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Physical immobilization | * None | * Outrigger/arm in design phase to recover from this condition |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.6)** Power loss | * Dead battery * Electrical lead disconnection | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of control authority over rover | * Physical immobilization * RAFCO Mission failure | * Charge battery pre-flight * Firm electrical connections |
| **Failure Mode** | | **Hazard Category** |
| **(RVR.7)** Propulsion failure | * Dead battery * Electrical lead disconnection * Bad motor | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Physical immobilization | * None | * Charge battery pre-flight * Firm electrical connections |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.8)** Antenna disconnection from GNC | * Excessive vibration in flight * Excessive ground impact velocity | 1D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of control authority over rover | * Physical immobilization * RAFCO Mission failure | * Firm electrical connections * Pad landing, reduce velocity |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.9)** GNC unit failure | * Bad component * Power loss | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of control authority over rover | * Physical immobilization * RAFCO Mission failure | * Firm electrical connections |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.10)** Foreword looking camera failure | * Broken lens during ground impact * Power loss | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Loss of ability to see terrain ahead of rover | * Technical immobilization * RAFCO Mission failure | * Padding around camera assembly * Firm electrical connections |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RVR.11)** Camera actuation system failure | * Motor failure * Obstructed gears * Power loss | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Camera cannot swivel camera | * RAFCO Mission failure | * Firm electrical connections * Clean gear mechanism |

Table 38: Environment FMEA

|  |  |  |
| --- | --- | --- |
| **Vehicle Risks to Environment** | | |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.1)** Launch pad/recovery area fire (energetic initiated) | * Dry vegetation in vicinity of motor ignition | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Danger to wildlife * Danger to habitat * Danger to personnel | * Potential for fire growth if left unmitigated | * Clear launch area of vegetation |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.2)** Launch pad/recovery area fire (LiPo battery initiated) | * Battery overcharge, over discharge, over-temp | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Danger to wildlife * Danger to habitat * Danger to personnel * HazMat release | * Pollution of crops with HazMat * Pollution of groundwater with HazMat | * Clear launch area of vegetation * Do not use battery improperly |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.3)** Interstage insulation littered in launch/ recovery area | * Insulation used in body tube to minimize void space and insulate parachutes from ejection charge gasses | 1C |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Ingestion of insulation by wildlife | * Disrespectful to property owners to eject litter on their land | * Biodegradable insulation (popcorn) |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.4)** Litter spread over launch site by personnel | * Lack of trashcans * Poor team leadership | 1D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Ingestion of litter by wildlife | * Disrespectful to property owners to litter on their land | * Bring trash bags * Firm leadership. Zero tolerance for littering |

Personnel risk assessment was conducted using the same FMEA format as was used for vehicle systems and environmental risk assessment.

Table 39: Personnel FMEA

|  |  |  |
| --- | --- | --- |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.1)** Skin contact with APCP solid propellant | * Improper material handling * Lack of PPE | 3D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Chemical burns * Eye irritation | * None | * Provide safety training * Provide PPE |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.2)** Electrocution | * Improper safety procedures followed * Live electrical while wiring | 2D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Discomfort/pain * Burns | * Greater or grave injury with prolonged exposure | * Provide safety training |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.3)** Proximity to high-pressure burst event (CO2 charge) | * Overpressure in pressure vessel * Pressure vessel tipping * Human error | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Hearing damage * Struck/Impaled by flying object(s) | * None | * Provide safety training * Do not overfill pressure vessels * Pressure vessels chained to walls * Declare all testing and clear area prior to initiation |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.4)** Proximity to explosive event (Black powder charge) | * Accidental initiation (human error, static discharge) | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Hearing damage * Burns from expanding hot gasses | * Severity increased with proximity * Severity increased with decreased angle-off-bore of charge | * Ground vehicle components * Minimize personnel handling charges * Isolate firing mechanism until range clear |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.5)** Proximity to combustion event | * Motor ignition (intentional) * Motor ignition (unintentional) * Loose black powder burn | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Hearing damage * Burns from expanding hot gasses | * Severity increased with proximity * Severity increased with decreased angle-off-bore of charge | * Ground vehicle components * Minimize personnel handling motor * Isolate ignition mechanism until range clear |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.6)** Injury: slip and fall, minor cuts, accidental collisions | * Uneven terrain * Tripping hazards on flat ground * Improperly stored sharp objects | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Pain/discomfort * Bruises * Small lacerations | * Infection of lacerations not immediately treated | * Situational awareness * Clean lab spaces * Proper safety procedures |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.7)** Dehydration, heat exhaustion, heat stroke | * Lack of water * Lack of adequate sun protection or shade | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Thirst * Disorientation * Loss of consciousness | * None | * Provide ample water * Bring portable awning/tent * Bring sunscreen, hats, etc. |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.8)** Soldering iron burns | * Improper use or stowage of soldering iron | 3D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| * Minor burns | * Increased severity with prolonged contact | * Proper training in use of soldering iron * Minimize personnel involved |

The risk classification matrix is overlayed with the number of risk items and percentage of total items that appear in each risk category. Our assessment identified a total of 63 risk items, with 40% of these items falling into the 3B and 4B categories. These categories represent substantial consequences in the event of failure with only a minor chance of failure, thus we can conclude that the bulk of our risk can be considered tolerable. 30 items fall into the 3D and 4D categories. These risks present substantial consequences and a substantial chance of failure. Mitigation strategies for items in these risk categories must be numerous, effective, and well-implemented by the team to ensure safety and mission success.

All 1-series (~30% of items) and A-series (~30% of items) risks can be considered tolerable risks. 1-series are the most tolerable because regardless of their likelihood of occurrence, the outcomes have marginal impact to safety and mission success. The 3A and 4A risk categories present substantial risk to safety and mission success but have an exceptionally low probability of failure. The entire A-series can be effectively considered negligible with the implementation of mitigation measures discussed.

Table 40: Overall Risk Item Distribution

Diagram

Description automatically generated

# References

**There are no sources in the current document.**