Vanderbilt University

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The Swapbot 2.0: Systems Engineering Report

NASA Robotics Mining Competition

2017 - 2018

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Vanderbilt® School of Engineering

Contents

1 Introduction

1.1 Competition Purpose

As the Earth's population increases and its natural resources deplete, it is essential that the world looks to the solar system for its surplus of natural resources. The aerospace industry has made huge strides towards interplanetary travel, and Mars colonization missions are now on the horizon. It is not feasible to frequently supply natural resources from Earth due to launch costs and the lead time on interplanetary travel. With the recent discovery of hydrated minerals in the Martian regolith, it is clear that In-Situ Resource Utilization (ISRU) would be essential to the development of a sustainable Mars civilization. Therefore, it is necessary to develop autonomous robotics for efficient water collection on Mars. The NASA Robotic Mining Competition (RMC) was established to promote the development of Mars excavation rovers and inspire the future generation of engineers to pursue ISRU technologies. Each team is tasked with designing, building, and testing a robotic excavation system in a simulated Martian environment.

1.2 Problem Statement

The robot must be capable of mining and depositing at least 1 kg of icy regolith simulant in a collector bin within 10 minutes. The mining area consists of a 7.38 meter by 3.88 meter container with three zones: the starting zone, obstacle zone, and mining zone. The robot must begin in the starting zone with an unknown orientation and traverse the obstacle zone, mine gravel from the mining zone, and return it to the collector bin. Performance of the robot is quantified using a point system. Points are awarded and deducted based on the amount of collected gravel as well as design parameters including the mass of the robot, energy consumption, communication bandwidth utilization, level of autonomy, and dust-free operation.

To simulate the limitations in the Mars environment, the robot must also adhere to certain operating limitations. The robot cannot use sound ranging systems, barometers, magnetometers, GPS, hydraulics, foam cells, or foam-filled tires, as these technologies do not work in the Martian environment. This constraint necessitates researching novel solutions to challenges which already have well-established solutions on Earth.

1.3 Purpose of Systems Engineering

The Vanderbilt Robotics Team followed a systems engineering design process outlined by the V-chart presented below. The excavation robot has many conflicting constraints and multiple subsystems that all need to perform equally well in order to accomplish the presented challenge. The systems engineering process provides a structured methodology to optimize competing requirements and available resources. It provides a holistic, big-picture approach to the decision making process.

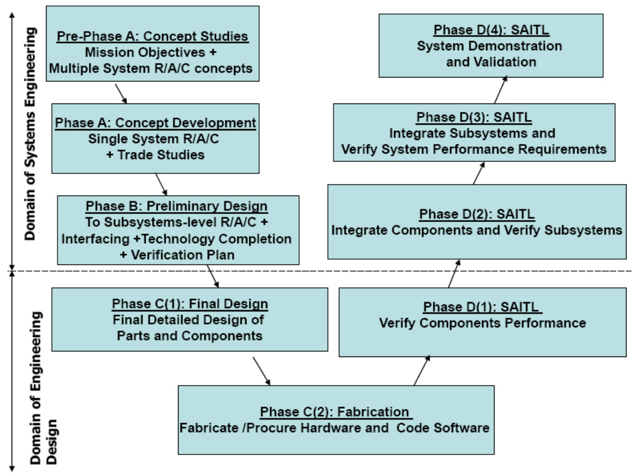

Figure 1: Systems Engineering Vee Chart

2 Systems Engineering

2.1 Concept Development

2.1.1 Design Philosophy

An entirely new rover design had to be developed for the teams first year competing in the RMC. With so many design parameters, it was essential to identify a few key design considerations to focus the brainstorming and concept development process. The team focused on maximizing gravel collection, optimizing all systems for autonomy, and simplifying the fabrication process.

Optimizing gravel collection was the highest priority. The rover must excavate gravel to fulfill its main purpose. Weight and power requirements were considered as well, but it was decided to provide the weight and power necessary to reach the desired goal of excavating 40 kg of gravel. Autonomy was also essential to the design, as the success of future manned missions to Mars depends on reliable autonomous robotic aid. All systems were optimized to be fully autonomous, with the implementation of SLAM and path planning algorithms a major priority for the programming team. With only a nine month project timeline, it was important to eliminate complexity with the use of off-the-shelf components. Stock parts increase system reliability since they are manufactured to higher tolerances than possible in-house. Fabricating custom parts increases lead time and halts progress on dependent systems. However, the team decided to fabricate custom parts when needed so to not limit the design process.

2.1.2 System Requirements

The robot was designed according to the system requirements defined by NASA as well as requirements defined by Vanderbilt Robotics. The system requirements were classified by the following categories: functional, performance, and budget. All of the requirements are presented in Tables 1 and 2 below.

Functional
The robot shall fit within dimensions of 0.75 m x 1.5 m x 0.75 m at the beginning of the competition run.
The robot shall weigh no more than 80 kg.
Performance
The robot must be able to capable of collecting and depositing a minimum of 1 kg of icy simulant within 10 minutes.
The robot shall be designed to minimize dust kickup and have a dust tolerant design.
The robot shall be able to function fully autonomously and failover to human control in the case of an error.
Budget
The robot design shall be complete and verified by May 1, 2018

Table 1: NASA Defined System Requirements

Functional
The robot must be capable of elevating the collected simulant a minimum of 3 inches above the collector bin.
Performance
The robot must be able to capable of collecting and depositing a minimum of 10 kg of icy simulant within 10 minutes.
Budget
The project cost for development of the robot shall cost no more than $8000.

Table 2: Vanderbilt Robotics Defined System Requirements

2.1.3 System Hierarchy

The system hierarchy is depicted in Figure 2. The frame consists of the structural base of the robot, drive system, and the power distribution systems. The drivetrain was designed for direct drive. Without a suspension system, it was important to be able to control each wheel independently to maneuver obstacles and improve turning capabilities. The excavation system must dig through BP-1 and collect gravel. It was considered making these two independent processes so to not collect BP-1. The collected gravel The robot controller software handles all input and output for the robot and maintains a state machine for higher-level control of the robot. The autonomy module includes all of the sensors for localizing the robot and mapping the environment. Additionally, all of the software associated with localization, mapping, and path planning are included in the autonomy module. The teleoperation module provides the human robot drivers with control inputs and data readouts. The autonomy module and driver station interface with the robot controller identically.

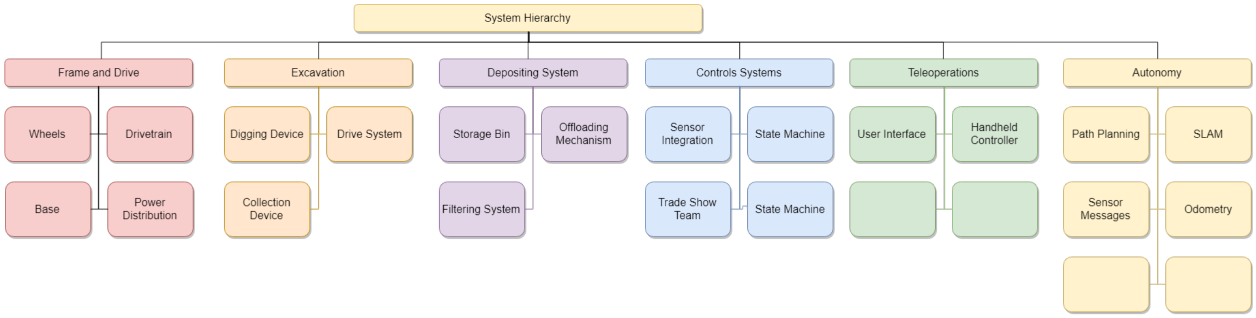

Figure 2: Robot System Hierarchy

2.1.4 Concept of Operations

The concept of operations are described in Table 3. The order of operations was derived from the system requirements and key design considerations listed in Section 2.1.2.

3 below.

Setup
Place robot at starting location and set up control station
Power on robot and establish network communication link
Perform calibration for sensor and control systems on the robot
Competition Start
Autonomously scan environment to determine current pose
Navigate to excavation zone while avoiding obstacles
Excavation
Mine gravel until section is depleted or storage limit is reached
Post-Competition Run
Record power consumption and turn off the robot
Clean the robot to remove particulate
Verify system integrity qfor next round

Table 3: Robot Concept of Operations

2.1.5 System Requirements Review

On September 28, 2017, the executive team members met with the teams faculty advisor and reviewed the system requirements in preparation for the preliminary design process. The system requirements were confirmed to align with the teams design philosophy and the competition objectives...The system hierarchy was well modulated to allow for efficient task distribution and system integration. The team agreed that the concept of operations was the correct approach to satisfy both NASAs requirements and the team-imposed autonomy and gravel collection requirements. The team received approval to proceed to the next design phase.

3 Safety

3.1 Overview

The VADL team takes individual, group, and project safety very seriously. As such, a safety hierarchy (depicted in Figure 3) has been developed to ensure that all team operations in the lab and on the launch field are verified and monitored by informed and qualified personnel, and that operations are stopped should a risk become uncontrollable.

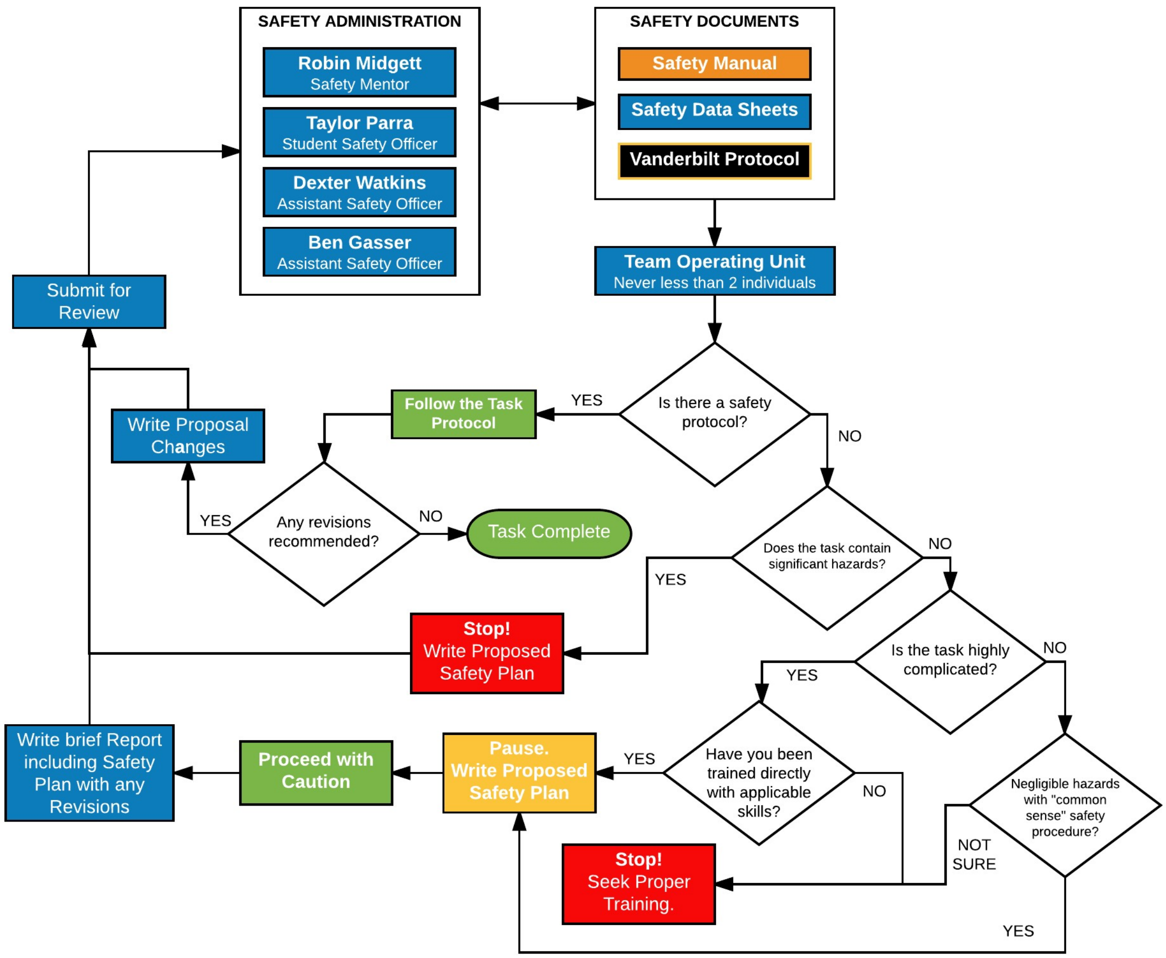

Figure 3: Vanderbilt Aerospace Design Laboratory Safety Protocol

The top level contains a four-person Safety Administration and the Safety Documents. Robin Midgett (Safety Officer; NAR II), Taylor Parra (Student Safety Officer), Dexter Watkins (Assistant Safety Officer; NAR I) and Ben Gasser (Assistant Safety Officer; NAR II) are responsible for management of the safety materials and maintain the authority to make substantive changes to the protocols and safety documentation as needed. They are also vested with the power to make go and no-go decisions for the team when new processes or procedures are required.

In accordance with the Safety Hierarchy, all procedures will be performed by a Team Operating Unit (TOU). For the purposes of safety and accountability, a TOU will never consist of fewer than two individuals. All TOUs are informed by the Safety Administration and Safety Documents and are expected to pause prior to beginning any task to ask the questions outlined in Figure 3.

This team structure offers a significant safety net while also encouraging safety to each individual. Operating under this safety hierarchy and in TOUs ensures that every team member plays a role in hazard recognition and accident avoidance, and ensures that hazards and risks are identified and addressed early, often, and repeatedly. In addition, the common objective of safety encourages team unity, creative thinking, and problem solving skills that will promote individual and team success throughout the Student Launch competition and in students' future careers.

3.2 Safety and Environment: Hazard Analysis

3.2.1 Risk Assessment Matrix

A risk assessment matrix (see Figure 4) is used to categorize and rank risks according to the likelihood of occurrence and severity of consequence, so that particularly dangerous risks may be identified. An event's likelihood of occurrence is assigned a rating of 1, 2, 3, 4, or 5, corresponding to the designation of rare, unlikely, moderate, probable, and very likely, respectively. Similarly, an event's severity of consequence is given a rating of A, B, C, D, or E, corresponding to the designation of trivial, minor, moderate, high, or critical, respectively. When these two scales are crossed in a matrix, the resulting combinations provide enlightening information in terms of the risk level. Low alphanumeric combinations represent typically negligible risk, while high alphanumeric combinations indicate much larger risks. Color-coding has also been included in the matrix to visually depict extent of risk. Events that fall within squares highlighted in green are considered low risk and require no mitigation or have no reasonable means of mitigation. In other words, "green" risks either occur infrequently or assume low consequence, such that serious consideration to mitigate the risk is not necessary. Similarly, squares highlighted in yellow contain events with moderate risk that should be mitigated, but the overall risk posed to the mission and general safety has been deemed acceptable. "Yellow" risks are more serious than "green" risks and could result in nontrivial consequences for the success of the mission or to the safety of those involved. However, this category of risk does not necessarily represent no-go situations once potential mitigation strategies have been evaluated and implemented. The third and most critical category is highlighted in red, signifying events that pose hazardous and unacceptable risks to either mission success or personal safety. Without exception, "red" risks must be mitigated to a "yellow" or "green" level before the rocket and payload are considered safe for launch.

		Consequence				
Likelihood		Trivial	Minor	Moderate	High	Critical
	Rare	A1	B1	C1	D1	E1
	Unlikely	A2	B2	C2	D2	E2
	Moderate	A3	B3	C3	D3	E3
	Probable	A4	B4	C4	D4	E4
	Very Likely	A5	B5	C5	D5	E5

Figure 4: Risk Assessment Matrix

The explicit meanings of each of the rating designations are outlined as follows:

Likelihood of Occurrence

- 1 (Rare) - Probability of occurrence is almost non-existent. Mitigation need only exist for the most critical risks.
- 2 (Unlikely) - Probability of occurrence is very low, but does exist. Mitigation should exist for high-risk consequences.
- 3 (Moderate) - Probability of occurrence is moderate. Mitigation efforts should exist for all risks resulting in greater than minor consequence.
- 4 (Probable) - Occurrence is more likely than not. Mitigation efforts should occur for all but the most trivial consequences.
- 5 (Very Likely) - Occurrence is to be expected. Mitigation is required for all but the most trivial consequences.

Severity of Consequence

- A (Trivial) - Occurrence of risk results in no effect on rocket/payload performance or safety of all persons involved. No mitigation is needed.
- B (Minor) - Occurrence of risk results in minor damage that is either easily reparable or has no effect on rocket/payload performance. No risk for injury to persons involved. Mitigation efforts should exist for the most likely risks.
- C (Moderate) - Occurrence of risks results in some damage to rocket/payload that could negatively affect performance and/or result in minor injury to persons involved. Mitigation efforts should exist for most risks.
- D (High) - Occurrence of risk results in major damage to rocket/payload that will negatively affect performance and/or result in serious injury to persons involved. Mitigation efforts should exist for all but the rarest risks.

- E (Critical) - Occurrence of risk results in catastrophic damage to rocket/payload that will eliminate performance capability and/or result in serious injury/death to persons involved or bystanders. Mitigation is necessary.

Combined Rating

- Green (Low) - Risk falls within an acceptable range of probability and consequence. Mitigation strategies should be implemented if possible but are not mission critical.
- Yellow (Moderate) - Risk may or may not be acceptable. Risk should be evaluated thoroughly for potential mitigation strategies.
- Red (Critical) - Risk has an unacceptable level of likelihood and consequence. Mission should not proceed until viable mitigation strategies are created and implemented.

All risks recognized by members of the team have been recorded and evaluated by the Student Safety Officer. The results are compiled in the following risk assessment tables, wherein each risk has been outlined along with possible causes, overall effect to the rocket/payload, verified mitigation strategy, and two risk assessment ratings for pre- and post-mitigation that have been colored accordingly for easy comparison. These ratings are abbreviated RR and PMRR, respectively. The evaluated risks, which span all aspects of project management, construction and launch day, have been organized into the following categories: Personnel, Propulsion Failure Modes, Payload Failure Modes, Recovery System Failure Modes, Vehicle Failure Modes, Environmental Concerns and Project Management.

3.2.2 Personnel Hazard Analysis

Personnel safety is of utmost importance in all construction, testing, and launch operations. Use of any equipment or chemicals requires a thorough understanding of the safety protocol and mitigation strategies for preventing and reducing the consequences of a potential failure.

Table 4: Personnel Hazard Risk Assessment

Risk	**Cause**	**Effect**	**RR**	**Mitigation Strategy**	**Verification of Mitigation**	**PMRR**
			Shop Safety			
Electric shock	Static build-up on equipment handler	Destruction of electrical components; black powder explosion	E3	Handlers of sensitive equipment will ground themselves to discharge static build-up. Furthermore, all high voltage components will be properly marked as "HIGH VOLTAGE" and locked while in use.	Consultation of shop safety guidelines	E1

Personnel Hazard Risk Assessment

Risk	Cause	Effect	RR	Mitigation Strategy	Verification of Mitigation	PMRR
Lacerations or cuts from machines and tools	Improper use of machines/ equipment	Injury potentially requiring medical attention	E3	All team members performing potentially hazardous operations will be properly trained. At least two members must be present for hazardous operations.	Consultation of safety protocol flowchart	D2
Black powder explosion/ ignition while handling	Accidental connection to voltage source; Static discharge	Hearing damage; Disorientation; Personal injury	E3	Black powder handlers will only work with small amounts at a time and ground themselves prior.	Consultation of SDS	E1
Getting caught in a machine	Loose fitting clothing or jewelry; long hair not tied back	Potential for serious injury or death	E3	Those performing machining operations will never wear loose fitting clothing or jewelry. All long hair must be tied back.	Consultation of shop safety guidelines and safety protocol flowsheet	E1
Eye contact with chemicals or particulates; exposure to arc from arc-weld	Improper handling of chemicals	Discomfort and/or vision impairment	D3	Appropriate eye protection will be worn for all activities involving machinery, chemicals, and welding.	Consultation of SDS, PPE: eye protection	D1
Prolonged exposure to loud machinery	Prolonged operation of heavy machinery	Disorientation and/or hearing loss	D3	Hearing protection will be worn when operating heavy machinery.	PPE: hearing protection	D1
Physical contact with hot surfaces	Leaving soldering iron on; touching welded parts immediately after welding	Burns	D3	All heat-producing tools will be turned off when not in use. Heat-resistant gloves will be worn when handling hot parts. Chemicals will be stored and handled safely.	Consultation of shop safety guidelines	D2
Inhalation of chemical fumes or carbon fiber particulates	Improper handling of chemicals	Discomfort and/or damage to lungs	D3	Volatile chemicals will only be handled in well-ventilated rooms and under a fume-hood when possible. A respirator will be worn when cutting, drilling, and sanding carbon fiber.	Consultation of SDS before use; PPE: eye protection, respirator	D1

Personnel Hazard Risk Assessment

Risk	**Cause**	**Effect**	**RR**	**Mitigation Strategy**	**Verification of Mitigation**	**PMRR**
Contact with flying debris from machining operations	Standard or improper tool use	Burns, abrasions, irritation of eyes or skin	C3	Closed-toed shoes and long pants will be worn at all times in the shop. All members present during cutting operations will wear eye protection.	PPE: clothes that cover the body, eye protection	C2
Contact with falling tools/parts	Improper storage of tools/parts	Personal injury	C3	All team members will wear closed-toed footwear and long pants while machining in the shop.	Consultation of shop safety guidelines involving cleanup; PPE: clothes that cover the body	C2
Tripping over loose cords	Long power cords/wires being run across the shop floor	Personal injury	C3	Power strips have been installed near all machines/workspaces that may require a power outlet.	Consultation of shop safety guidelines	C1
Exposure to chemical-s/allergens	Improper handling of chemicals and known allergens	Chemical burns, irritation of skin, allergic reaction	C2	Latex or vinyl gloves will be worn when handling chemicals or known allergens.	PPE: chemically resistant gloves	C1

Personnel Hazard Risk Assessment

Risk	Cause	Effect	RR	Mitigation Strategy	Verification of Mitigation	PMRR
Testing on the FRAME						
Personnel caught in motor belt	Belt plastic failure and/or improper placement in operation whilst operator is adjusting the FRAME	Potential for injury to operating personnel	E2	Perform all belt operations while power is disconnected. Inspect belt before each use for damage. Stay clear of FRAME during testing operation.	FRAME was proven in by the 2016-2017 VADL Team; Following of testing procedure	C2
Fall while securing nosecone interface	Unstable ladder base; unsafe practices	Potential for serious injury	D3	Optimal positioning of step ladder; visual monitoring of ladder movement while in use.	Consultation of shop safety guidelines	E1
Rocket dislodged	Improper axial constraint	Potential for serious injury	D3	Ensure tight compression fit of top and bottom mounts; be ready to adapt setup to different vibrational situations.	FRAME was proven in by the 2016-2017 VADL Team; Following of testing procedure	E1
Structural failure	Excessive vibration; joint failure	Potential for injury to operating personnel	D3	Monitor construction; ensure proper joint tightness; maintain safe distance from test facility during tests.	FRAME was proven in by the 2016-2017 VADL Team; following of testing procedure to ensure structural stability of system prior to experiment deployment	C2

Personnel Hazard Risk Assessment

Risk	**Cause**	**Effect**	**RR**	**Mitigation Strategy**	**Verification of Mitigation**	**PMRR**
Hotbox						
Electric shock	Improper shielding of control system	Potential for serious injury or death	E4	Follow electrical codes in wiring; maintain safe distance from hotbox while in use. Furthermore, the compartment containing high voltage electronics is marked with a warning sign and locked while the hotbox is in use.	Consultation of safety guidelines for handling high voltage components	C1
Shop fire	Runaway heating	Potential for serious injury or death	E3	PTC Thermistor used to cut off power to hotbox; webcam to monitor progress; digital thermometer included for redundancy in measurement; fire extinguishers kept in shop.	Hotbox design was proven in by the 2016-2017 VADL Team; Visual monitoring during use	D1
Shop fire	Improper wiring or mounting of light bulbs	Potential for serious injury or death	E2	High power circuitry completed with safety officer present; fire extinguishers kept in shop.	Hotbox design was proven in by the 2016-2017 VADL Team; Visual monitoring during use	D1
Shop fire	Overheating of components	Potential for serious injury or death	E2	Maximum temperature possible greater than temperature ratings of every part exposed to heat; fire extinguishers kept in shop.	Hotbox design was proven in by the 2016-2017 VADL Team; Visual monitoring during use; consultation of SDS for components to be heat-treated	D1

3.2.3 Propulsion Failure Modes

Table 5: Propulsion Failure Modes

Risk	Cause	Effect	RR	Mitigation Strategy	Verification of Mitigation	PMRR
Propellant fails to ignite	Improper motor packing; faulty propellant grain; damage during transportation	"Live" situation; rocket does not launch; necessary replacement	E3	Proper ignition setup; safety advisor oversees motor packing by student safety officer.	Consultation of strict safety protocol regarding motor and propellant issues	D1
Premature propellant burnout	Improper motor packing; faulty propellant grain	Altitude estimate not reached; main parachute may not deploy	E3	Proper motor assembly; obtain motor only from reputable source.	Static fire testing; consultation of safety protocol	E1
Improper assembly of motor	Incorrect spacing between propellant grains; motor case improperly cleaned; end caps improperly secured	Motor failure; unstable flight; target altitude not reached; damage or loss of rocket	E3	Ensure proper training and supervision by safety advisor for motor assembly by student safety officer.	Consultation of strict safety protocol regarding motor and propellant issues	E1
Motor mount fails	Insufficient mount strength; damage during previous launch or transportation	Motor launches through rocket; damage to/loss of rocket; unstable flight	E3	Proper motor mount construction; load verification testing; test launches.	Load verification testing; design analysis of motor mount; pre- and post-flight inspections of motor mount ??	E1

Propulsion Failure Modes

Risk	Cause	Effect	RR	Mitigation Strategy	Verification of Mitigation	PMRR
Transportation/ handling damage	Improper protection during transportation/ handling	Unusable motor; incapable of safe launch; potential damage to/loss of rocket	E3	Proper storage overseen by safety advisor and student safety officer; certified member handling.	Consultation of strict safety protocol regarding motor and propellant issues	E2
Center ring failure	Unable to withstand motor force during launch; weak ring; poor seal to body and motor tube	Reduced stability; damage to/loss of vehicle	E3	Proper ring size and construction; sufficiently strong materials used (6061-T6 aluminum); redundant load path design that can sustain failure of fins or centering rings and still retain motor.	Finite element modeling to verify rings to hold conservative thrust loads using von Mises failure criterion; See CDR for FEA	E2
Propellant explodes	Improper motor packing; faulty propellant grain; damage during transportation	Destruction of motor casing; catastrophic failure of rocket; potential injury to personnel	E2	Proper motor assembly; safety advisor oversees motor packing by student safety officer.	Consultation of strict safety protocol regarding motor and propellant issues	E1
Propellant burns through casing	Improper motor packing; faulty propellant grain; damage during transportation	Loss of thrust; loss of stability; catastrophic failure of rocket	E2	Proper motor assembly; safety advisor oversees motor packing by student safety officer.	Static fire testing to verify proper motor assembly	E1
Motor tube dislodges from rocket body during launch	Failure of fin attachment, exposing motor tube connection	Catastrophic launch failure, uncontrolled flight	E2	Thorough construction of motor tube mounting through fins. For the motor tube to tear out, the fins would have to tear through the carbon fiber body.	Design analysis of tail section structure; visual inspection of tail section pre-flight **??**	E1

Propulsion Failure Modes

Risk	**Cause**	**Effect**	**RR**	**Mitigation Strategy**	**Verification of Mitigation**	**PMRR**
Motor is misaligned	Centering rings misaligned; fins assembled to motor tube at an angle	Unexpected flight trajectory; unstable flight	C4	Careful machining of center rings on lathe with order of magnitude higher tolerance than laser cut plywood; proper assembly of tail section using centering rings and fin alignment jig.	Design analysis of motor alignment equipment; pre-flight visual inspection of motor alignment **??**	C1
Motor igniter fails	Faulty or incorrect igniter	"Live" situation; rocket does not launch; necessary replacement	C2	Proper igniter selection setup; proper power source.	Adherence to safety protocol	C1

4 Launch Operations Procedures

Detailed pre-launch checklists have been developed to ensure safety and success in all field operations. For every aspect of the launch field process, a list of necessary hardware and a detailed checklist for the assembly process are included. Procedures on troubleshooting and post-flight steps are also detailed. Safety warnings are highlighted with red text and required PPE is highlighted with blue text. Checklists require verification signatures from all personnel involved. These checklists have been refined with feedback from team Rocketry Mentor Robin Midgett and Graduate Student Mentor Ben Gasser, and their reliability was verified through the full scale test launches of late February.

4.1 Launch Field General Setup

Necessary Hardware

- ☐ Tent
- ☐ Tarps (2)
- ☐ Tables (2)
- ☐ Chairs (6)
- ☐ Garbage bags (2)
- ☐ X-frames (3)
- ☐ Robin's toolkit
- ☐ Electronics box
- ☐ Spare nuts and bolts and bolts bag
- ☐ Tape measure (2)
- ☐ Wire cutters
- ☐ Needle nose pliers
- ☐ Shears
- ☐ Zip Ties
- ☐ Metal file
- ☐ Box cutter
- ☐ Gorilla tape
- ☐ Sealant putty (blue) for sealing all holes between payload and electronics
- ☐ Epoxy kit (5-minute epoxy resin and hardener, mixing cups, popsicle sticks)
- ☐ Drill (with spare battery and bits)
- ☐ Sand paper

Assembly Procedure

Required Personnel: Rocketry Mentor, Safety Officer (Robin, Taylor)

- ☐ Unload equipment and materials from van. Bring to field setup location.
- ☐ Identify expected launch pad location, and begin field assembly at least 500 feet away.
- ☐ Set up tent and secure with stakes.

- ☐ Assemble portable tables. **WARNING!** Ensure ground is level and clear from obstructions.
- ☐ Set up bags for trash collection. **WARNING!** Littering presents an environmental hazard.
- ☐ Place X-frames for each section on tables.
- ☐ Place independent sections of rocket on X-frames (payload, avionics, tail).
- ☐ Place all electronics on their own table.

Signatures:

Rocketry Mentor: ______________________________

Safety Officer: ______________________________

4.2 Pack List: Full List of Necessary Hardware

- ☐ Tent
- ☐ Tarps (2)
- ☐ Tables (2)
- ☐ Ladder (1)
- ☐ Chairs (6)
- ☐ Garbage bags (2)
- ☐ X-frames (3)
- ☐ Scale for massing rocket
- ☐ Robin's toolkit
- ☐ Electronics box
- ☐ Spare nuts and bolts bag
- ☐ Tape measure (2)
- ☐ Wire cutters
- ☐ Needle nose pliers
- ☐ Shears
- ☐ Zip Ties
- ☐ Metal file
- ☐ Box cutter
- ☐ X-acto knife
- ☐ Gorilla tape
- ☐ Sealant tape (gray) for sealing bulkhead holes that contain wires
- ☐ Sealant putty (blue) for sealing all holes between payload and electronics
- ☐ Epoxy kit (5-minute epoxy resin and hardener, mixing cups, popsicle sticks)
- ☐ Drill (with spare battery and all needed bits)
- ☐ Launch pad
- ☐ Stakes for launch pad
- ☐ Adjustable wrench (2)
- ☐ Launch rail (12 ft)
- ☐ Vaseline
- ☐ Paper towels
- ☐ Latex Gloves
- ☐ Hex Allen wrench (blue)
- ☐ Level
- ☐ Small Phillips head (grey/orange) for screw switches (check w/ screw while packing)
- ☐ Multimeter (yellow) to check voltage across battery
- ☐ 5/64" Allen wrench for VN100 IMU
- ☐ Spare Lipo batteries
- ☐ Spare SD card with BBB image
- ☐ Spare connectors with leads
- ☐ Spare wire
- ☐ Altimeter manual
- ☐ Hex Allen wrench (blue)
- ☐ 4-40 nylon shear pins
- ☐ Black electrical tape
- ☐ Parachutes (Fruity Chutes 18" elliptical drogue and 8-ft. toroidal main)
- ☐ Shock cords

- ☐ Quick-connects for shock cords
- ☐ Fireballs for anti-zippering
- ☐ Blast charges (pre-prepared)
- ☐ Blue 3M tape
- ☐ Shock cords
- ☐ Quick-connects for shock cords (4)
- ☐ Fireballs for anti-zippering (2)
- ☐ Nomex blanket (2)
- ☐ 7/16” wrench (2)
- ☐ 9/16” wrench
- ☐ 5/8” wrench
- ☐ 1/4”-20 hex nuts
- ☐ Washers
- ☐ Thread seal tape
- ☐ Spare Li-ion batteries
- ☐ Wire stripper/cutter
- ☐ Crimpers
- ☐ Phillips screw driver
- ☐ Small precision flat-head screw driver
- ☐ Computer of Software and Controls Lead
- ☐ Motor retaining ring
- ☐ Motor refuel kit
- ☐ Baby powder
- ☐ Tweezers
- ☐ Safety glasses
- ☐ Igniter stick
- ☐ Launch electrics (in blue tub)
- ☐ Extra Kevlar