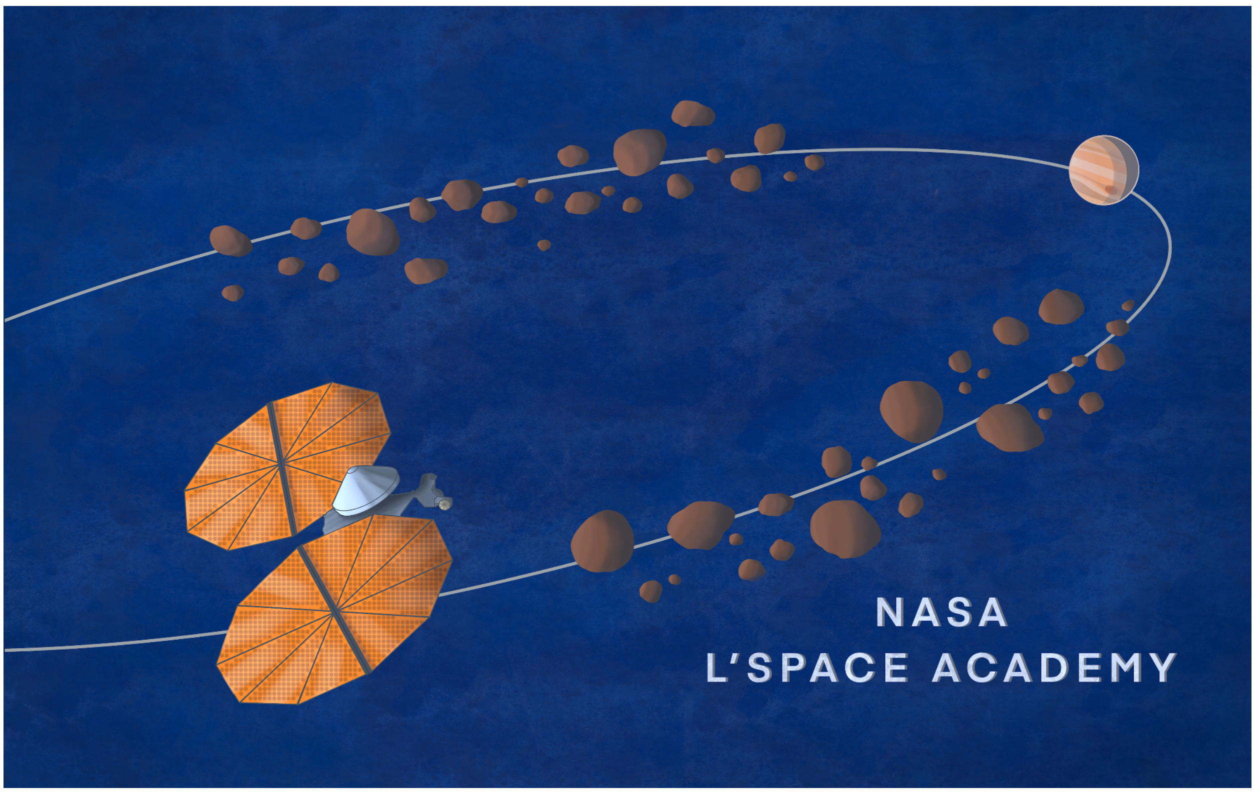
L’SPACE MCA Preliminary Design Review Report

The Dream Team #33



Authors:
Jeffrey Callaway, Rabhat Chaiprapa, Abraham Chavarria
Jonathan Cordova, Roger Nguyen, Hong Joo Ryoo, Brandon Tabata
Daniel Ponce, Daisy Salmeron, Yiyu Chen, Qianyi Lin, Joshua Kozlowski

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Section 1: Introduction and Summary

1.1. Team Introduction

Name	Biography
Joshua Kozlowski Project Manager/ Astrobiologist/ Outreach Officer Santa Rosa Junior College Mathematics	Joshua is from Santa Rosa, California, where he is a sophomore at the Santa Rosa Junior College. He is studying mathematics, but his interest in biology led him to be a part of the science team as an astrobiologist. His experience as a track and field coach has given him practice in navigating the many aspects of group work. As project manager of Team 33, he hopes to bring this group of talented individuals together into a team.
Brandon Tabata Mechanical Engineer University of California, Riverside Mechanical Engineering	Brandon Tabata is a second-year student at University of California, Riverside (UCR) pursuing a Bachelors of Science degree in Mechanical Engineering. Aside from academics, Brandon manages the development of autonomous aerial technologies at UCR Unmanned Aerial Systems. With his background in management and engineering, Brandon aims to take his team to new heights this coming year. His strengths include project management, SolidWorks, MATLAB, and ANSYS.
Hong Joo Ryoo Deputy Project Manager/ Physicist / Chemist / Business Officer University of California, Berkeley Physics	Hong is a physics major from the University of California Berkeley. He is the Deputy Project Manager of Team 33 and worked as the Principal investigator on a L'Space NPWEE team, and has had research experience at LBNL.
Yiyu Chen Computer Engineer Diablo Valley College Computer Science	Yiyu is a freshman majoring in computer science at Diablo Valley College. Her role in team 33 is a computer hardware engineer. She is a member of DVC WICS, which works to empower women in engineering and computing.
Jonathan Cordova Data Scientist Western Governors University	Jonathan Cordova is from Fresno, California where he is remotely attending Western Governors University as a senior. He is studying Business

Business Administration/ Information Technology	Administration with a specialization in IT Management. He works as an Information Systems Technician for the Institute of Technology in Clovis, CA, and assists in servicing 10 other college campuses across the state of California.
Rabhat Chaiprapa Thermal Engineer University of California, San Diego Aerospace Engineering	Rabhat is a junior at the University of California, San Diego studying Aerospace engineering. He is a part of the Rocket Propulsion Lab (RPL) propulsion team, where they engineer a bi-propellent rocket fueled by liquid natural gas and liquid oxygen. He is currently attending summer sessions on system controls and spacecraft guidance.
Daisy Salmeron Chief Scientist/ Researcher California State University, Long Beach Mechanical Engineer	Daisy is a sophomore at California State University, Long Beach and is majoring in Mechanical Engineering. She is doing research at a company located in Long Beach.
Qianyi Lin Researcher University of California, Los Angeles Materials Science and Engineering	Qianyi is a senior at the University of California, Los Angeles studying Materials Science and Engineering with a minor in Film and Television. She is a dedicated member of ASME and Rocket Project. Qianyi successfully completed an internship at UCSB about Quantum Materials which is similar to what she is planning to do in her future.
Jeffrey Callaway Lead Systems Engineer Arizona State University Electrical Engineering	Jeffrey Callaway is a rising sophomore at Arizona State University, online campus. He is currently pursuing a major in Electrical Engineering with a minor in Human Systems Engineering. Jeffrey is a member of SEDS Rocketry Division at ASU, where he contributes as club treasurer and avionics specialist. As an amateur rocketry enthusiast, he currently holds a NAR L1 high power certification. Jeffrey is originally from El Paso, Texas.
Roger Nguyen Mechanical Engineer University of California, San Diego Mechanical Engineering	Roger Nguyen is a rising junior from the University of California, San Diego in the city of La Jolla. His major is Mechanical Engineering with a specialization in controls and robots and his role in team 33 is a mechanical engineer. Roger has been a part of Triton Robotics, a student organization at UC San Diego, for 1.5 years. There are six unique

	robots and last year, he worked on the robot called Infantry, which is a ground robot that is capable of shooting 17 mm projectiles. As the lead engineer, Roger has helped design and manufacture the chassis, suspension system, and turret.
Daniel Ponce Mechanical Engineer California State University, Long Beach Mechanical Engineering	Daniel Ponce is a senior from the California State University of Long Beach. He is majoring in Mechanical Engineering. He is a member of the BAJA SAE working for the brake division, designing the brake rotor and the pedal box.
Abraham Chavarria Test Engineer/ Safety Officer California State Polytechnic University, Pomona Aerospace Engineering	Abraham Chavarria is a senior at California State Polytechnic University, Pomona, and is majoring in Aerospace Engineering with a minor in mathematics. He serves as the team lead for the Rocket-Powered Lander project within Project Phoenix, which aims to create a monopropellant lander using thrust vector control and hydrogen peroxide. As Team Lead, he helped develop the proposals, system architecture, and budget for the project and helped carry out the manufacturing of the craft to completion. He also worked within the testing team for the engine division of the Liquid Rocket Lab at Cal Poly Pomona, which worked on the testing and development of a bipropellant liquid rocket system.

1.2. Mission Overview

1.2.1 Mission Statement

The purpose of this mission is to further human understanding of the Martian cave environment by gathering information pertaining to the topics of astrobiology, especially whether life could have existed in the past and if life can exist in the future. Caves offer protection against weather and radiation, allowing for long-term preservation. The search for the existence of water ice and biological molecules in the cave network is the principal science goal of the mission due to the importance of both for living organisms. Methane concentration in the caves is also an important science goal because scientists are unable to understand the disparity in methane concentrations in the atmosphere across seasons using data from the Curiosity Rover and the Trace Gas Orbiter. In order to determine if the cave is safe for human exploration within the cave, patterns of radiation flux, temperature, and pressure will be investigated.

An ideal cave candidate for this mission would be CC0068, a cave in the northern Tharsis region. This cave has a high potential for seasonal or permanent hoarfrost formation (Schörghofer, 2021), and is part of a lava tube network. A wheeled rover will descend and traverse the Martian cave network using a LiDAR camera to navigate the terrain and a MASTCAM-Z camera (Bell, Et. al) to detect water ice formation in the cave. With the help of a ChemCAM (Grecious, Et. al), a Tunable Laser Spectrometer (Grecious, Et. al) will also be used to detect the presence of biological molecules, measure the concentration of water gas, and methane in the air. To determine if the cave is safe for human beings, a Rover Environment Monitoring System (Gomez-Elvira, Et. al) will be used. The robot will be attached to a base station on the primary payload and lowered into the cave via a tether that provides both power and communications directly to it, resulting in a safety line for the robot to the base station.

1.2.2 Mission Requirements

This mission shall explore the Martian cave environment in an effort to better understand the viability of Martian caves as a place where either past or present Martian life, or future human life, could exist and flourish.

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem
SYS.01	Determine the percent abundance of water ice within the Martian cave.	Science goal 1 for the mission.	STM		Science Review	All
SYS.02	System shall collect data on atmospheric samples within the cave.	Science goal 2 for the mission.	STM	FUN.01	Science Review	All
SYS.03	Determine the viability of human habititation in the radiation environment within the Martian caves.	Science goal 3 for the mission.	STM		Science Review	All
SYS.04	System shall send and receive data to Earth ground station.	Necessary for both remote operations, and for sending instrument data.	Customer		Demonstration	Communications
FUN.01	System shall be capable of recording and storing data.	It is necessary to store data before radio transmission to Earth.	SYS.02		Analysis and Modeling	Instruments
FUN.02	System shall have sufficient power to operate for 2 weeks duration.	System needs power for operations, communication, and instruments.	None		Demonstration	Electrical
PER.01	System shall be able to withstand thermal environment of a Martian cave for 2 weeks duration.	The mission needs to be able to survive the extreme environments on the surface and within the Martian caves.	None		Demonstration	Thermal, Electrical
PER.02	System shall have the ability to manuever into, and around the cave.	Probe must enter cave, and manuever to points of scientific interest.	None		Demonstration	Mechanical, Software
CON.01	System will not exceed a mass of 50kg.	Defined by primary payload's targeted mass.	None		Inspection	Mechanical
CON.01	System will not exceed a volume of 1.5 cubic meters.	This requirement was given by the customer	None		Inspection	Mehcanical

Figure 1.2.2.1. (Mission Requirements Spreadsheet)

1.2.3 Mission Success Criteria

The criteria for mission success is furthering the scientific understanding of the role that Martian cave microclimates have in fostering past or present Martian life. In particular, the collection of strong evidence for signs of life during the lifetime of the mission would qualify the mission as successful. If one of the following criteria below is fulfilled, the mission would be considered successful.

- One criteria about sending a picture of hoarfrost or fallen ice crystals boasting a length of 10mm - 20mm to Earth with 95.0% accuracy
- One criteria about detecting 400 ppb concentration of carbonates, sulfates, and chloride materials in the cave and sending information to Earth with 97.5% accuracy
- One criteria about detecting 0.200% concentration of water vapor in the cave atmosphere and sending information to Earth with 99.0% accuracy

1.2.4 Concept of Operation

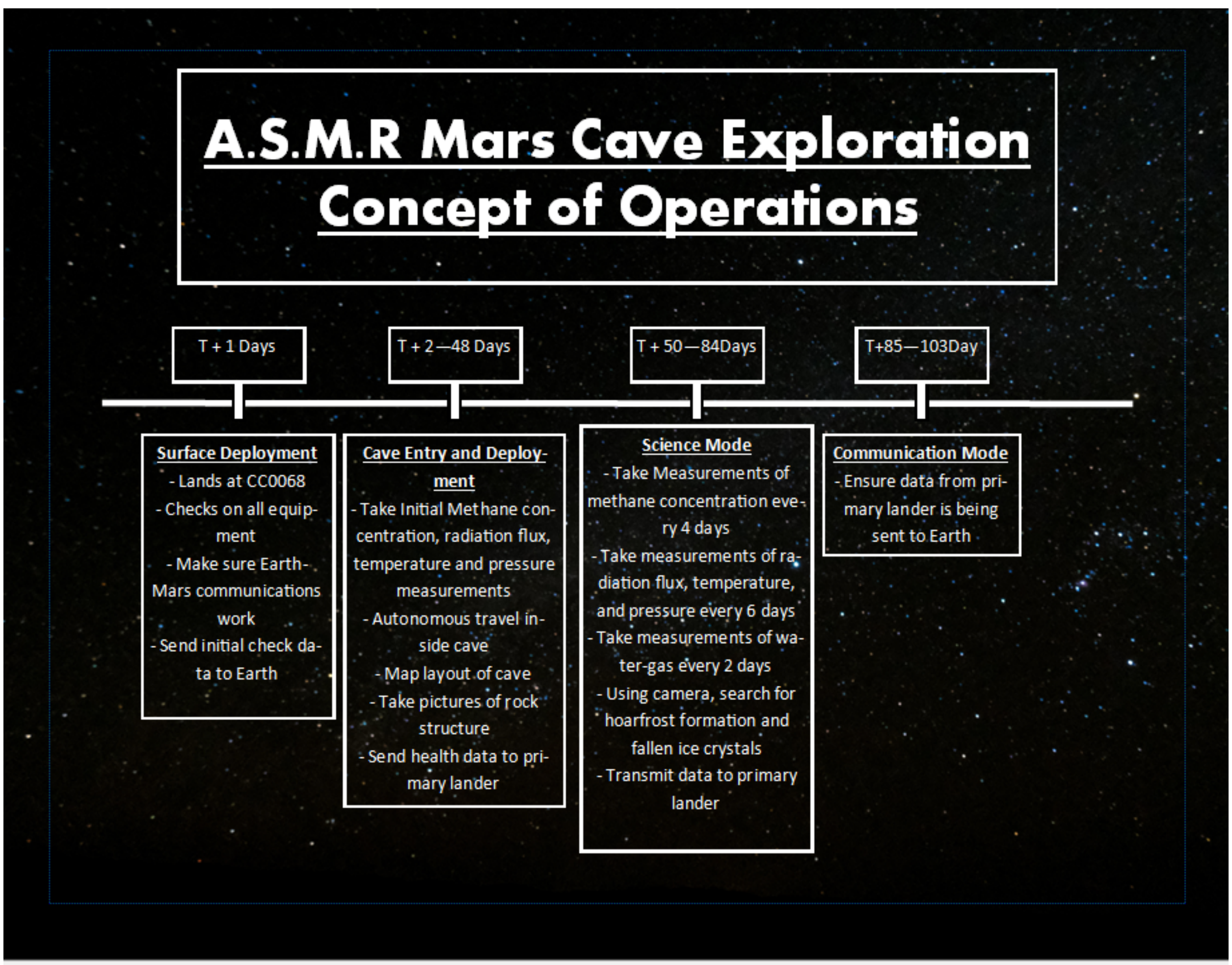


Figure 1.2.4.1. (ConOps Graphic)

The mission takes up to 103 days after deployment at CC0068. Moments after its landing, equipment will be checked and an initial check is done with the primary payload. After systems are working, the rover enters the cave and deploys its equipment. Methane, temperature, and pressure are checked as the rover autonomously moves throughout the cave, mapping it out. Halfway through the mission, when hoarfrost is estimated to be detected, readings will be done on it. For the last quarter of its lifecycle, the rover ensures its data is transmitted back to earth.

1.2.5 Major Milestones Schedule

Astrobiology in Martian Caves

Team Number: #33

Project Team Members: Jeffrey Callaway, Rabhat Chaiprapa, Abraham Chavarria, Jonathan Cordova, Roger Nguyen, Hong Joo Ryoo, Brandon Tabata, Daniel Ponce, Daisy Salmeron, Yiyu Chen, Karen Lin, and Joshua Kozlowski

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
1	Conceptual Development		100%	5/24/22	7/4/22	42	28
1.6	◆ SRR: System Requirements Review Completion		Complete	7/4/22	7/4/22	1	
2	Preliminary Design and Analysis		0%	7/12/22	8/15/22	35	12
2.6	◆PDR: Preliminary Design Review Completed		Not complete	8/1/22	8/15/22	15	
3	Verification and Validation		0%	10/12/22	4/10/23	181	32
3.6	◆ CDR: Critical Design Review Completion		Not complete	4/10/23	4/10/23	1	
4	Begin Manufacturing		0%	4/10/23	1/5/24	271	66
4.6	◆ ORR: Operational Readiness Review Completion		Not complete	1/5/24	1/5/24	1	
5	System Assembly and Testing		0%	1/8/24	12/2/24	330	64
5.6	◆ Launch Date	Primary Payload	Not complete	12/2/24	12/2/24	1	
6	Cruise Stage		0%	12/5/24	8/13/25	252	N/A
6.6	◆ Landing Date		Not complete	8/13/25	8/13/25	1	
7	Science Mission		0%	9/18/25	7/3/26	289	90
7.6	◆ Robot Completes Science Mission		Not complete	7/3/26	7/3/26	1	

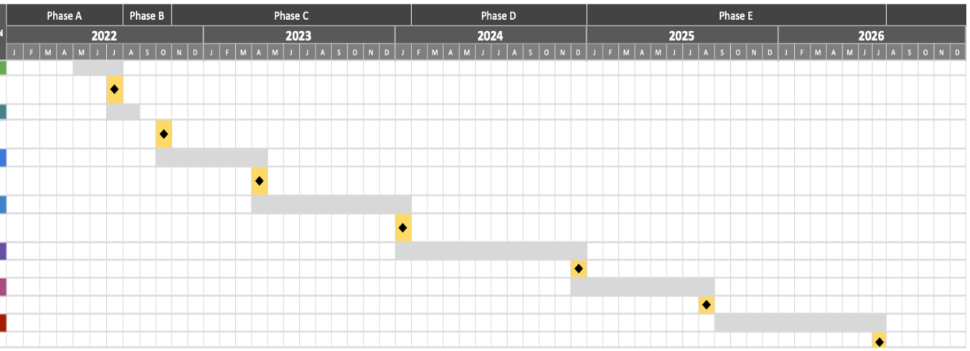


Figure 1.2.5.1. (Major Milestone Schedule)

The mission begins on 5/24/22 with the conceptual development phase. The major milestone for this phase is the System Requirements Review (SSR), detailing the proposed science objectives and brief vehicle solutions. The next phase is preliminary design and analysis with the milestone being the Preliminary Design Review (PDR). Further milestone documents will flush out details from the previous phase. This means that science objectives are further defined and clarified; vehicle design is more thought-out, risks are identified and mitigated, and testing occurs in the later stages of the project; logistics are detailed and up-to-date; etc. The next major document milestones are the Critical Design Review and Operational Readiness Review. The CDR is important because manufacturing cannot occur unless it has been approved. The ORR is also important because it helps verify and validate that the entire system is good and is ready for assembly, integration, and testing. The most important milestone and a date that cannot be missed is the Launch Date on 12/2/24, which leads to a landing date of 8/13/25. The lifespan of the mission is expected to be approximately one year, ending on 7/3/26.

1.3. Vehicle Design Summary

The rover will be using the Perseverance and Curiosity rover as a template. Through a trade study, wheels were chosen to be the best option for the mission when considering criteria like complexity, weight, heritage, and more. Similarly, the rocker-bogie suspension to traverse the cave terrain and the warm electronics box chassis (WEB) to protect and hold electronics will be used. However, changes will be made to adapt the rover to a cave environment and the new instrumentation. The rover's volume is expected to be 1m by 0.9m by 1.2m and the mass is expected to be 49kg. Most of the instrumentation being used can collect samples via the atmosphere or with limited movement. As a result, these instruments will either be mounted on the top, side, or bottom of the rover. One of the instruments, the Planetary Instrument for X-ray Lithochemistry (PIXL), requires a robotic arm to collect samples and will be mounted on the top at the front of the rover. The rover will receive power and be able to send data to the primary payload via a tether cable.

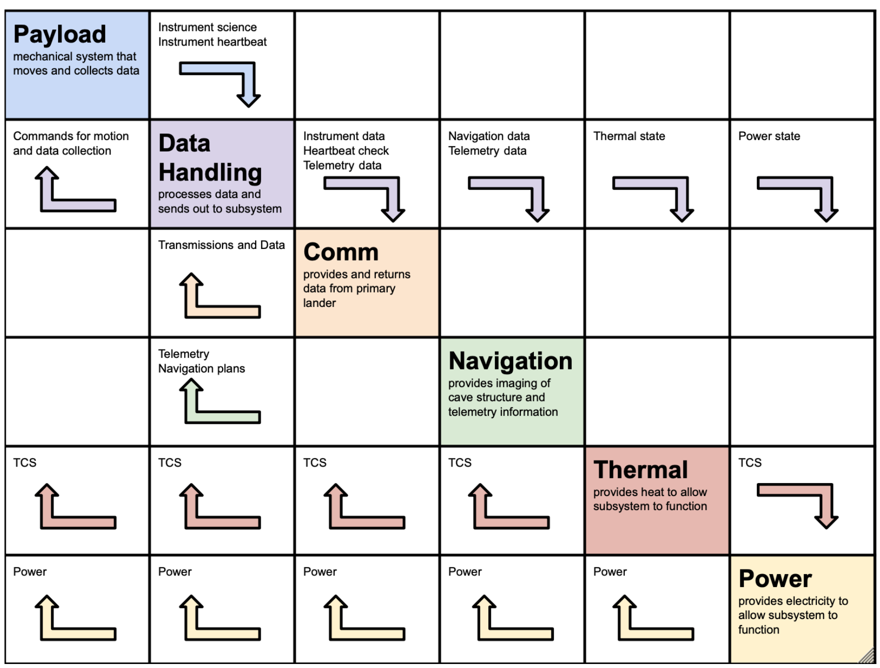
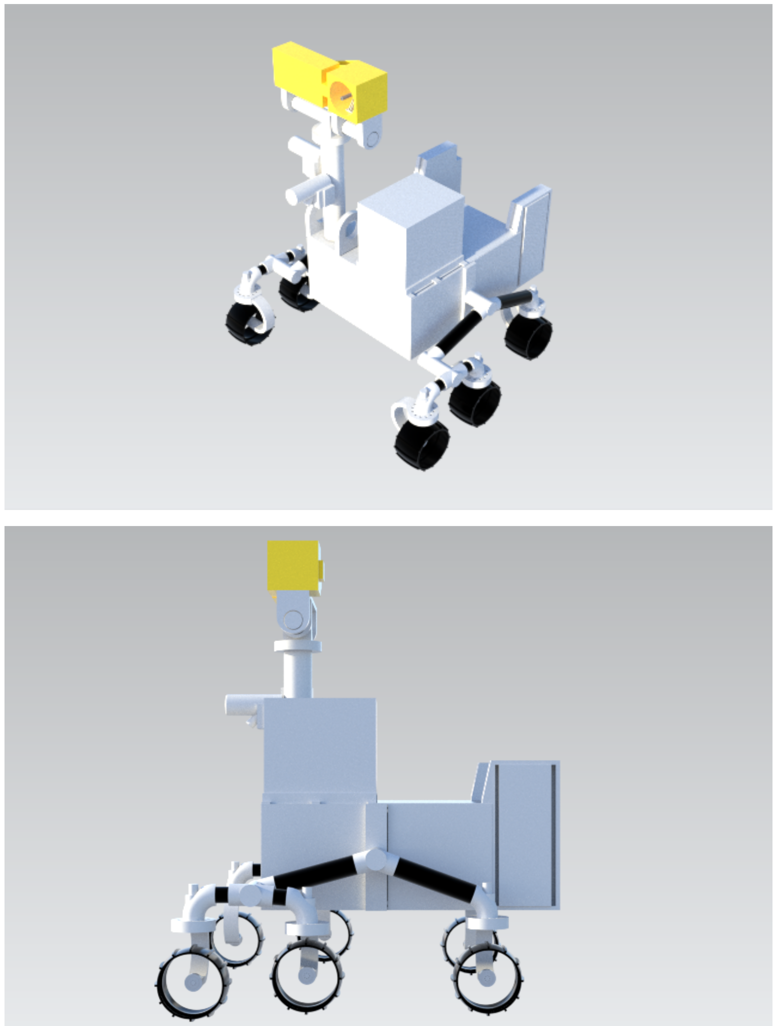


Figure 1.3.1. (N^2 Block Diagram of Interfaces)



Figures 1.3.2 and 1.3.3. (NX Renders of Vehicle Design)

1.4. Payload and Science Instrumentation

The first instrument used is the Planetary Instrument for X-Ray Lithochemistry or PIXL. PIXL is a small tool that will be used to identify chemical elements and molecules in the soil/rocks that will be analyzed and will collect data in the form of pictures as well. The PIXL sensor head will be mounted on a small robotic arm with most of the electronics residing on the body of the rover.

The Tunable Laser Spectrometer, or TLS, will be a key instrument for the mission. It is a relatively small instrument that's purpose is to take in Martian atmosphere and analyze the methane/water presence within it. It can be placed in many places on the rover and is key to understanding two of the science goals laid out in this mission.

The rover will also utilize the ChemCam which is an instrument package that contains two remote sensing instruments. The first being a Laser-Induced Breakdown Spectrometer and the second being a Remote Micro-Imager. The one that the rover will be utilizing the most is the LIBS device and it will aid in analyzing the water-ice as well as the soil/rocks around it. The LIBS device shoots focused lasers at a surface and collects data on the plasma light generated and uses that to look at chemical compositions of the surface. The primary laser, telescope and camera will need to sit on an arm/mast while the rest of the spectrometer lies upon the body of the rover.

The last device that will be utilized will be the Rover Environmental Monitoring Station (REMS) and it is a suite of instruments that provide reports on meteorological conditions surrounding the rover. The device will need to be placed on the rover’s mast and will read pressure, temperature, humidity, winds and radiation levels.

Section 2: Evolution of Project

2.1. Evolution of Mission Experiment Plan

During the initial stages of the mission concept, the science goal was to investigate the Martian Caves in order to provide information on whether life could have existed in the past and help broaden the knowledge if the caves are a liable location for future human exploration. The science goal has since changed to focus more on the concept of investigating potential life being present in the past and have gone the route of also investigating if the environment demonstrates any habitability of life.

Since the science goal went through some adjustments, the mission objectives have changed along with it. For instance, initially one of the mission objectives consisted of determining the percent abundance of water-ice within the Martian Caves. This mission objective has hence been modified to reflect on the interest if it is possible to demonstrate habitability of life in the Martian Caves. The modified and official mission objective consists of measuring and mapping out water evidence within the Martian Caves.

More recently, after the mission objectives became more centered and are more correlated with the mission concept and science goal; there has been a final decision to one of the science objectives. The science objective now deals with the investigation of the existence of molecules of water-ice substances in the Martian caves instead of the second option which was, determining the percentage of organic materials within water evidence samples.

2.2. Evolution of Vehicle Design

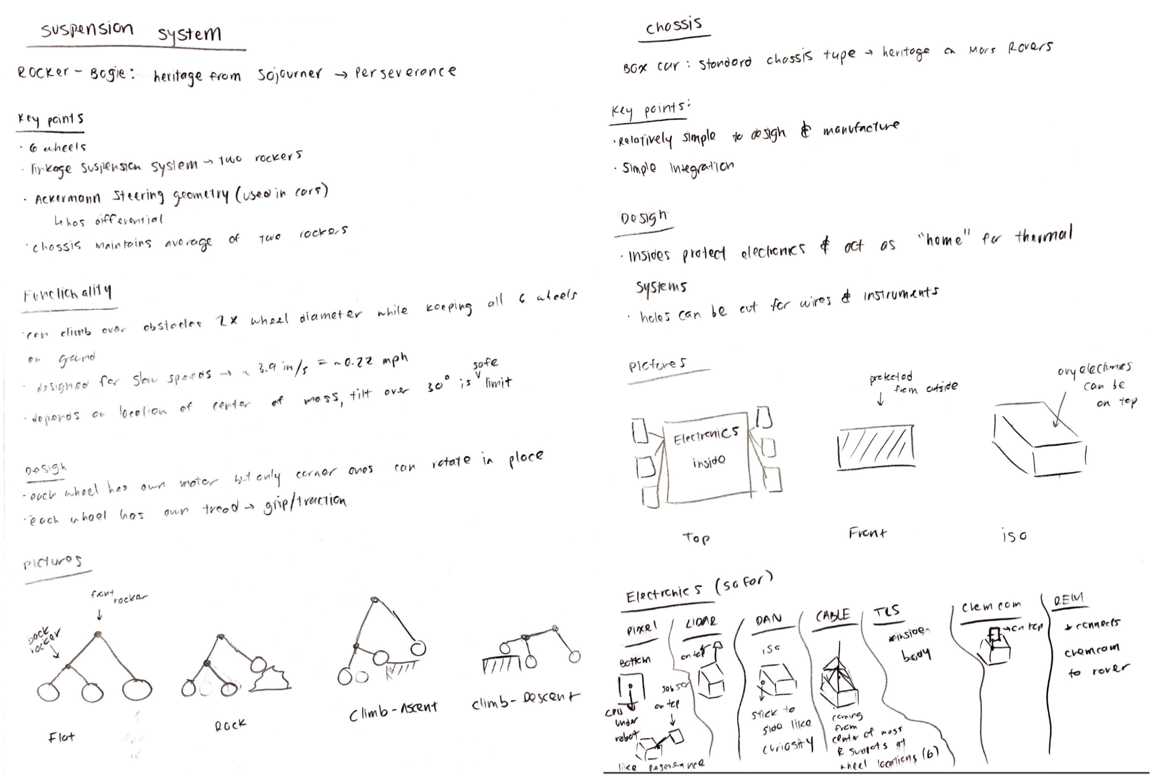
The vehicle design began with the formulation of the mission experiment plan. Once the scientific areas of interest were established, priority was placed on how to reach these areas of interest. Firstly, a decision was made to utilize a tether system for connecting to the primary payload. This tether shall be capable of stabilizing the descending cave robot, while also providing a power and data pathway to the primary vehicle. The next big decision point at this stage of design was the method of movement for the robot. Four pathways were identified early in this process: Wheels, tank treads, four-legged movement similar to the SPOT robot, and a wall-climbing robot similar to the JPL Lemur 3. A trade study was conducted in order to facilitate the decision among the engineering team.

Drive Train Trade Study

Criteria	Explanation	Grade	Weight	Lemur 3	Spot	Tread Tank	Wheels
Relative Mechanical Complexity	More complexity requires more research, testing, and analysis	1: New concept 4: Easy to make	10.00%	2	2.5	4	4
Relative Software Complexity	More complexity requires more research, testing, and is prone to errors	1: New concept 4: Existing tested software	10.00%	2	2	4	4
Relative Cost	Budget constraints	1: Expensive 4: Economic	15.00%	2	2	3	4
Relative Mass	Mass constraints	1: Heavy 4: Light	15.00%	3	2	1	2
Power Efficiency	Life of mission depends on power	1: Not very efficient 4: Very efficient	10.00%	1	2	4	4
Mobility in Cave	Necessary to explore cave structure and gather data/take measurements	1: Can only travel on flat terrain 4: Can travel on all types of cave environments	20.00%	4	3	2	2
Relative Speed (assuming Ideal Conditions)	Slower speed means longer mission	1: Slow 4: Fast	5.00%	1	2.5	4	4
Heritage	More heritage means higher confidence since a previous design is being used	1: In Development 4: Tested in Martian Mission	15.00%	1	2	3	3.5
		TOTAL	100.00%	28.13%	28.44%	35.63%	40.31%

Figure 2.2.1. (DriveTrain Trade Study)

Wheels were chosen as the method of movement for the robot, for the reasons shown above. Afterwards, some sketches were drawn to provide an idea of how the robot would look and function before any CAD models were created.



Figures 2.2.2. and 2.2.3. (Sketches of Suspension and Chassis)

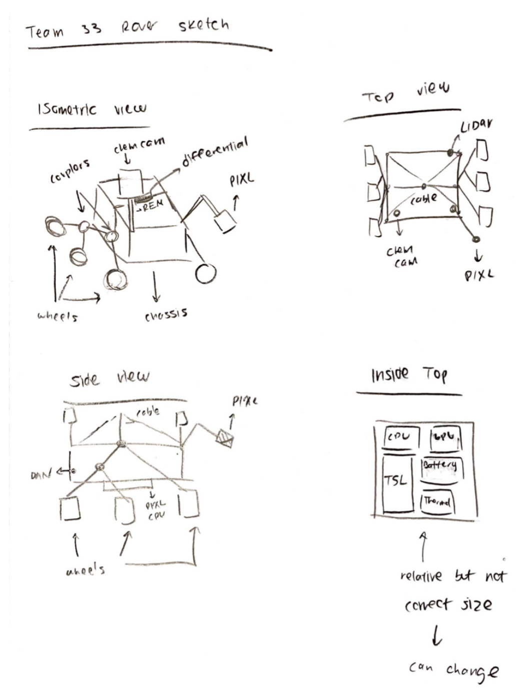


Figure 2.2.4. (Sketches of Rover)

The overall design of the rover is similar to Perseverance and Curiosity, but much smaller. However, the design will be changed to adapt the rover to a cave environment.

2.3. Evolution of Payload and Science Instrumentation

The science instrumentation to be used on the mission changed as the goals did, and underwent various evolutions and changes to get where it is right now.
The first iteration of tools included the MASTCAM-Z, the Planetary Instrument for X-ray Lithochemistry or PIXL, the Tunable Laser Spectrometer or TLS, and the Radiation Assessment Detector or RAD. When the mission goals moved away from searching for signs of radiation, the RAD was removed from the final product.

The second iteration of science instrumentation came after the research into the MASTCAM-Z and how it aligned to the mission's goals. MASTCAM-Z is used for more photographic purposes, however, one of the instruments nearby on the Curiosity rover they are both on, the ChemCam, fit the mission goals far better than the MASTCAM-Z. This is because the ChemCam can identify elements important to the mission, like Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorus, and Sulfur.

The third iteration of the science instruments added two instruments, the DAN or Dynamic Albedo of Neutrons tool and the REMS or Rover Environmental Monitoring System. The DAN instrument identifies water within the Martian regolith by searching for hydrogen in the ground. The second instrument, the REMS, is a tool that reads atmospheric pressure and temperature using two tools called booms.

The final iteration of the science instruments are the 4 tools Chemcam, TLS, PIXL, and REMS. DAN was removed from the rover because of its low level of usefulness in other goals of the mission, and weight restraints. All of this culminates for the robot containing the PIXL, the TLS, ChemCam, and REMS tools.

Instrumentation Trade Study										
Criteria	Explanation	Grade	Weight	Dynamic Albedo of Neutrons	Radiation Assessment Detector	MASTCAM-Z	Planetary Instrument for X-ray LithoChemstry	ChemCam	Rover Environmental Monitoring Station	Tunable Laser Spectrometer
Determining water ice abundance	Important for determining the possibility of life	3 = Intended Use 2 = Potential Usage 1 = No Use	30%	3	1	2	1	3	2	2
Determine Chemical Composiion	Important for determining the methane and water-ice substances	3 = Intended Use 2 = Potential Usage 1 = No Use	50%	1	1	1	3	3	1	2
Gather data on atmospheric conditions	Important for determining atmospheric pressure and temperature	3 = Intended Use 2 = Potential Usage 1 = No Use	20%	1	2	1	2	1	3	3
		TOTAL	100%	14.70%	11.4%	11.40%	18.20%	21.90%	18.20%	21.90%

Figure 2.3.1. (Instrumentation Trade Study)

Section 3: Overall Vehicle and System Design

3.1 Selection, Design, and Verification

3.1.1 System Overview

The system is composed of a 6-wheeled rover, lowered into the cave system on a 100m tether that provides a path for both power and data transmission to the primary payload. It also allows for a controlled descent of the rover into the cave system. The mass of the entire system is 48.62 kg and its volume is .976 x 1.002 x 1.189 meters. The six wheels are attached to the primary chassis using a rocker-bogie suspension system. The overall design of the rover is heavily influenced by both NASA's Curiosity and Perseverance rover. This results in a simple, proven design; much of the system has been implemented on the Martian surface in the past. The chassis will act as a warm electronics box (WEB) and with the help of the thermal control unit, insulate the electronics inside that are necessary for the rover to function. The chassis utilizes aluminum t-slot extrusions as the base and aluminum panels to protect the inside for the elements. The rover uses the rocker-bogie suspension system to traverse the cavernous terrain; the treads have been altered to make it more suitable for rock traversal.

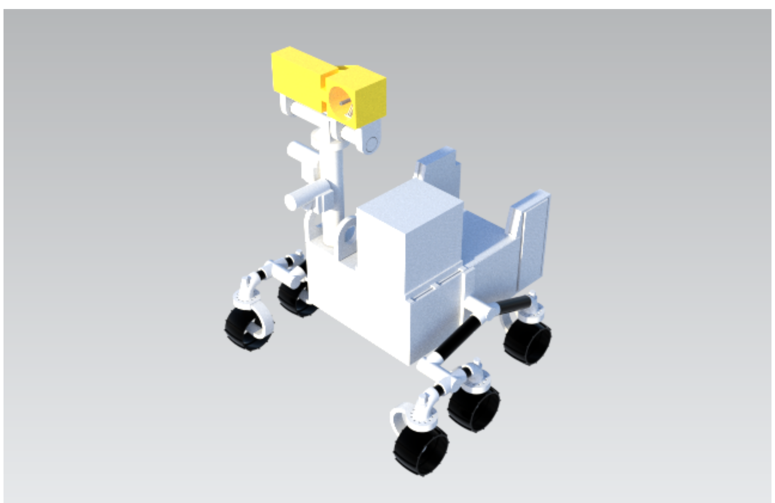


Figure 3.1.1.1. (Isometric View of Rover CAD)

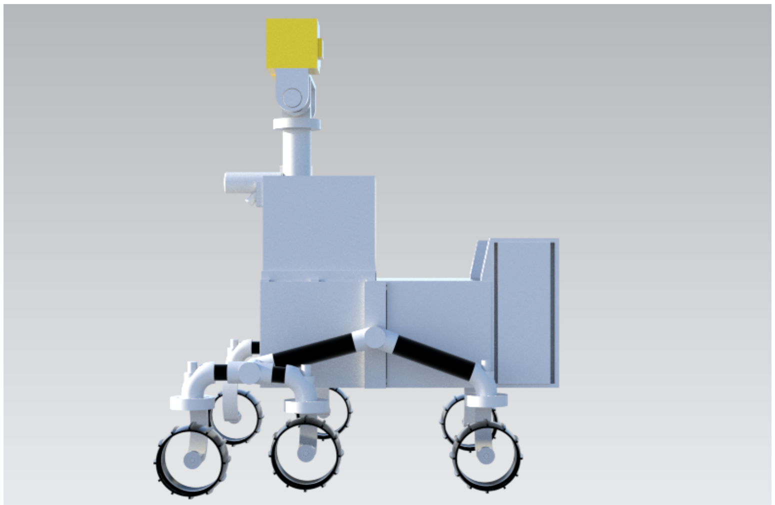


Figure 3.1.1.2. (Side View of Rover CAD)

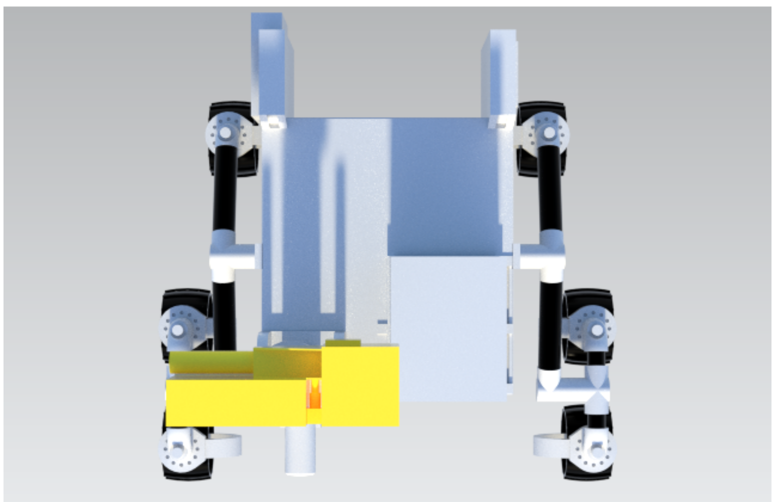


Figure 3.1.1.3. (Top View of Rover CAD)

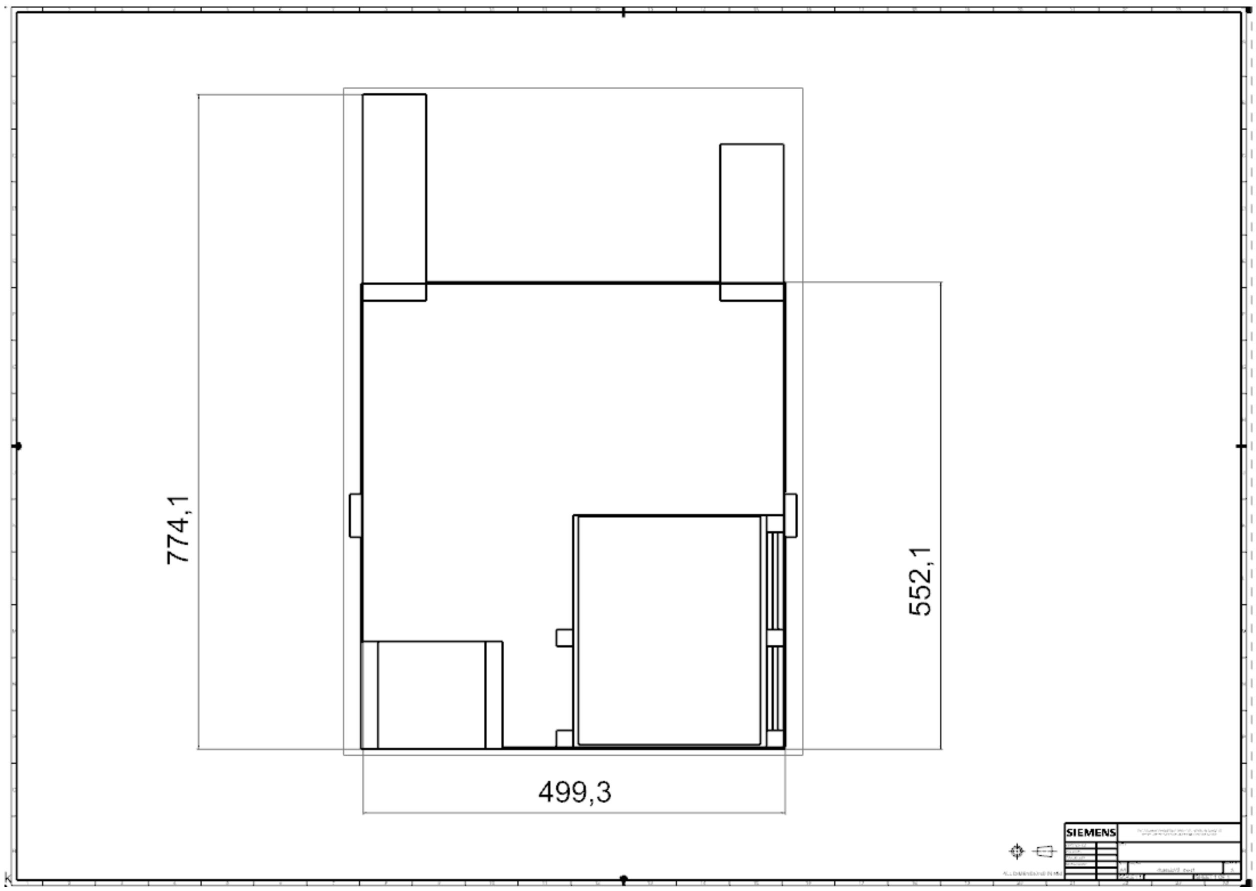


Figure 3.1.1.4 (Size Dimensions from Top View)

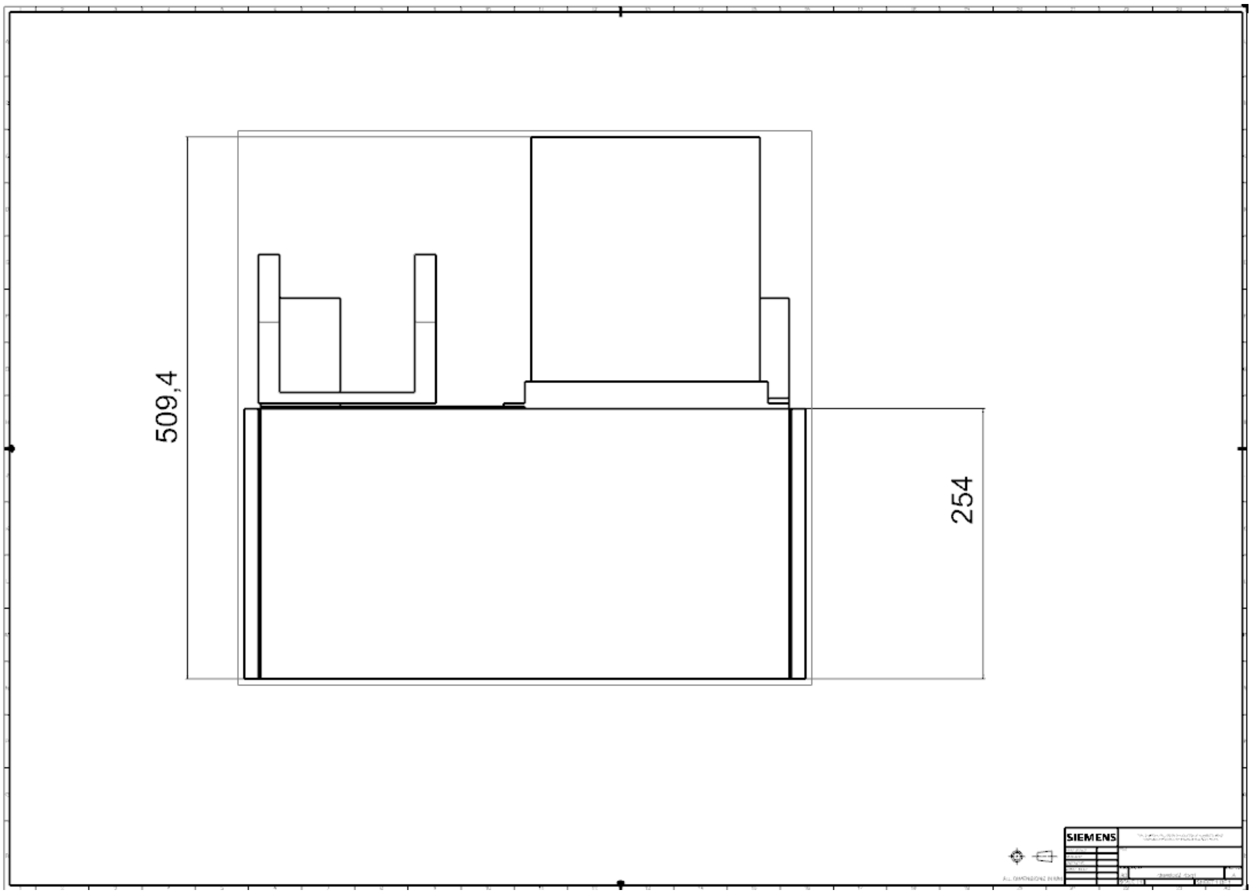


Figure 3.1.1.5 (Size Dimensions from Front View)

Req #	Requirement	Rationale	Parent Req	Child Req	Verification method	Relevant Subsystem
SYS.01	Determine the percent abundance of water ice within the Martian cave.	Science goal 1 for the mission.	STM		Science Review	All
SYS.02	System shall collect data on atmospheric samples within the cave.	Science goal 2 for the mission.	STM	FUN.01	Science Review	All
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FUN.02	System shall have sufficient power to operate for 2 weeks duration.	System needs power for operations, communication, and instruments.	None		Demonstration	Electrical
PER.01	System shall be able to withstand thermal environment of a Martian cave for 2 weeks duration.	The mission needs to be able to survive the extreme environments on the surface and within the Martian caves.	None		Demonstration	Thermal, Electrical
PER.02	System shall have the ability to manuever into, and around the cave.	Probe must enter cave, and manuever to points of scientific interest.	None		Demonstration	Mechanical, Software
CON.01	System will not exceed a mass of 50kg.	Defined by primary payload's targeted mass.	None		Inspection	Mechanical
CON.01	System will not exceed a volume of 1.5 cubic meters.	This requirement was given by the customer	None		Inspection	Mehcanical

Figure 3.1.1.6 (Top Level Requirements)

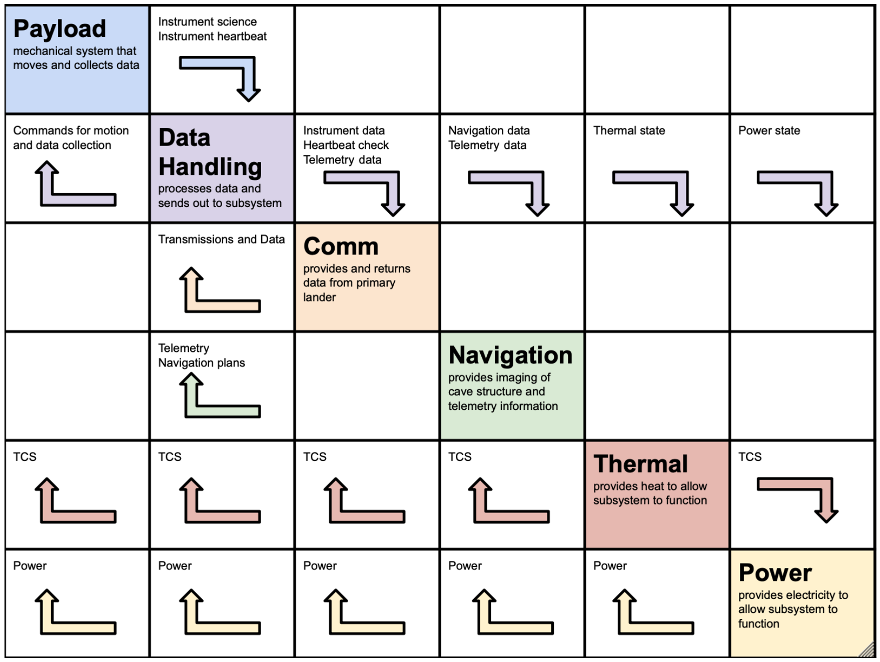


Figure 3.1.1.7. (N^2 Block Diagram of System Interfaces)

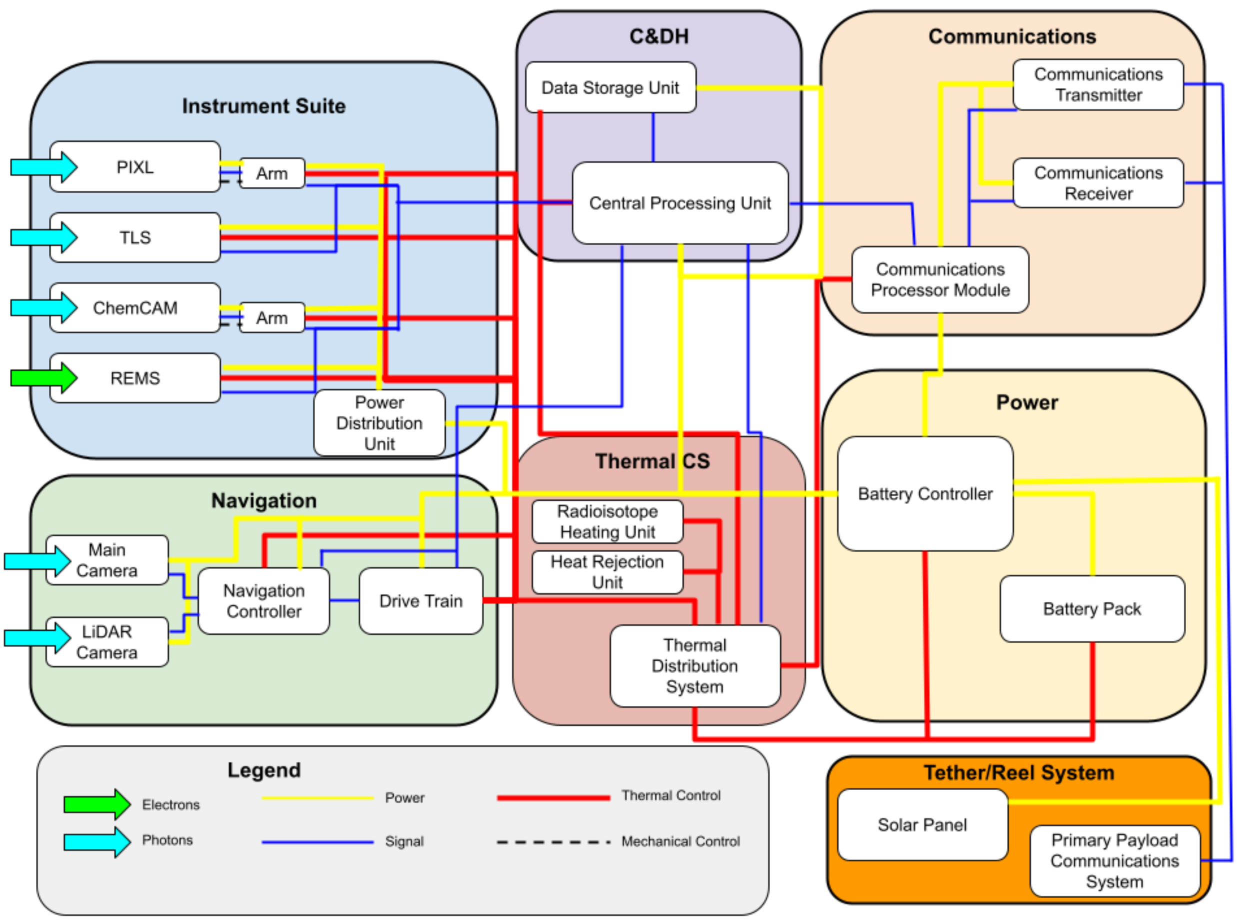


Figure 3.1.1.8. (System Interfaces Block Diagram)

3.1.2 Mechanical System Overview

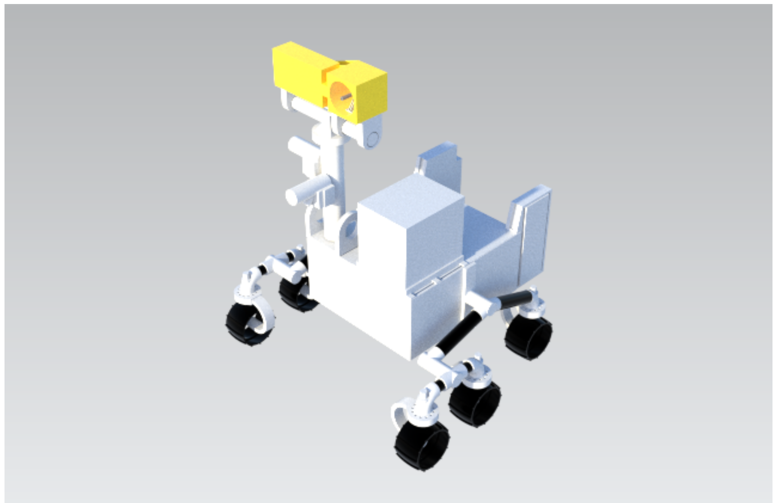


Figure 3.1.2.1. (Isometric View of Rover CAD)

The chassis is made of Aluminum 6061 20 mm x 20 mm t-slots. The reason for choosing aluminum is because its properties are that it has tensile yield strength of 276 MPa and an ultimate yield strength of 310 MPa. Aluminum is also lightweight and has great corrosion resistance which is important to note because of the mass constraint that is given. Half of the mass alone is allocated to the instruments and because of this only 25 kg are allowed for the chassis, instrument mounts, wheels, and suspension. The trickiest part of designing the chassis is finding a volume that would be sufficient enough to carry all of the instruments while not exceeding the mass limit or the size constraints. The structure of the rover is box like perseverance and curiosity. Knowing the effectiveness of both perseverance and curiosity, a similar model would be cost effective as well be less risk as both rovers have shown to be successful.

The wheels and suspension are made of Aluminum Alloy AA6061 and Titanium 6A1-4V. Both are chosen because of their common use onboard spacecraft and Jet Propulsion Laboratory's Perseverance.

The wheels are 160mm in diameter and are made of Aluminum Alloy AA6061 on the outer wheel and the treads. In the middle, Titanium 6A1-4V is used as the internal suspension system in the wheel itself. Titanium 6A1-4V is chosen because of its tensile yield strength of 880 MPa. Titanium by order of weight percentage consists of Titanium, Aluminum, Vanadium, Iron, and Oxygen. The tire treads on the counterpart of the model provided traction on the ground.

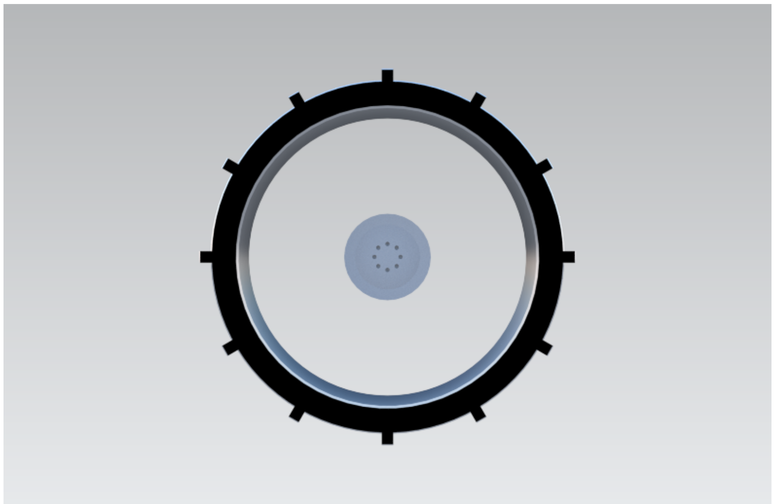


Figure 3.1.2.2. (Side View of Wheel CAD)

The suspension consists of both swivels, joints, and tubes to connect and function as an adaptive frame for traversing the terrain within the caves. The tubes are made of the same material as the wheels because it needs to be extremely rigid to prevent failure due to bending moments.The joints and swivels are designed with the Titanium alloy used previously.

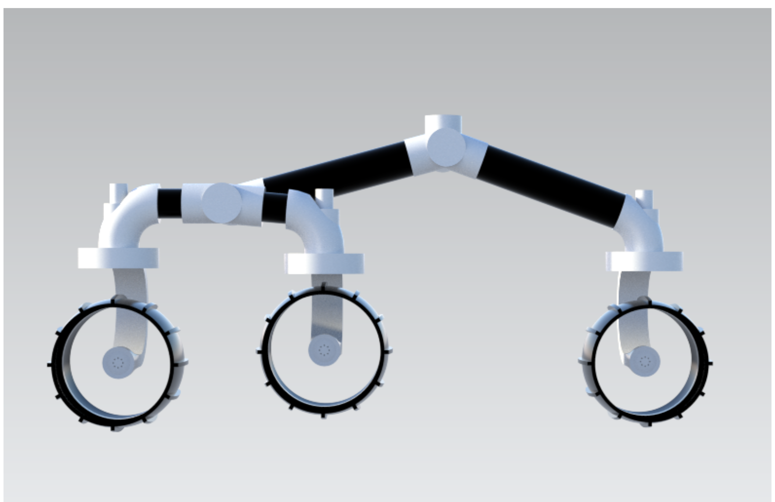


Figure 3.1.2.3. (Side View of Suspension CAD)

When designing the instrument mounts the material being used is titanium because it is twice as strong as aluminum meaning it is necessary to use less of it compared to aluminum and it is 45% lighter than steel and just as strong as steel and is corrosion resistant which is a factor in deciding.The instruments that needed to be carefully designed and more thought out are for the ChemCam. The ChemCam sits on a mast that needed to pivot so it could be laid down when put into the payload. The TLS is inside the chassis itself. PIXL is an instrument that on Perseverance and Curiosity is on the robotic arm and since the decision that the robotic arm is not going to be used, PIXL would be mounted near the front of the chassis.

For the chassis, the tether is a pivotal component, which allows for the transfers of power and communication to the primary payload. Hand calculations are done to determine the minimum area to avoid failure. The materials referenced are those already used by NASA, which are a mix of kevlar and spectra fibers. The tether is expected to support the entire weight of the rover and max parameters are used to assume a worse-cast scenario. With a tensile force of 186.05 Newtons, the minimum area is approximately 0.1 millimeters squared. It is important to note that this area is for tensile strength, meaning the max load the tether can withstand before it snaps. Tensile strength is used instead of yield strength because maximum load is more important than the load before the material enters the in-elastic range. This is because failure is defined as when the tether breaks and not when it plastically deforms. If yield strength is considered, the area needed would be greater.

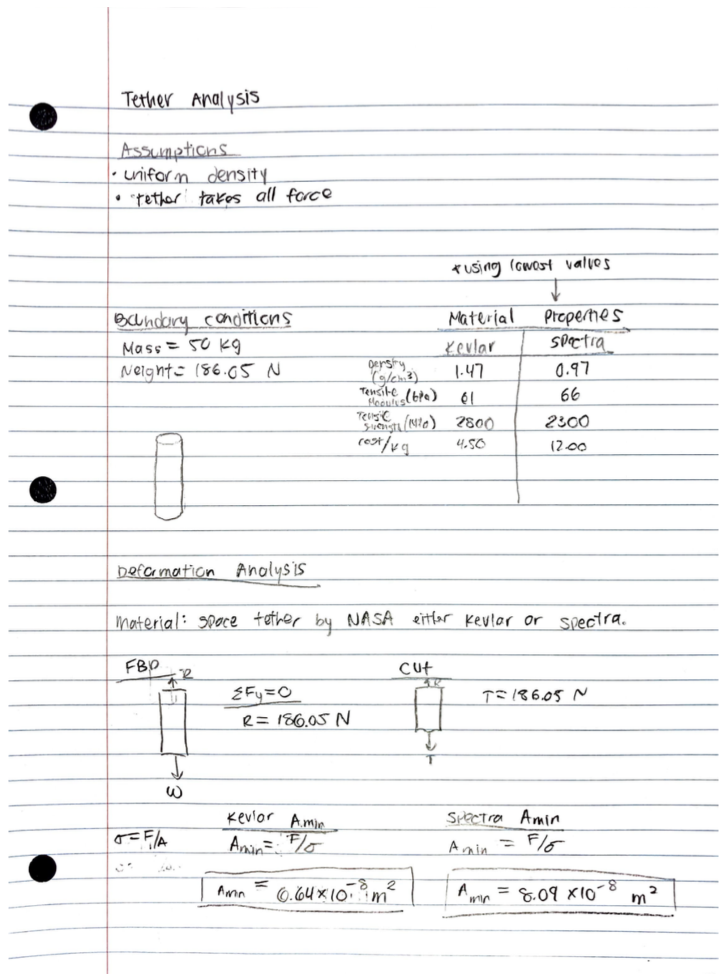


Figure 3.1.2.4. (Tether Analysis)

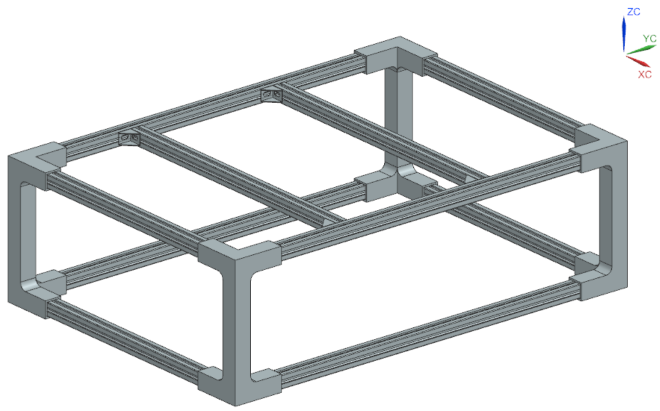


Figure 3.1.2.5. (Isometric View of Chassis Frame CAD)

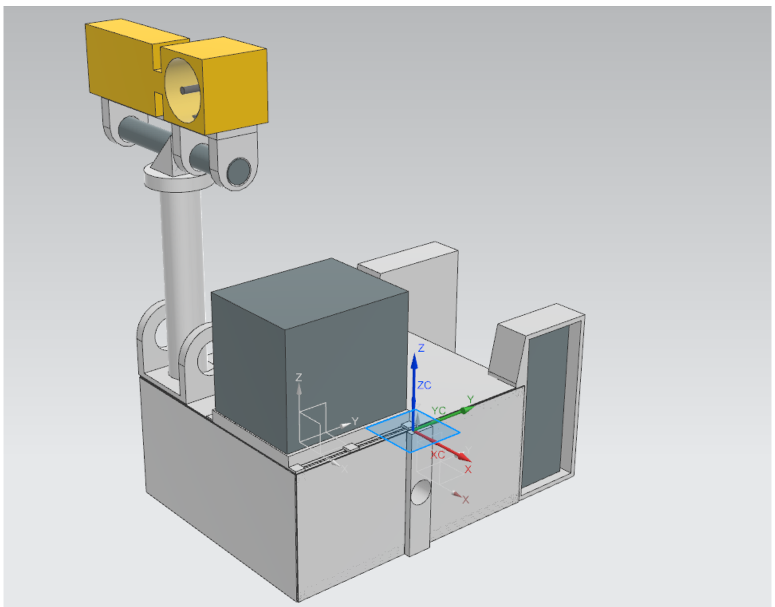


Figure 3.1.2.6. (Isometric View of Instrumentation CAD)

Descriptive Part Name	Info	R...	M..	Count	Reference Set	Mass (...	material
Sections							
chassisV2 (Order: Chronological)				55		23.22...	
Constraints				63			
tslot508L x 4					Model ("MODEL...	0.2465	Aluminum_6061
tslot497.2w x 4					Model ("MODEL...	0.2407	Aluminum_6061
corner bracket x 16					Model ("MODEL...	0.0026	Aluminum_6061
mountsuspen x 2					Model ("MODEL...	0.8892	Magnesium_Cast
tslot457.2 x 4					Model ("MODEL...	0.2194	Aluminum_6061
png					Model ("MODEL...	3.6059	Aluminum_6061
DEmount					Model ("MODEL...	4.3865	Aluminum_6061
mastmount					Model ("MODEL...	2.8853	Titanium_Alloy
panelbottom					Model ("MODEL...	1.5013	Aluminum_6061
backpanel					Model ("MODEL...	0.5590	Aluminum_6061
sidepanels x 4					Model ("MODEL...	0.3526	Aluminum_6061
topdeckpanel					Model ("MODEL...	1.1558	Aluminum_6061
frontpanel					Model ("MODEL...	0.7053	Aluminum_6061
pixlmount					Model ("MODEL...	2.3693	Titanium_Alloy
PIXL					Model ("MODEL...	0.0000	
TLS					Entire Part	0.0000	
bodyunitchemcam					Entire Part	0.0000	
chemCAM assem				7	Entire Part	0.0000	

Figure 3.1.2.7. (Assembly Manager)

The mass of the chassis plus the instrument mounts came out to be 23.22 kg and given only 50 kg, a way is needed to reduce weight either by changing parts or taking out a couple of instruments in order to have more mass available for the chassis, mounts, suspensions, and wheels.

T-slot aluminum extrusion is a fabrication that uses a t-shaped die. The unique t-shape allows for versatility of the material while maintaining the strength of aluminum. Since T-slots are extremely modular, they can be used easily to customize and build with. Leading manufacturers in the aluminum roll forming industry like Johnson Bros. Rolling Forming Co. can be used to manufacture the parts or can be manufactured in-house. Panels that cover the body and electronics can be manufactured in house and as well would be made of aluminum 6061. For the mounts, making them out of titanium is given the properties of the metal but the real difficulty with working with titanium is it's extremely difficult to work with in terms of machining. The inherent difficulty of the material meant simplifying the mount design to avoid breaking or damaging machining tools.

The wheels and suspension parts will be fabricated from stock material bought from Johnson Bros. Rolling Forming Co. and custom-made from in-house NASA centers like the NASA Sheet Metal Center. The aluminum tubes that connect in between each joint of the suspension are hollowed out to reduce mass, while maintaining the strength of the frame.

With regards to mechanical design, it is concluded that the suspension system would be the most likely to fail. As a result, hand calculations and analysis were done to prevent this from happening.

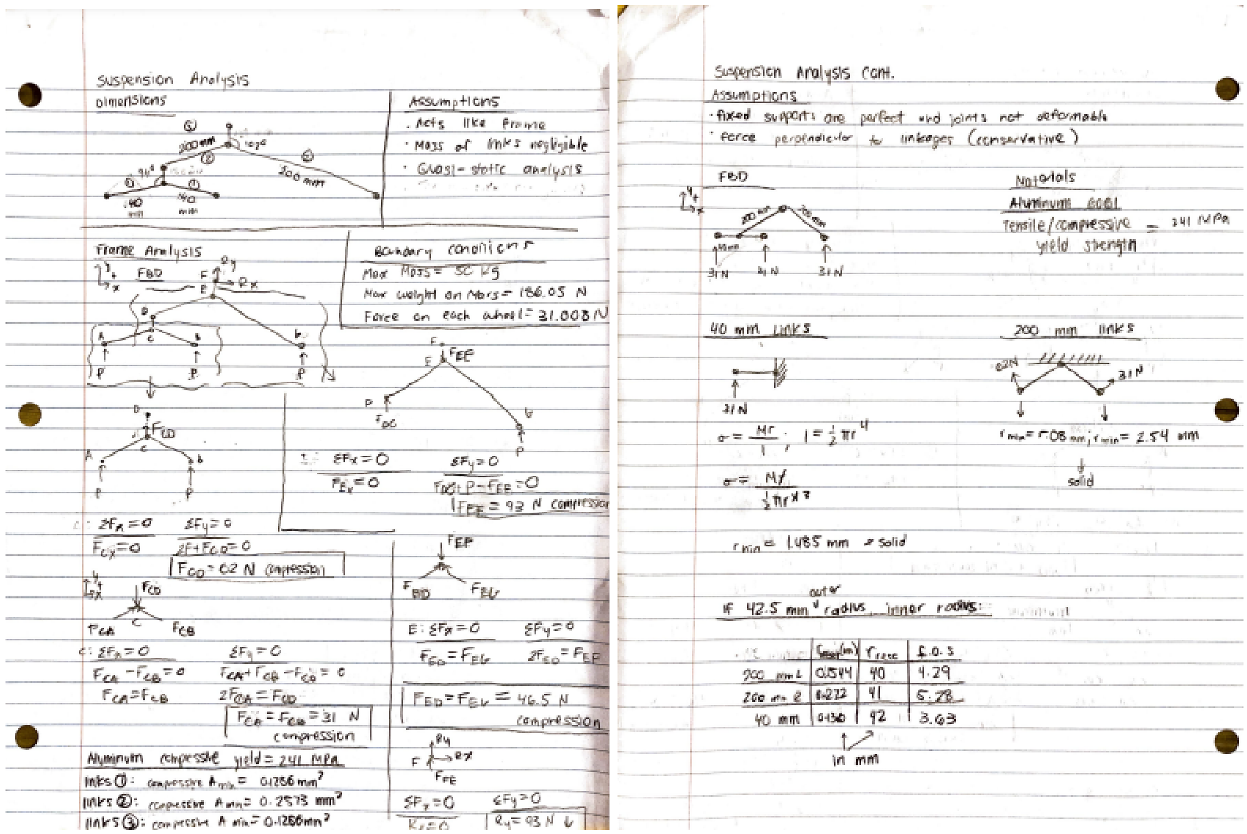


Figure 3.1.2.8.(Suspension Frame Analysis)

The rover is expected to move at a rate of 0.2 miles per hour inside the cave. As a result, it is concluded that the system could be analyzed as a quasi-static model. For simplification, the linkage structure of the suspension system is modeled as a basic truss structure, meaning that forces only act on the joints and the mass of the system is negligible. The reason for this is to get a broad idea of the forces in each of the joints and linkages. This would help determine which ones are the most vulnerable. With a force of 186.05 Newtons, the weight of the rover assuming max parameters, spread throughout the six wheels, it is determined that the linkage mounted directly to the chassis experienced the most force of 93 Newtons in compression. FEA analysis is done to get a more accurate display of the mechanics at play. It is important to understand that assumptions are made in this analysis much like the hand calculations. This is a static structural analysis, focusing on the weight of the rover. This means stresses caused by thermal effects and other forces are not accounted for.

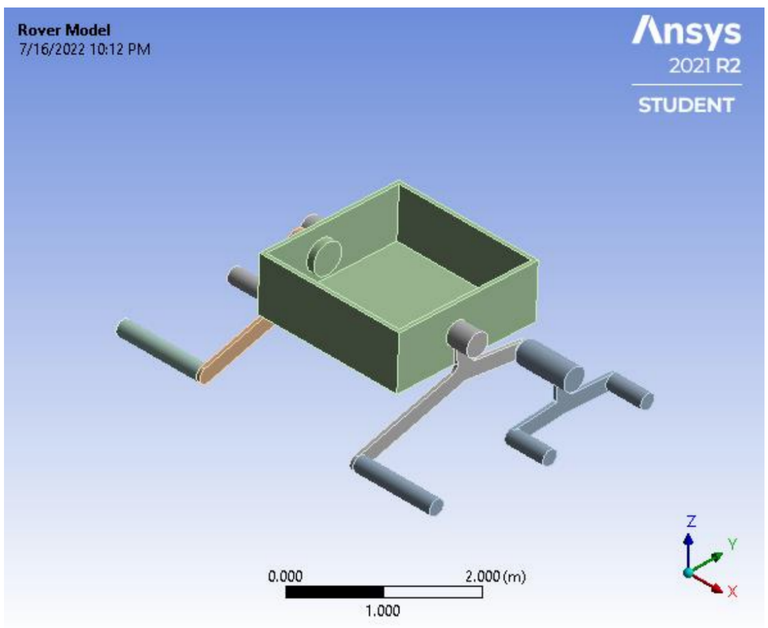
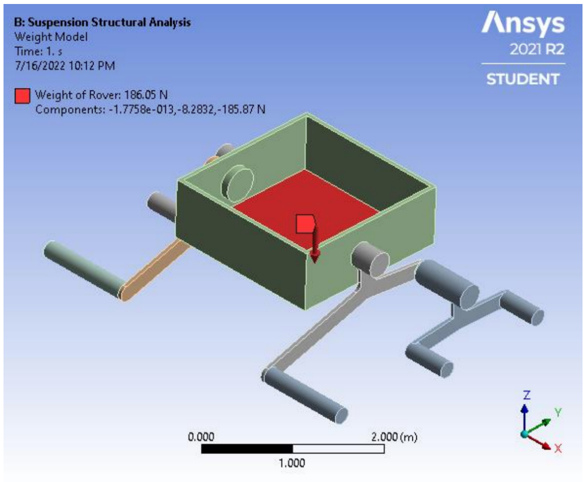
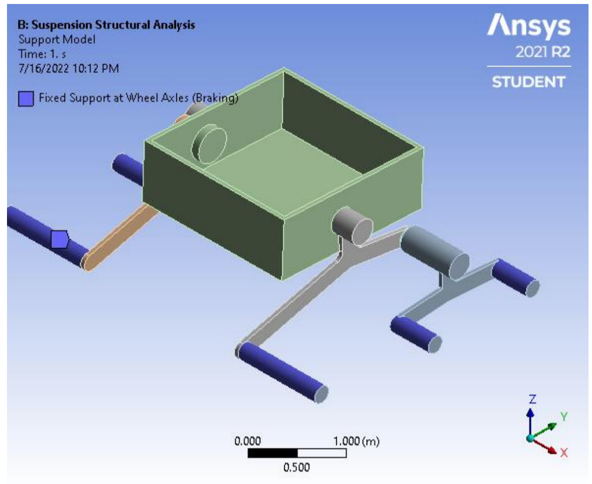


Figure 3.1.2.9. (Minimal Rover Model)

A minimal model of the rover is analyzed. The materials followed those used by NASA, which is aluminum 6061 for the chassis and titanium for the suspension linkages.





Figures 3.1.2.10. And 3.1.2.11. (Boundary Conditions)

The boundary conditions used in this analysis are the weight due to gravity on Mars and fixed supports on the wheel axles. The reason for the fixed supports on the axles is the assumption of the quasi-static model and active-braking of the rover.

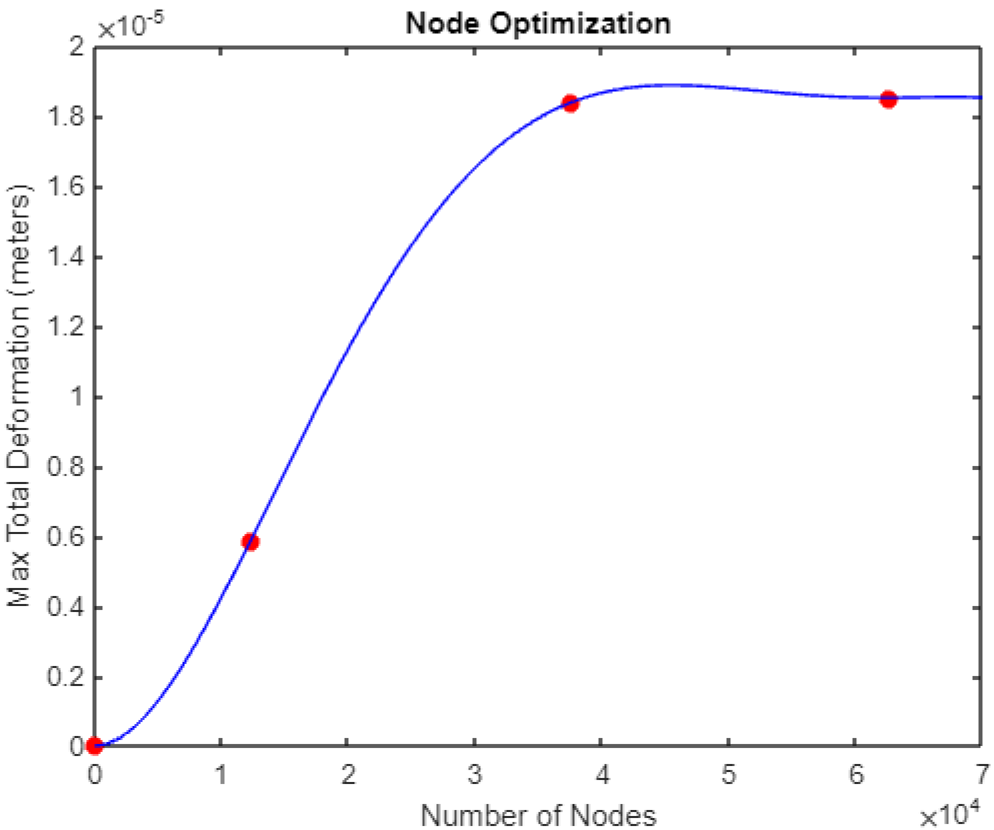


Figure 3.1.2.12. (Total Deformation Convergence based on Number of Nodes)

Three different mesh configurations are used to determine the convergence value of analysis. The point (0,0) is added because if there is no node, there is no deformation since no analysis occurs; this value should be undefined instead but zero is used for simplicity. Based on the image above, the total deformation converges towards 18 micrometers.

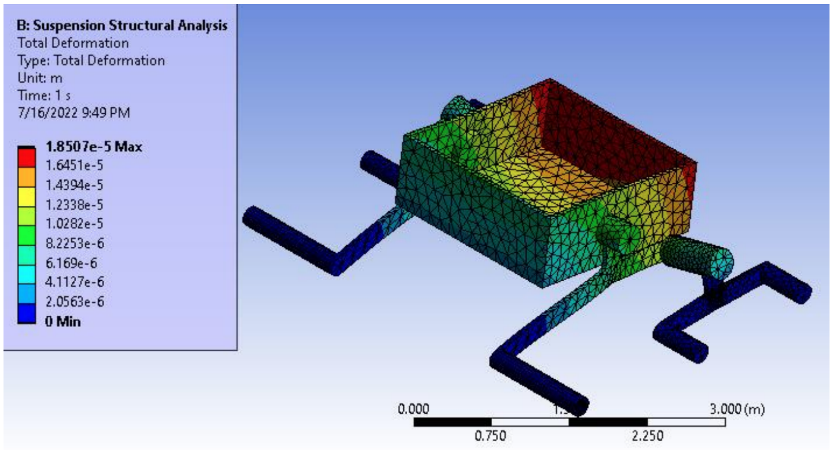


Figure 3.1.2.13. (Total Deformation Plot)

The image above is the plot of the total deformation. This is plotted as a verification step to ensure that the model acted as expected.

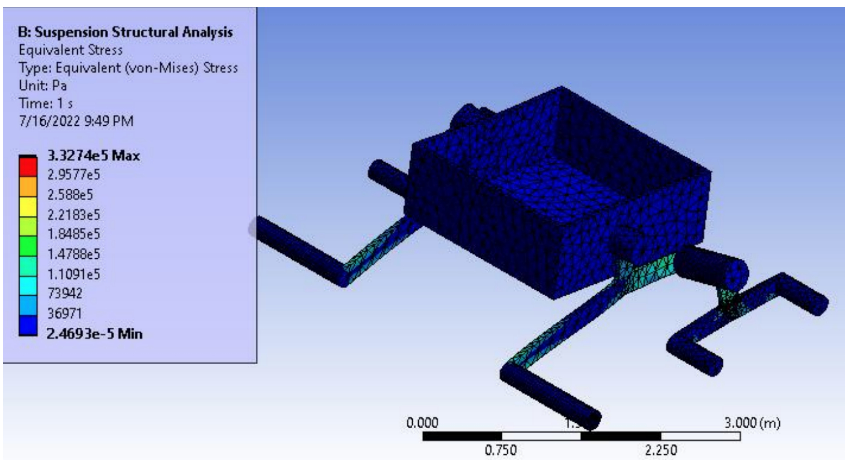


Figure 3.1.2.14. (von-Mises Stress)

The image above is the plot of the von-Mises stress. This is plotted to ensure the model would not fail in a quasi-static position. The max value of stress is 0.3 MPa which is under the yield stress for both aluminum 6061 (241 MPa) and titanium (240 MPa). As a final verification step, a reaction probe is created to determine the reactions at the fixed supports. The total reaction is 186.05 Newtons, which is expected since it has to be the same as the weight of the rover.

3.1.3 Power System Overview

The subsystems that require electrical power include the brushless motor system for turning and spinning the wheels, the instrument package, and communications and data handling subsystems. The electrical subsystem utilizes a 60ah lithium battery pack for storage; the estimated mass of the lithium battery pack is 3 kilograms, including the radioisotope heater unit (RHU) and insulation. A dedicated $1m^2$ surface solar panel, attached to the primary payload tether attachment on the surface, will collect power to recharge a battery pack. At this size, the surface solar panel can provide up to 140 watts over a 4-hour period surrounding local noontime. In order to transfer power to the rover itself, the tether is able to conduct electricity through a pair of copper wires. Lithium ion batteries were selected for the battery pack due to their high energy density relative to mass, at around 150Wh/kg. They are also heritage hardware, proven on the Martian surface on the Mars Exploration Rovers, Mars Science Laboratory and Mars 2020 missions. 28 volts, direct-current (VDC) is the bus voltage used on the system.

The approach to designing the power system is chosen due to the prohibitively high mass(45kg) and cost of a Multi-Mission Radioisotope Thermal Generator (MMRTG). Alternatively, batteries alone would have severely restricted the mission duration, and therefore the ability to achieve the state mission success criteria. Solar panels mounted directly on the rover would not be a viable power source, as there is limited to no solar irradiance within the cave.

Each subsystem has a given power budget. For the brushless motor system, power use shall not exceed 15 watt-hours(Wh). The instrument package has the highest power consumption at 61.8 watts, with all instruments operating. However, only the REMS instrument and the TLS will be constantly operating. The baseline power requirement for these systems shall not exceed 30 watt-hours. During noon hours, when the surface solar panel can provide peak power output, the instrument package will have a ‘surge’ power requirement of 61.8 watt-hours. Finally, the communications and data handling system has an around-the-clock requirement of 30 watt-hours.

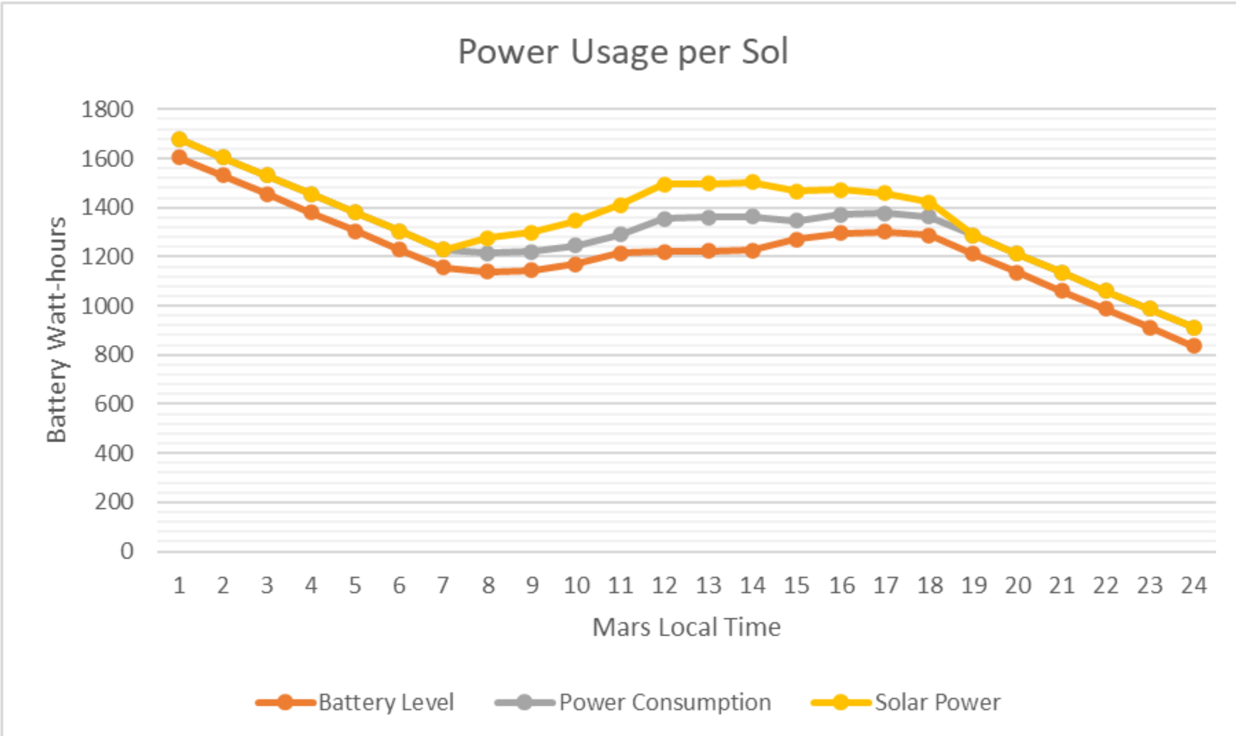


Figure 3.1.3.1 Power usage over time plot

For the power system, the components needed to be manufactured are the battery pack, and solar panels. The battery system consists of commercially available 18650 cells and will be manufactured in-house at NASA's JPL. Due to commercial readiness, time to manufacture is not of concern; and the cost of these battery cells is $5 each. The solar panels will be outsourced to a current NASA solar panel provider, SolAero. The estimated time is 6 months and the cost of these panels may be estimated up to $280,000. The components will be tested individually to ensure functionality. They will then be mounted to any mechanical components. Testing through detailed CAD models and assembly will be used to ensure that the parts fit together. The power system will integrate itself with different subsystems to test that the power system works with that particular subsystem. It will test mechanical, thermal, communications, etc. This is to ensure the isolation of different subsystems in case of any problems. Once all systems have been tested, the complete power system will be integrated.

3.1.4 Comms and Data Handling Overview

Communication with the earth base station will be completed by the primary payload's radio communication system. The primary payload communicates with the Earth base station directly over X-band (8-9Ghz frequency) and to Mars orbiter relays via UHF (400 mhz). Communications between the cave rover and the primary payload will be achieved utilizing a cable connection on the tether. The tether's communications connection is 100 meters of shielded twisted pair copper cable, utilizing the 10BaseT communications standard- also known as Ethernet. This will provide plenty of bandwidth for transmission of science data from the cave, and IP-based networking with the primary payload will allow error checking and redundancy. There is no radio communication system on the rover.

The computer system selected for this mission is the BAE Systems 5515 System-on-a-Chip (SoC), which is a radiation-hardened system ideal for space environments. The 5515 is a 64-bit single processor architecture, and allows communication with peripheral devices such as the instrument suite and battery charger controller over the SpaceWire bus and I2C. 256mb of dynamic, random-access memory (DRAM) will be utilized for each computer, along with 2 gigabytes of solid-state flash memory. All memory systems shall be error-checking code (ECC) type, allowing for error detection and correction (EDAC) functionality. Two redundant computer systems will ensure that the communication and data handling systems are always accessible by mission controllers on Earth. The power consumption for both computer systems shall be no more than 30 watts.

Software for the hardware will be written in C. Verification of the communication and data handling hardware will be conducted by the SoC manufacturer. Validation of the combined hardware and software package will be conducted utilizing hardware-in-the-loop (HITL) testing before integration into the vehicle for all-up testing.

3.1.5 Thermal Management System Overview

Maintaining a subsystem's temperature within the allowed limits in any space mission is a difficult challenge. Mars exploration rovers cannot function well under excessively hot or cold temperatures. The instruments that are crucial in achieving the scientific objective could usually withstand a temperature range from -20° Celsius to +30° Celsius [253K to 303K], but the functional range is narrower; the rover's essentials, such as ChemCam, have an operating temperature between -10° Celsius to 0° Celsius [263K to 273K]. With the exploration site's surface, CC0068, the temperature varies between -90° Celsius and +8° Celsius [183K to 281K]; the integral electronics must be kept in the required stable thermal condition in a Warm Electronics Box (WEB), commonly called the "rover body.". The thermal management system will be discussed in detail in this subsection, including a first-order heat flow map with hand calculation.

There are multiple ways of generating heat on Mars, heat as a byproduct of electronics, electrical heaters, and Radioisotope Heater Units (RHUs). The first two methods require electricity to produce heat. However, electric power is a precious commodity on Mars, and even more so during Martian night, when the rover relies solely on the batteries for power. The solar panels would power the necessary needs during the daytime while also storing the excess electrical power for thermal regulation during the nighttime. This, though, would not be able to sustain a prolonged mission lifetime due to degradation in the electrical holding capacity of the battery. RHU helps provide additional heat through radioactive decay. With a similar concept to radioisotope thermoelectric generators (RTG), RHU provides a constant 1 Watt of power per unit through Plutonium-238 with a half-life of 87 years. With its small size and weight of roughly 1x1.3 in and 34 grams, respectively, RHU helps reduce the electrical need from a battery while providing additional heat to the rover, thus expanding the landed mission lifetime.

With equal importance to heat generation, heat loss prevention aids in the retention of produced heat, thus reducing the power requirement to retain a stable temperature. AZ-3700-LSW Low Thermal Emittance, Electrostatic Dissipative Paint / Coating from AZ Technology was selected for its absorbance and emittance profile that satisfies the need of this mission. In addition, AZ-3700-LSW could be sprayed onto a surface with minimal difficulty without the need to use a primer so that it could be integrated early in the project. The target absorbance and emittance are decided from the amount of energy generated/required for the system and the temperature profile, heritage, and energy usage to minimize the power use during Martian night before selection. Also, to keep the electronics warm during the night time CO_2 insulation gaps could reduce parasitic heat loss. Due to weight efficiency, space between 5 cm is left, so, at mars, the mainly composed CO_2 atmosphere would fill this gap, offering a conductivity constant of only 0.01 at that low pressure which is comparable to aerogel. The calculation is demonstrated below.

Similar to Perseverance and MSL, the rover would employ a Heat Rejection System (HRS) using integrated pump assembly with Freon-11 as a working fluid. The HRS would regulate heat energy produced from RHU in cold conditions and a bypass in hot conditions. The heat rejection system comprises a pump and tubing that snakes across the rover to pick up the heat (including RHUs) and release the heat into the environment. This is a vital system since the rover would overheat from the internal RHU and power used to operate the rover. In contrast to those present in Perseverance and MSL, the system would not be able to double as a primary heater due to a lack of RTG to supply sufficient power. HRS would power accordingly when the temperature began to cool or heat up.

Many of the thermal designs used in the rover have been flight-proven through many successful flight missions. RHU has enabled many missions such as Apollo 11 and Voyager 1 & 2, CO_2 insulation and HRU demonstrated by Perseverance and MSL, and AZ-3700-LSW paint was used in space applications that are exposed to the deleterious effects of vehicle launch and space environment. These systems and components will be manufactured in-house at NASA's JPL. The paint will be provided by AZ technology. Each system will be tested individually to ensure functionality. CO_2 insulation gap size will be assessed using CFD and test samples of representative geometries in a CO_2-filled chamber to measure the thermal isolation. They will then be assembled with a refer cad model to ensure that it fits together. The subsystem then will be tested with other subsystems such as power and communication to confirm cohesion. Once done, the final thermal subsystem will be integrated into the rover.

Dimension: 0.4572m x 0.508m x 0.254m

A_1 = 0.4572m x 0.508m = 0.232m^2

A_2 = 0.4572m x 0.254m = 0.116m^2

A_3= 0.508m x 0.254m = 0.129m^2

Calculation:

AZ-3700-LSW | α = .22, ε = .33

Mars = 1.5 AU

q_{solar} = 1367/AU^2 W/m^2 = 607.6 W/m^2

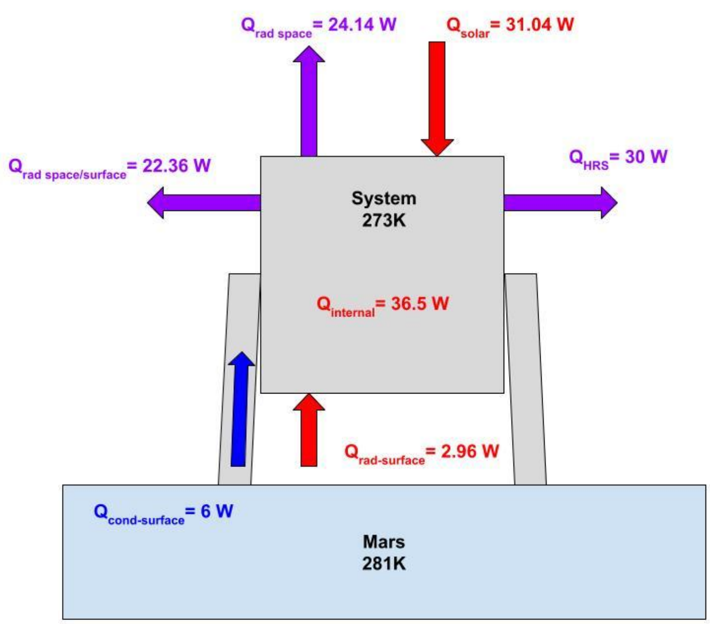


Figure 3.1.5.1 (Hot Case)

Hot case: [Surface(T_1) = 281K, System(T_2) = 273K, Space(T_3) = 3K]

$Q_{solar} = q_{solar}*A*\alpha = 31.04$ W

$Q_{internal}$ = 36.5 W

$Q_{rad\text{-}surface} = \varepsilon\sigma F A_1(T_1^4 - T_2^4) = 2.96$ W

$Q_{rad\ space} = \varepsilon\sigma F A_1(T_3^4 - T_2^4) = -24.14$ W

$Q_{rad\ space/surface} = 2*(0.5*Q_{rad\text{-}surface,A2}+0.5*Q_{rad\ space,A2}) + 2*(0.5*Q_{rad\text{-}surface,A3}+0.5*Q_{rad\ space,A3}) = -22.36$ W

$Q_{cond\text{-}surface} = 6$ W

$Q_{HRS} = -30$ W

$\sum Q_{in} = Q_{solar} + Q_{interna} + Q_{rad\text{-}surface} + Q_{cond\text{-}surface} = 76.5$ W

$\sum Q_{out} = Q_{rad\ space/surface} + Q_{rad\ space} + Q_{HRS} = 76.5$ W

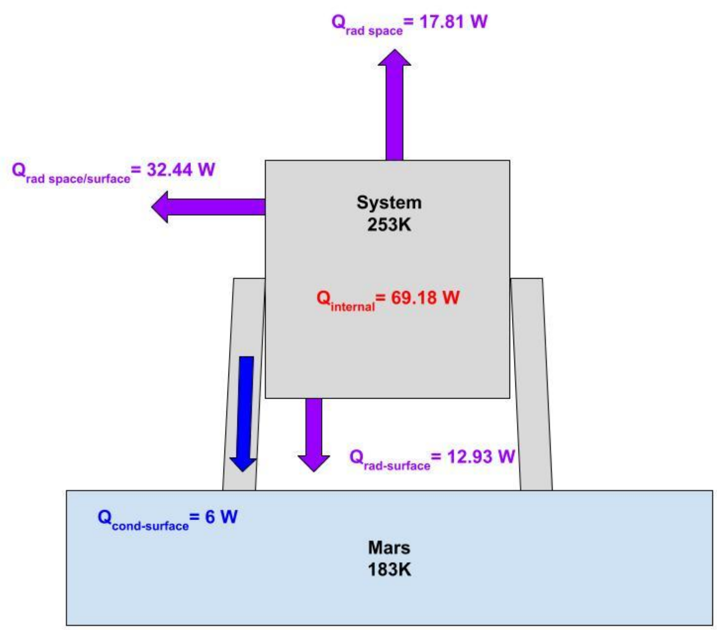


Figure 3.1.5.2 (Cold Case)

Cold case: [Surface(T_1) = 281K, System(T_2) = 273K, Space(T_3) = 3K]

$Q_{solar} = q_{solar}*A*\alpha = 0$ W

$Q_{internal} = 69.18$ W

$Q_{rad\text{-}surface} = \varepsilon\sigma F A_1(T_1^4 - T_2^4) = -12.93$ W

$Q_{rad\ space} = \varepsilon\sigma F A_1(T_3^4 - T_2^4) = -17.81$ W

$Q_{rad\ space/surface} = 2*(0.5*Q_{rad\text{-}surface,A2}+0.5*Q_{rad\ space,A2}) + 2*(0.5*Q_{rad\text{-}surface,A3}+0.5*Q_{rad\ space,A3}) =$ -32.44 W

$Q_{cond\text{-}surface} = -6$ W

$Q_{HRS} = 0$ W

$\sum Q_{in} = Q_{solar} + Q_{interna} + Q_{rad\text{-}surface} + Q_{cond\text{-}surface} = 69.18$ W

$\sum Q_{out} = Q_{rad\ space/surface} + Q_{rad\ space} + Q_{HRS} = 69.18$ W

3.1.6 FMEA and Risk Mitigation

Function: What system or function of the spacecraft or instrument is being considered?	**Failure Mode:** How might this does this function fail?	**Effects:** How might this failure affect the mission?	**Severity:** On a scale of 1(least) - 5(Most) how severe would the consequences of this failure be?	**Cause:** What might cause this failure to occur?	**Occurance:** On a scale of 1(least) - 5 (Most) how likely is it that this failure would occur?	**Prevention:** What methods can be used to prevent this failure from happening?	**Detection:** On a scale of 1(least) - 5 (Most) how easily could this failure be detected?	**Risk Priority Number:** This is the product of the Severity, Occurance, and Detection scores. The higher this number is, the most important it is.	**Actions:** What can be done if this failure continues?
Function	**Failure Mode**	**Effects**	**Sev**	**Cause**	**Occ**	**Prevention**	**Det**	**RPN**	**Actions**
The rover should be capable of traversing a cavernous terrain	Rover gets stuck in a hole	Rover is unable to move	2	Wheel diameter is too small and rover is unable to avoid the hole	2	Make wheel diameter bigger and improve software aspects	3	12	Increase wheel diameter
	Rover falls down a hole	Rover is potentially unable to move but most likely damaged	5	Rover is unable to avoid the hole	2	Improve software aspects	1	10	
	Rover is tipped over	Rover is likely permanently unable to move	3	Rover has too high of a center of mass or limit-switches fail to activate	2	Improve software aspects and reduce center of mass	4	24	Reduce the height of the center of mass
	Suspension system fails	Rover is likely permanently unable to move	3	Mechanical failure	1	Further analysis and testing	5	15	Do more analysis
The rover should receive power and communications from the primary lander	Power is not delivered	Rover is unable to function	5	Electricity generation, battery, or tether fails	3	Back up generator and electronics	3	45	
	Communicate data is lost	Rover is unable to send science data to Earth	5	Central processing unit, data storage unit, or tether fails	3	Back up electronics	3	45	
	Tether fails	Rover is unable to function	5	Tensile failure or cut by a rock	2	High factor of safety	2	20	Improve design

Figure 3.1.6.1. (FMEA Chart)

Risks	Mitigation
Rover gets stuck in a hole	Make wheel diameter bigger and improve software aspects
Rover falls down a hole	Improve software aspects
Rover is tipped over	Improve software aspects and reduce center of mass
Suspension system fails	Further analysis and testing
Power is not delivered	Back up generator and electronics
Communicate data is lost	Back up electronics
Tether fails	High factor of safety

The most significant risks that came to the rover were with regards to functionality. There is a lot of uncertainty when traversing unknown terrain like a cave. Some potential risks identified were getting stuck, falling in an unknown-depth hole, and tipping over. Due to the nature of uncertainty, mitigation protocols were to improve software capability through navigation and how the robot decides where to move. In a similar regard, the general power system also had some inherent risks. There were generic risks that could be solved with back-up components. The tether system was a component that had the largest amount of risk. Depth of the cave was unknown and the potential for tearing and jamming was evident. The proposed mitigation solution was to introduce a high factor of safety.

Martian Cave Exploration Risk Summary

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Robot gets stuck / tips over and is upside down or on its side	2	3	↓	W	The Robot has to be able to traverse the landscape within the cavern and recover in an unintended orientation. Wheeled rovers are not well suited to navigate through extremely rough terrain or access highly sloped surfaces anticipated to be present in subsurface environments. The rocker bogie suspension system allows the rover to prevent tilts of up to TBD degrees and allows for all six wheels to be in contact with the ground. Some instruments will still be able to function and collect data even if the rover cannot move.	Likelyhood from 3 to 2; Consequence from 4 to 3
2	Failure to deliver power to the robot	2	5	→	R	Robot has to be able to reliably acquire power source without readily available solar energy in the cavern environment. The inherent risk of the cable spool is entanglement with cavern terrain and weight. Also, since the nature of the cavern interior is unknown, it is impossible to know exactly how much longer the tether would have to be.	
3	Lost in communication	2	4	→	R	The method of communication is supported through redundancy. The Robot could transmit scientific findings through an antenna or spool cord linked.	
4	Robot fails to identify obstacle during auto navigation	3	3	↓	R	Robot has to be able to identify obstacles and navigate around unexplored terrain automatically. This risk is associated with Rover misidentifying obstructions and becoming lodged. Some instruments will still be able to function and collect data even if the rover cannot move.	Consequence from 4 to 3
5	Robot falls into a hole in the cave	2	3	↓	W	As the Robot is navigating the subsurface terrain, it is possible that it would fall into a hole that is not possible to circumvent through its mode of locomotion. The spooling cord serves as redundancy for recovery in this scenario. The robot is capable of passing over holes of two times the wheel diameter. Some instruments will still be able to function and collect data even if the rover cannot move.	Likelyhood from 3 to 2; Consequence from 4 to 3
6	Mechanical failure	1	3	↓	A	Robot is designed to cross cavern terrain based on cave entrance survey and earth equivalence environment. With uncertain cave formation, this Robot must be built to be sufficiently robust for unforeseen circumstances. Some instruments will still be able to function and collect data even if the rover cannot move. Heritage level makes chance of mechanical failure less likely.	Likelyhood from 2 to 1; Consequence from 4 to 3
7	Instrument failure	2	5	→	R	The Robot's instrument suite is not redundant; if the instrument is lost, Robot could not perform science with another instrument	
8	Crucial Robot components exceed allowable operating temperatures	3	4	→	R	Robot has to be able to withstand TBD temperature gradient from hoarfrost cavern entrance and possible thermal plume beyond the twilight zone. This temperature change will require an active system to keep the components within operating parameters or temperature resistive material that would function under those conditions. Research and mitigate.	
9	Spooling system jams or tether fails	2	3	↓	W	The spooling system has a possibility of jamming and the tether itself can be prone to tangling. In a cave system, the tether is used as not only a power and communications cable, but also as a life reel for the rover. The uncertainty of the depth of the cave, possible holes, and tangling on rocks makes it likely for failure of the tether system to occur. Analysis has been done to ensure the tether has a lower chance of failure. Some instruments will still be able to function and collect data even if the rover cannot move.	Likelyhood from 3 to 2; Consequence from 5 to 3

Figure 3.1.6.2. (Risk Summary)

The risk summary is a broad overview of potential risks during the mission. It includes some risks mentioned in the FMEA chart and some related to the science objectives. Over the course of the preliminary project life cycle, some of the risks were mitigated through engineering design. However, some were a lot harder to directly mitigate due to uncertainty. This can be seen in instrument failure and similar failures, where the only choice is to add back-up components which are not possible due to current weight constraints.

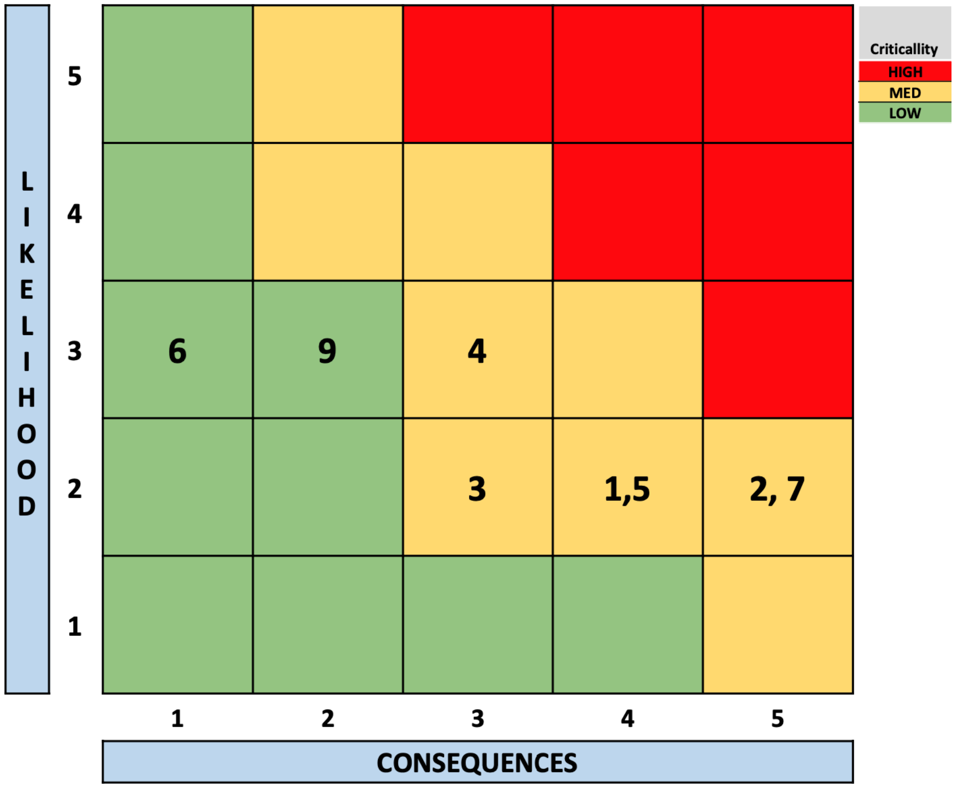


Figure 3.1.6.3. (Risk Matrix)

The risk matrix is to showcase the criticality of each risk detailed in the risk summary. Majority of the risk evaluations were conservative due to the level of uncertainty. As a result, most of the risks are in the medium criticality level.

3.1.7 Performance Characteristics and Predictions

The mechanical systems consist of a drive and chassis. The drive train is adopted from Jet Propulsion Laboratory's Perseverance therefore can carry the payload forward/background and left/right, while presenting a high heritage characteristic. Within the Martian caves, expectations are to see water-ice, specifically perennial hoarfrost formations along the ceiling and walls. On the ground will be a mixture of both the fallen ice-crystals and brittle rocky terrain. The derived challenges from driving over the cave's mixture of water-ice and rocky terrain is resolved by the size and traction of the wheels. Despite the inclusion of water-ice as an obstacle, the additional material does not impose any additional parameters that have not been designed on the adopted design. In addition, the suspension is nearly identical and the chassis utilizes a similar configuration. Further stress testing in the specific environment on Earth will prove that the mechanical system will work. Lithium ion battery packs have significant heritage on space missions to Mars, and have a very high TRL. Due to its high Technology Readiness Level (TRL), the rover will work in the cave environment.

Solar panels are of similar flight heritage, having been utilized on several past missions. The computer system chosen for this mission, the RAD5515, is the next generation in the line of RAD750 SoC computers. The RAD750 has a significant heritage in NASA exploration missions, having flown on all previous Mars landing missions since Mars Pathfinder in 1997. The RAD5515 has not flown to Mars yet; however, it is built to the same radiation-hardened principles as the RAD750. This system will be sufficient to operate on the Martian surface, and will be in a lower-radiation environment once inside the cave system, conducting the science mission.

The timeframe of the planned approach to the cave is primarily dictated by the arrival of the primary payload on the cave edge. With entry, descent and landing planned to occur in August 2025, cave deployment is assumed to occur in September 2025. In Martian terms, this is two months before the autumnal equinox of Mars year 38, and avoids the global dust storm season. This is critical for visibility on approach to the cave edge, and to ensure visibility within the cave; it is unknown at this time how dust storms affect the interior of Martian caves. At landing, the rover is expected to perform a number of heartbeat checks to ascertain functionality of instruments, communications, thermal control, and other subsystems. Once the checks pass, the rover will begin entering the cave and start collection of science data in the atmosphere. At the same time, the rover will be mapping the cave to avoid obstacles. The rover will continue to collect data and transmit this data to the primary payload via a tether cable that also provides power to the rover.

3.1.8 Confidence and Maturity of Design

At the beginning of the design process, a trade study was used to determine how the vehicle would move. The ideas compared are a wheeled rover, quadruped, tank, and hexapod. In the end, a wheeled rover was chosen to reduce complexity and higher levels of heritage. The mechanical design of the rover is influenced by NASA's previous Mars rovers like Perseverance and Curiosity. A static structural analysis is done on the suspension system to determine if it would be able to withstand its own weight on Mars. Structural analysis needs to be done on the chassis in order to prove that the rover's chassis can hold the 25 kg of instruments on board, but the chassis as well needs to be light in order to be within the constraints. The chassis has changed over time from being a simple box and taking that design and understanding that this is not the best way to design a chassis that only has about 25 kg to work with. The next CAD design for the chassis is to use 20 mm x 20mm aluminum T-slot extrusions to provide structural stability but most importantly reduce the weight of the overall chassis. Placing the

T-slots where they need to be is crucial to provide the strength and sturdiness of the chassis. The design of the chassis can be improved upon once the structural analysis is performed as well as if some instruments are taken off to give more mass to the chassis. The ongoing problem with the design is that only 25 kg are allocated to the chassis, suspension, and wheels. The fix would make the chassis smaller but the problem with that is that a risk of not being able to fit the instruments required will arise. Another solution to the mass problem could simply be taking out instruments. This can be accomplished by re-evaluating which instruments are necessary for the mission and doing this can help allocate more mass for the chassis, suspension, and wheels. There is a lot of confidence in the thermal system because this subsystem is more calculation-based and not as much design work compared to mechanical. In section 3.1.5, a hot and cold case was discussed in order to determine the most appropriate thermal design with regards to coating and more.

The TRL of the systems are higher up on the TRL as they are known to have worked on previous missions and are applied to the mission and constraints. The mechanical subsystems of the rover are influenced heavily by Perseverance. The design of the rover is very similar to Perseverance and the mission terrain will be similar to the obstacles that Perseverance will deal with. The chassis is similar but not quite the same as its predecessors, using T-slots instead of thick panels became the choice because of the mass constraint. The chassis on the TRL scale would be a 2-3 because it's inspired by previous rovers but not exactly the same. The suspension is nearly identical and the chassis utilizes a similar configuration. The power source of the system is not heritage as a tether that is attached to the rover to power everything on board. The communications system has a high TRL. Bus communication on the rover between computer elements and peripheral devices will be accomplished with proven standards that have flight heritage, such as I2C and Spacewire. Other standards such as the Ethernet protocol for communication to the primary payload have significant commercial use in harsh environments on Earth.

3.2 Recover/Redundancy System

For communication, electronics, and thermal systems on the rover, redundancy will be assured by identical backups. As an example, two redundant computer systems will ensure that the communication and data handling systems are always accessible by mission controllers on Earth. Physical components which cannot have redundancy, such as the structure or wheels, will be made to have a margin of safety of 1.5. Some physical components which can have redundancy, such as the suspension and electronic motors, will have redundant systems according to mass limits.

In the event the Rover becomes caught in the terrain of the cave, such as a hole, it will be unable to move and result in a risk to mission completion. This could be caused by the wheel diameter being too small resulting in low traction and causing the rover to be susceptible to difficult terrain. Therefore, the wheel diameter will be made large enough to overcome these conditions, and traction control will be completed through the software of the rover. If the Rover falls down a hole, this may cause the rover to be unable to move and cause damage to components of the system. To mitigate this, the height of the Rover will be designed to produce a low center of mass capable of overcoming the terrain. Software will also be utilized for traction control and to optimize the center of mass while the Rover moves through the terrain.

Power system redundancy is achieved through implementing a cross-connection with the primary payload. In the event that power is lost from the solar panel, electrical power for resetting power electronics can be obtained from the primary payload's power system. Communications redundancy exists through redundant TX/RX multiplexers for the Ethernet connection between the primary payload and the rover. The shielded twisted pair cable on the tether itself is a single-point-of-failure item, but will be shielded from damage and abrasion by the tether material itself. A failure of the tether will result in the Rover being unable to function and will result in a mission failure. This could be caused by tensile failure as the rover moves or due to an alien object cutting the tether, and will be mitigated through a margin of safety of 1.5.

3.3 Payload Integration

5 science instruments have been selected for the rover. The first instrument on the list is the PIXL with a total mass of 7 kg. Since the rover does not have a robotic arm to attach the PIXL, it is required to mount the PIXL at the front end of the rover. The second instrument is the TLS, which is going to be inside the chassis of the rover. The last two instruments are the ChemCam and REMS tool. The Chemcam instrument has two parts: a mast package and a body unit. The mast package and the REMS tool are both mounted on the rover mast on the rover top deck, the ChemCam mast package

sitting on top of the rover mast and the REMS tools that contain two booms, which are on the sides of the rover mast and are located 38 and 43 cm above the rover deck.The two booms are separated in azimuth by 120 degrees to help insure that at least one of them will record clean wind data for any given wind direction. The ChemCam body unit is inside of the chassis.

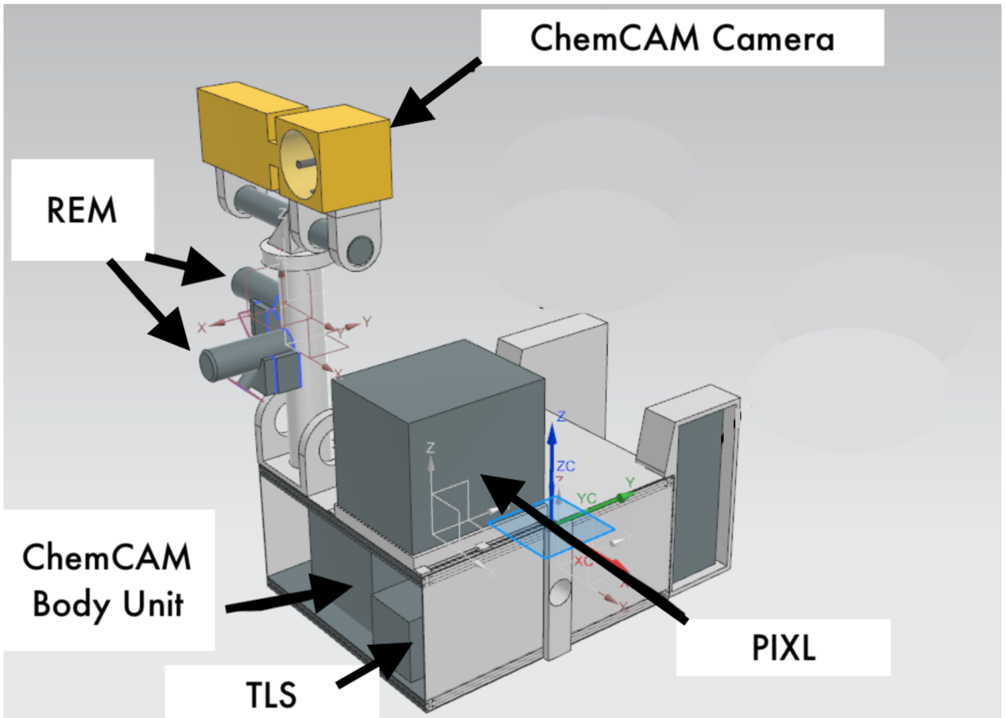


Figure 3.3.1. (Labeled Instruments)

Section 4: Payload Design and Science Instrumentation

4.1 Selection, Design, and Verification

4.1.1 System Overview

The rovers power subsystem powers the instrumentation of the rover along with communications, thermal control, and command and data handling. Once all of the instrumentation is powered, different types of data are gathered by every instrument. PIXL is also a part of a mechanical arm component which is being controlled by the command and data handling subsystem. All data gathered is stored within that same system. When data is ready to be sent out, the communications subsystem, which transmits and receives data, sends out the data gathered from the instruments. All while this is happening, the thermal subsystem keeps the temperature of all subsystems from over heating and cooling.

The power system is responsible for all electric needs of any of the subsystems on the rover. This is why on Figure 4.1.1.1. It shows that it is responsible for every subsystem. The second most important subsystem is thermal control. While all of the subsystems are running from power, the thermal control keeps subsystems from overheating and prevents subsystems from being too cold to operate. The next subsystem is the communication system. This provides feedback from the rover itself back to the primary payload and vice versa. Communications and data handling go hand in hand because the data that the communication subsystem sends out comms from processed data from the data handling subsystem. Data handling itself also goes hand in hand with instrumentation. This is because the readings from the instruments are recorded and given to the data handling subsystem. Once the data is taken, the robot is prompted to move to the next point to collect more data and the process continues.

In figure 4.1.1.2. which is an instruments system block diagram shows how power (shown in yellow) is distributed to all the systems that being communications, thermal, data handling and the instrument suite. Then, thermal connects to the communications processor module, data storage unit, central processing unit, and all the instruments in the instrument suite. Meanwhile, communications provides information to data handling which then processes data. Data handling provides data to communications, provides data collection to the instrument suite, and processes data for thermal and power. The diagram also shows how PIXL and REMS will have an arm.

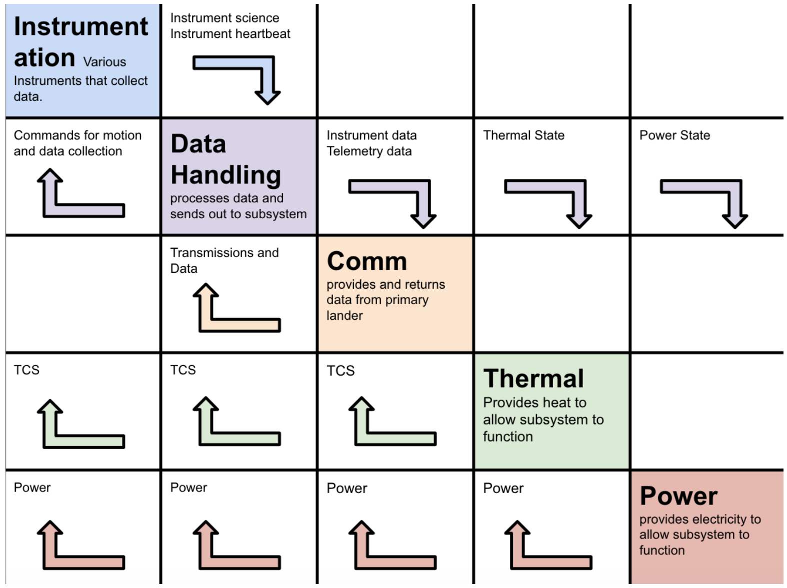


Figure 4.1.1.1.(Instruments N^2 Chart)

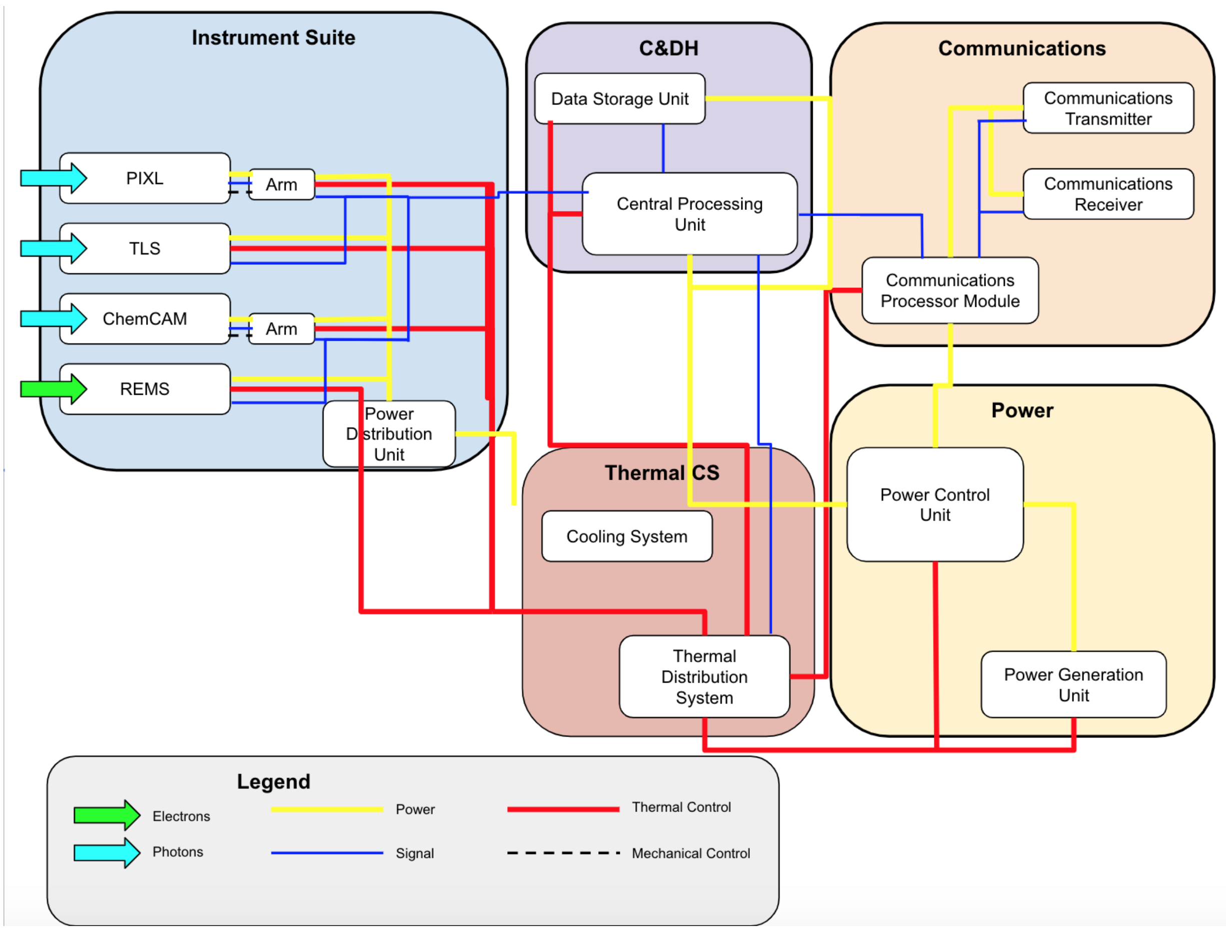


Figure 4.1.1.2. (Instruments System Block Diagram)

4.1.2. Subsystem Overview

The tools of the mission work in conjunction with each other to identify the composition of the top of the cave, the atmosphere of the cave, and the soil in the cave. In the case of ice crystals and hoarfrost, Chemcam will be able to recognize this. Chemcam, weighing in at 10kg using 11.8W of power, operates by being positioned at most 7 meters away from its target, and firing a laser from its mast portion. The body portion of Chemcam analyzes the wavelengths of light emitted to classify what it is looking at. For the atmosphere of the cave, two tools will be used. The Rover Environmental Monitoring Station, using 5 watts power, contains two booms. Boom 1, weighing 154 grams, tracks temperature and wind sensors. Boom 2, weighing 147 grams, tracks humidity and more wind sensors. Both booms have air temperature sensors. Data is recorded every 5 minutes. The other instrument, the Tunable Laser Spectrometer, weighing 3.7 kg and using at maximum 25W, is capable of measuring water vapor, and is going to be the main instrument in measuring methane. It does this by capturing sample gas, passing a laser through the sample 81 times and detecting the wavelength of the sample. The tools analyzing the ground of the cave are PIXL, as well as Chemcam. PIXL, weighing 7.015 kg using 25W, shoots a small X-ray to analyze other elements in the ground that are necessary for life.

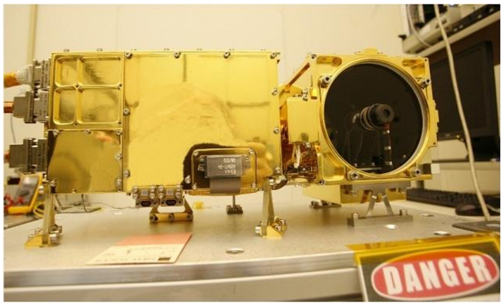


Figure 4.1.2.1. (ChemCAM)

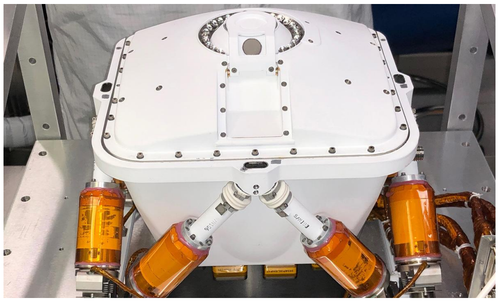


Figure 4.1.2.2. (PIXL)

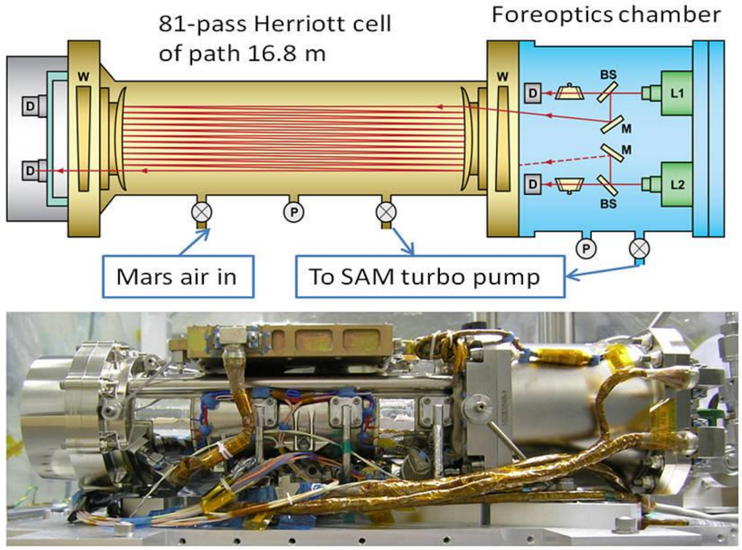


Figure 4.1.2.3. (TSL)

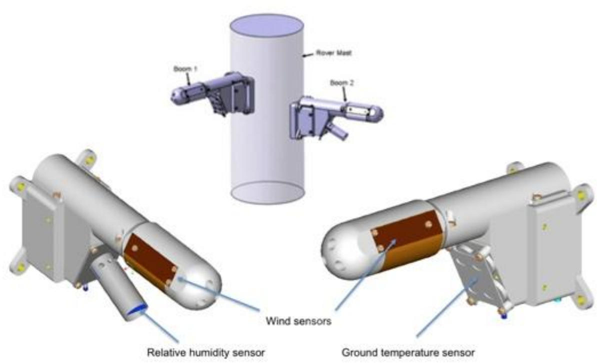


Figure 4.1.2.4. (REMS)

4.1.3. Manufacturing Plan

All of the tools on the robot have been to Mars, a majority of them on Curiosity. Chemcam was developed by a U.S.-French team from Los Alamos National Laboratory and the French government space agency. PIXL, the Planetary Instrument for X-ray Lithochemistry, is the only tool not on Curiosity, being on Perseverance instead. It was built by NASA’s Jet Propulsion Laboratory (JPL). The Tunable Laser Spectrometer was also built by JPL. Finally the Rover Environmental Monitoring Station was run by the Spanish Astrobiological Center and helped by the Finnish Meteorological Institute.

Two out of the four instruments can be built in house by NASA, these tools being PIXL, and the TLS. Creation of the REMS tool will be outsourced once again to the Spanish Astrobiological Center because of their experience and expertise in creating weather data gathering tools. Chemcam will be outsourced to the Los Alamos National Laboratory, but just as in the past, JPL will be a large part of the process. JPL will handle manufactoringPIXL and the TLS. The robot will be assembled and tested at the Jet Propulsion Laboratory making it easier for tools to be integrated and tested within JPL's Mars Yard.

PIXL and TLS' quicker manufacturing time allows for integration to happen first and is not affecting the timeline of the mission. Because of Chemcam's creation with two entities, margin time could be used in the development of it. REMS is the hardest tool to integrate because of the instruments outsourcing to a far away organization. Emphasis of REMS will be high, and margin is necessary for the creation of this weather tool. Because of its distance, REMS will be a priority on integrating with the robot. Next, Chemcam will be assembled, followed by the TLS, and PIXL. Delivery will take 30 days with integration of each tool taking 45 days.

4.1.4. Verification and Validation Plan

PIXL: Planetary Instrument for X-Ray Lithochemistry

- PIXL is an instrument that provides a deeper insight into ancient life. On PIXL, it has a tool called the X-ray spectrometer which identifies the chemical makeup of rocks at a very fine scale. A camera also resides on the instrument that takes up close images of different rocks and soil on the Martian caves. One of the objectives is to find signs of past life on Mars and this tool can do that with discovering microbial life. PIXL could detect even the smallest amount in parts per million with the 120 μm diameter X-ray beam of chemical fingerprints on rocks and could point out the exact spot it resides. PIXL is tested by using its camera to identify the chemicals it is capable of recognizing. For the mission the most important ones will be Phosphorus(P), and Sulfur(S). The camera is tested at incremental short distances. Speed is also tested to see how fast chemicals can be identified. Testing will be done by moving a sample to PIXLs sight and timing its speed from a distance of either P or S. They alternate 25 times at that distance then move an increment further.

TLS: Tunable Laser Spectrometer

- TLS will undergo a series of tests with different concentrations of methane, carbon dioxide, and water vapor. The goal of the mission is to look for concentrations of methane and water vapor within the caves of Mars, and TLS does just that. It uses different wavelengths of light to identify isotopes within an atmospheric sample and based on the wavelength used and the pressure within the environment can determine how much of a substance is in the sample. The testing will be done by saturating the atmosphere within a sealed box/room with the desired substance and then remotely activating TLS to collect the atmospheric sample and running the appropriate tests on the sample. Records will look a bit different on Earth based on the radiation and pressure differences and will need to be accounted for.

Chemcam: Chemistry and Camera

➢ Chemcam's distance accuracy will be tested through a series of trials less than or equal to 7 meters. Chemcam's test will also be to detect elements. The elements being tested will be Na, Mg, Al, Si, Ca, K, Ti, Mn, Fe, H, C, O, Li, Sr, Ba, S, N, P, Be, Ni, Zr, Zn, Cu, Rb, and Cs. The accuracy of distinguishing the elements will be recorded.

REMS: Rover Environmental Monitoring Station

➢ REMS will provide reports about the atmospheric pressure, atmospheric humidity, radiation, air temperature, and the ground temperature surrounding the rover. REMS will be able to provide this data based on the two booms it contains. Boom 1 mainly focuses on the temperature. For example, Boom 1 can measure the radiation being released by the ground, which is how the instrument estimates the ground temperature. Meanwhile, Boom 2 mainly focuses on atmospheric humidity. Both Booms are able to measure air temperature based on the sensors they have. REMS will do different tunnel tests and numerical analysis.

4.1.5. FMEA and Risk Mitigation

Function	Failure Mode	Effects	Sev	Cause	Occ	Prevention	Det	RPN	Actions
Heaters in all instruments	Not enough energy being reached through the rover in order to reach the instruments	The data that is needed will not delivered and slow down the process of collecting that data	70	Having too little energy reaching the instrument	30	Providing enough energy to the instrument	80	168000	In the occasion that this failure continues, waiting for enough energy to be reached or relying on another instrument could be a solution.
	Having too much energy reaching to the instruments that it overheats them	The data needed will not be collected	70	Having too much energy reaching the instrument	30	Not over providing energy to the instrument	80	168000	In the occasion that this failure continues, there is a possibility that relying on a different instrument might be a better solution to provide that data.
Damage on outer instruments caused by terrain or cave walls	Instruments not being to be at its fullest potential to provide data needed	The data needed will not be collect this including methane or elements inferring that there is a probability of life	75	Failure to detect the cave wall	25	Using other instruments capabilities to detect the cave walls and avoid damaging the instruments	90	168750	In the occasion that this failure continues, there will be a limited amount of data to be collected depending on how damaged the instruments become
	Damage towards instruments fail to provide information	Data can still be collected but will not get to a greater understanding to that of our science goal	75	Failure to detect surroundings on ground like large rocks	23	Using other instruments capabilities to detect surroundings before moving forwards	90	155250	Potentially, staying in place until further actions and analyzation of the terrain can be detected to avoid the large rocks
Wires in instruments become heated/damaged	The special material that protects the wires gets damaged	Damaged wires can affect the instruments capabilities to collect data	90	Damage to instrument wires can occur when rover collides with cave land or walls multiple times	20	Detection of instrument surroundings	90	162000	In case this failure continues, the other instruments on the rover will help with the surrounding detection and data
	Heated wires cause a failure in the circuit	A failure to the circuit can cause the damage of using that instrument to its fullest capabilities	90	Too much heat causing the wires to heat up and melt	20	Not over heating the instrument so the wires will not cause a circuit fail	85	153000	If this failure continues, to keep the well being of the rover and its entirety the instrument might have to stop providing more or certain data
The Booms on REMS stop functioning	Boom 1 interacts with the cave wall	Boom 1 will not measure infared radiation from ground to estimate the temperature of the ground	85	Not properly aware of Boom 1 surroundings	35	Use other instruments to know surroundings	85	252875	In case Boom 1 is not available to funaction use Boom 2
	Boom 2 interacts with the ca	Boom 2 will not be able to trail atmospheric humidity	85	Not properly aware of Boom 2 surroundings	35	Use other instruments to detect surroundings	85	252875	In case Boom 2 is not available to funaction use Boom 1
Instruments start failing to provide X-rays in PIXL	The laser for the X-rays stops functioning	Without the laser it would be more difficult to fully understand the entirety of the object	80	Not enough power or too little power going towards the laser	20	Checking temperature ito see if it is just right for the instrument parts to function properly before proceeding	75	120000	If the failure continues, rely on the camera on instrument to continue the data.
	The camera stops calculating the distance from the object of interest to investigate	Without knowledge of the distance of the object, moving the rover forwards will need to be slower	80	A wire malfunction can occur	20	Making sure the wires are still intact	75	120000	Actions needed could be relying on the laser for the information needed to calculate distance of the object
Instrument not being able to detect chemicals of main goal of interest in Chemcam	The laser beam stops functioning	The laser beams will not illuminate the area in order to provide a visual of that area	85	The photons in light waves are not moving at the same wavelength or speed	15	Making sure the photons are moving at the same speed and wavelength	80	102000	Figure out at what wavelength and speed the photons are moving, if not much is found rely on spectrographs or other instrument cameras
	The spectrographs stop functioning	Spectrographs will not be able to divide plasma light for analyzation of chemicals	85	The light going towards the spectrograph cannot disperse into a spectrum	15	Analyzing to see if the light disperses into a spectrum	80	102000	Rely on camera and laser beam for potential images of the chemicals

Figure 4.1.5.1. (Instrument FMEA Chart)

ID	Summary	L	C	Trend	Approach	Risk Statement	Status
1	Instruments not being able to heat to proper temperature in order for the instrument to function	3	4	NEW	M	The instruments have to heat or cool down at certain temperatures in order to properly collect data that can consist of temperature, radiation, methane etc. The risk of an instrument not being able to reach certain temperatures can potentially mean that the instrument will take longer to process the data or the need to start to rely on another instrument for that data.	
2	Outer instruments get damaged by cave wall or terrain interaction	2	4	NEW	M	In order for the outer instruments to provide, collect, and analyze the best results and data it is preferred that the outer instruments are intact. The likelihood of the risk is low but if the outer instruments do get damaged it can very hurtful to the mission since there is a possibility that the instrument can no longer provide all the information it once could.	
3	Wires in instruments become heated which causes a false in electrical circuit	2	5	NEW	M	Wires in the instruments are essentially what keeps them going and functioning in order to collect energy, data, move, etc. The risk of these wires becoming heated in the instruments can possibly lead to them having an electrical circuit that may cause certain characteristics of that instrument to stop functioning.	
4	Outer instruments get damaged by large ceiling cave debris	3	4	NEW	M	Since the cave CC0068 is unfamiliar terrain there could be surprises along the way like cave debris which can impact the state and well being of each instrument on the rover.	
5	Instruments start failing to provide X-rays	2	4	NEW	M	X-rays are used to investigate the ground.This risk would limit the capability of analyzing the ground and looking for potential water evidence as well as particles that are essential for the probability of life.	
6	Instrument sensors not being able to determine/detect areas with soil, rocks, chemicals in order to provide examinations and data	2	4	NEW	M	Instrument sensors are key to this mission since they detect areas with soil and chemicals like methane to provide data towards our mission goal. This risk would cause data seeked to not be collected but the instruments can still collect data but it would not be centered towards information that is being needed.	

L = Likelihood (1-5)	LxC Trend	Approach	Criticality
1 = not likely	↓ - Decreasing (improving)	A - accept	HIGH
5 = extremely likely	↑ - increasing (worsening)	M- mitigate	MED
C = Consequence (1-5)	→ - unchanged	W - watch	LOW
1 = low consequence	NEW - added this month	R - research	

Figure 4.1.5.2. (Instrument Risk Summary)

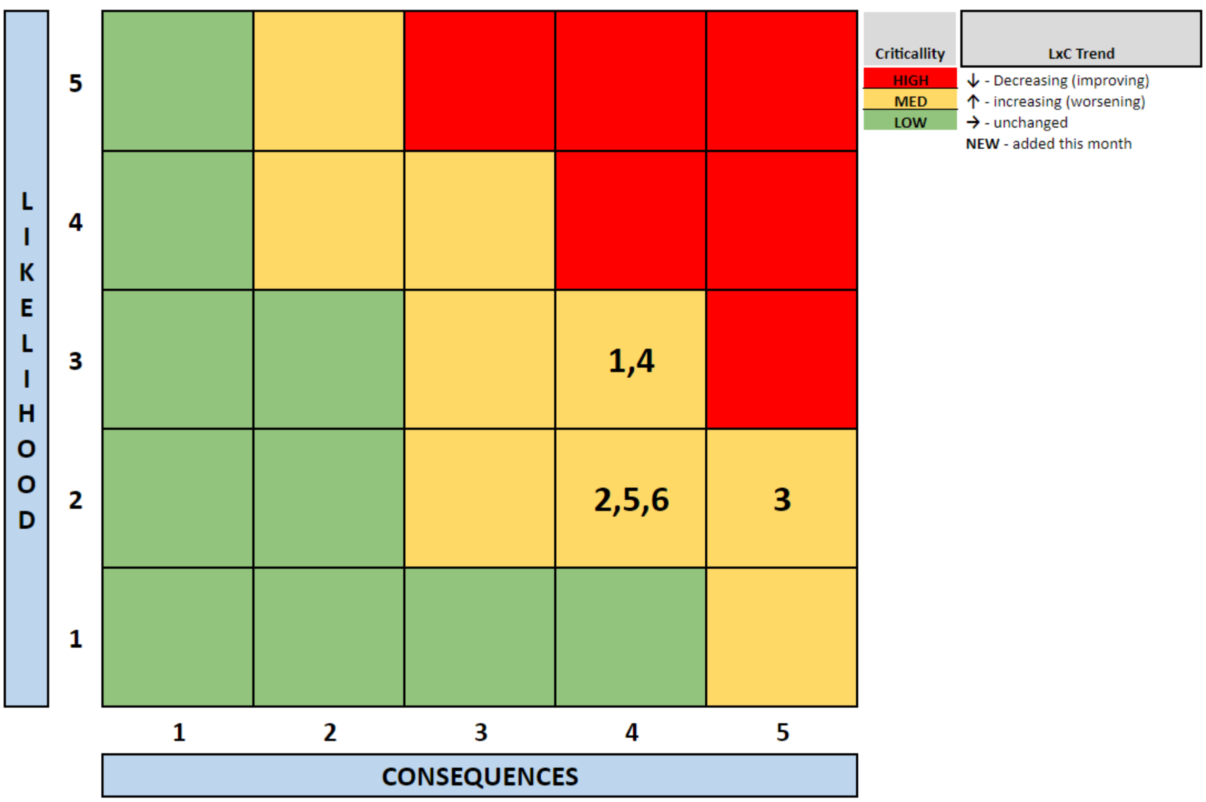


Figure 4.1.5.3.(Instrument Risk Matrix)

After research and in the event that any failure occurs to the instruments or instrument capabilities, there is still an ability of providing data about the rocks, methane, atmospheric temperatures. This is because if one instrument fails another instrument on the rover can still collect samples, it may not be very in depth but the data collected would give an idea of what is going on. Also, if damage occurs to the rover to the point it cannot move the instruments can still collect data where the rover is located without any movement. If this failure becomes a reality certain instruments would not be able to further collect data more inside of the cave and will limit information based on the science objective of finding evidence of water, and the probability of life.

4.1.6. Performance Characteristics

The vehicle will be arriving at cave CC0068 in August of 2025. During this time frame the seasonal temperatures outside the cave will be close to being in between summer and autumn temperatures. These temperatures can range from -15 C to -70 C. To visualize it in a Farenheit perspective, these temperatures would range from 0 F to -100 F.

In the sensory assembly on PIXL, it has the High Voltage Power Supply (HVPS) which contains the High Voltage Multiplier Module (HVMM) and the Low Voltage Control Module (LVCM). On the sensory assembly on PIXL, there are heaters that constantly cycle to keep the HVMM at its regular temperature. Which is essential since the high and low temperatures on Mars can affect these sensors which detect and produce X-rays for the science measurements PIXL obtains.

In order for the ASIC to function properly for the ground temperature sensor in REMS, it must survive temperatures of -130 C to 70 C and minimize its power consumption. In order for it to function properly, there is a Boom’s ASIC heater that switches on to start operating. Then, when the temperature gets to -50 C it turns off and if the temperature is not at operating temperature, the operation will be delayed until otherwise.

Because all of the tools on the rover are heritage, they are already equipped with working thermal insulation that protects the instruments from the extremities of the Martian temperatures.

4.2 Science Value

4.2.1. Science Payload Objectives

The science instrumentation is to reflect the science goals, and must find data based on those objectives/goals. PIXL should show that there is a presence of Calcium Carbonate, Calcium Sulfate and Sodium Chloride within the soils inside of CC0068. Which can be used to identify areas that may have had water concentration. ChemCam should show that there are certain elemental properties within water-ice found within CC0068 and these concentrations are going to be used to determine if biological life had/is present. TLS should analyze the martian atmosphere for methane concentrations and for water vapor within the caves of CC0068. Methane is a byproduct of many living systems. REMS should provide measurements of surface temperature, wind speeds, atmospheric pressure and air temperature. Determining the atmospheric characteristics will help when analyzing other sets of data.

4.2.2. Science Traceability Matrix

Science Goals	Science Objectives	Science Measurement Requirements		Instrument Performance Requirements		Instrument	Mission Requirements
		Physical Parameters	Observables				
Do Martian caves present past or present evidence of life or demonstrate habitibility for any life?	Measure and map water evidence within the Martian caves	Identify ice and minerals with water molecules in their crystal structures	Detect Hoarfroast formation	Distance from subject	<7 meters	ChemCam	Determine the percent abundance of water ice within the Martian cave
			Detects fallen ice crystals	Size of laser	1 mm		
	Determine the existence of biological molecules within water-ice within the Martian Caves.	Identify key elemnts for life in particular, Hydrogen (H), Nitrogen (N), Carbon (C), Oxygen (O), Phosphorous (P), and Sulfur (S).	Detect materials within the 2 - 535 Dalton range	Pixel Resolution	1024 x 1024 CCD		viability of human habitation in the radiation environment within the
				Wavelength Range:	240 - 850 nm		
			Collect elemental composition of regolith up to 10's ppm level	Beam Diameter	0.12 mm	Planetary Instrument for X-ray Lithochemstry (PIXL)	
				Measurement of elements	0.5 wt%		
	Determine the atmospheric patterns and methane concentration within the Martian caves.	Identify the methane gas concentration at various depths	Detect concentrations of methane gas in ppbv	Spatial Resolution	~ 2 - 10 um	Tunable Laser Spectrometer (TLS)	System shall collect data on atmospheric samples within the cave.
				Instrument Performance Req. Parameter 10	Instrument Performance Req. Value 10		
		Measure atmoshperic properties within the cave	Collect atmospheric pressure and temperature data	Temperature detection Range	-130 C - 70 C	Rover Environmental Monitoring Station (REMS)	
				Humidity Range	200 - 323 K		

Figure 4.2.2.1. (Science Traceability Matrix)

4.2.3. Payload Success Criteria

The science instrumentation is to reflect the science objectives, and must find data based on those objectives/goals. There is a certain criteria for success for each one and is as follows.

PIXL should show that there is a presence of Calcium Carbonate, Calcium Sulfate and Sodium Chloride within the soils inside of CC0068. Without these concentrations, it would seem that there is no sign of past water presence.

ChemCam should show that there are certain elemental properties within water-ice found within CC0068 and if they are not present then the assumption is that there are no biological materials in the martian ice deposits.

TLS should analyze the martian atmosphere for methane concentrations and for water vapor within the caves of CC0068. Methane is a byproduct of many living systems and a lack of methane may indicate that no life was/is present.

REMS should provide measurements of surface temperature, wind speeds, atmospheric pressure and air temperature.

The knowledge obtained from this mission gives insight into the rather unknown caves of Mars which could contain evidence of life and or the possibility of life, including humans. The mission is testing the atmospheric conditions of the cave for future life while also searching for the elemental building blocks of past life. The conditions on Mars have proven to be difficult for life to exist, however this mission may show insight into the sheltered conditions of Martian caves and test the extent of life in harsh conditions.

4.2.4. Experimental Logic, Approach, and Method of Investigation

Along with Chemcam, these ground tools are searching for any evidence of life or potential habitability. While the robot is stationary, the tools go to work searching from the top and surrounding cave, to the atmosphere, to the ground in that order before moving on.

Around the entrance of the cave, Martian regolith will be tested first. This is because the proximity to the surface may cause the atmospheric and cave ceiling to not have the features the robot's instruments are designed to find. Deeper into the cave, around 50 meters in, atmospheric readings will begin to take place in order to check for change in temperature and if Martian winds affect this deep into the cave. Further into the cave at 100 meters hoarfrost is predicted to be there so readings of the cave ceiling will be taken.

During its final week of living, the rover will focus on methane tests and readings, and taking data on elemental composition of the Martian soil; looking for H20 and elements C, N, P, and S will be priority. The rover will be given 2 weeks time to finish its readings and data submission before power is depleted. (Tools will be kept in check from using too much power, data transmitted from a data storage unit through a Central Processing Unit in Command and Data Handling. Afterwards, data goes through a communications processor module to the communications transmitter to the main payload.

Based on images from JMARS, it is deemed that samples analyzed must be from a distance or in gaseous form. PIXL analyzes from a distance while REMS, Chemcam, and TLS collect data from a distance. This is because images from JMARS show that the cave may be in a rocky and unstable environment so the rover must be able to adjust.

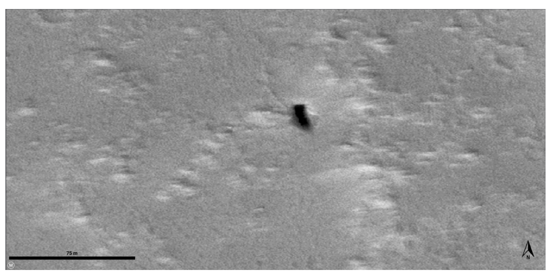


Figure 4.2.4.1. (Image of Lava Tube Entrance through JMARS)

4.2.5. Testing and Calibration Measurements

For the following five science instruments the team will be implementing: DAN, PIXL, ChemCam, TLS, and REMS, testing will be done to ensure the best quality and ability of each tool.

For the PIXL (Planetary Instrument for X-ray Lithochemistry) it would measure the chemical makeup of rocks at a very fine scale. To test this instrument, the usage of different materials is needed to provide an accurate understanding of each kind of chemical there is on the Martian surface. The elements that PIXL senses are Phosphorus(P) and Sulfur(S), so small amounts of them will be placed in contained space for PIXL to test for calibration. These amounts are no bigger than a grain of sand.

The ChemCam (Chemistry and Camera) is a camera and spectrograph that could identify the chemical composition of soils on Martian ground, specifically the caves. Calibrating this instrument will need a new type of calibration that was recently discovered that encompasses the partial least squares and Independent Component Analysis algorithms to decrease the differences between the laboratory conditions and the ground on Mars. When on Mars before full deployment, Chemcam has access to identify elements crucial for the mission such as Carbon(C), Hydrogen(H), Nitrogen(N), and Oxygen(O). Chemcam uses these small samples with the partial least squares and Independent Component Analysis algorithms to calibrate.

TLS (Tunable Laser Spectrometer) would analyze methane concentrations, carbon dioxide and findings of water vapor in the Mars caves. To test this, the instrument has a unit that provides the usage of calibration gasses that is a mix of ratios within the area of measured concentrations. The testing gas is recycled to be analyzed by TLS and is used as a benchmark for calibration.

REMS (Remote Sensing Mast) is an instrument used to measure the atmospheric pressure, temperature, humidity and UV radiation levels. Calibrating this needs to involve the Mast Cam that calibrates the camera angle for the instrument. Calibration is done by doing wind tunnel tests and numerical analysis in the environment of Mars. Then, simulations will be held in order to get results which cannot be duplicated on Earth.

4.2.6. Precision and Accuracy of Instrumentation

PIXL:

- ➢ High sensitivity: detect important trace elements at 10’s ppm level
- ➢ Fast spectral acquisition: measure most major and minor elements at 0.5 wt% in 5 seconds.
- ➢ Measurement flexibility: point, line, or map analysis at variable step size as small as 0.1 mm

TLS:

- ➢ Methane: 2 ppb direct
- ➢ Water: 2 ppm direct
- ➢ CSPL enrichment improves by ~100x
- ➢ Isotope Precision - Typically < 10 per mil

ChemCam:

- A spectra range of 240-850nm at resolutions of 0.09 to 0.3nm in 6144 channels can be analyzed. About 50 to 75 laser pulses will be fired at a single sample to achieve a desired accuracy of 10% at the maximum distance of 7m.

REMS:

- Pressure Sensor - Its measurement range goes from 1 to 1150 Pa with an end-of-life accuracy of 20 Pa (calibration tests give values around 3 Pa) and a resolution of 0.5 Pa.
- UV Sensor - 315-370 nm (UVA), 280-320 nm (UVB), 220-280 nm (UVC), 200-370 nm (total dose), 230-290 nm (UVD), and 300-350 nm (UVE), with an accuracy better than 8% of the full range for each channel, computed based on
- Mars radiation levels and minimum dust opacity. The photodiodes face the zenith direction and have a field of view of 60 degrees.
- Temperature Sensor - Its measurement range is 150 to 300 K. It has an accuracy of 5 K and a resolution of 0.1 K.
- Ground Temperature Sensor - range from 150 to 300 K with a resolution of 2 K and an accuracy of 10 K.
- Humidity Sensor - measure relative humidity with an accuracy of 10% in the 200-323 K range and with a resolution of 1%. A dust filter protects it from dust deposition.
- Wind Sensors - The requirement is to determine horizontal wind speed with 1 m/sec accuracy in the range of 0 to 70 m/sec, with a resolution of 0.5 m/sec. The directional accuracy is expected to be better than 30 degrees. For vertical wind the range is 0 to 10 m/sec, and the accuracy and resolution are the same as for horizontal wind.

4.2.7. Expected Data and Analysis

PIXL:

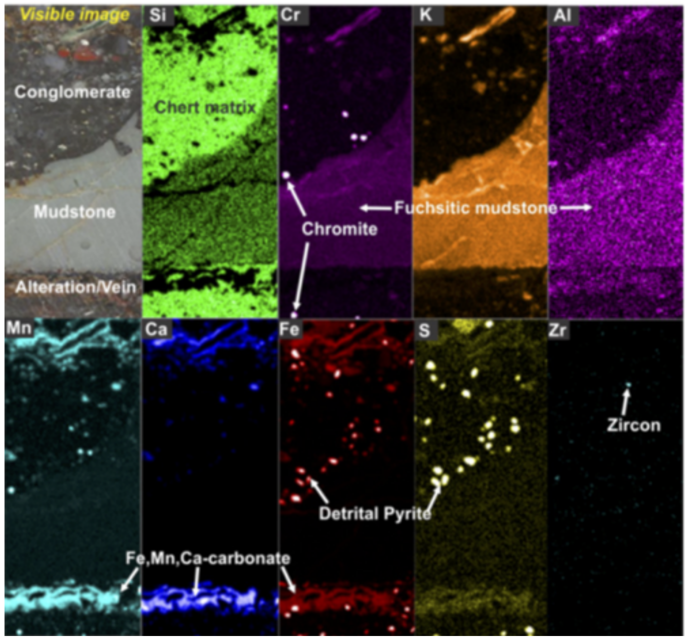


Figure 4.2.7.1. (PIXL Imaging Sample)

Scanning the beam reveals spatial variations in chemistry in relation to fine-scale geologic features such as laminae, grains, cements, veins, and concretions. What geologic features are in the Martian caves are not known yet, but should pick up any of its elements, especially Phosphorus(P) and Sulfur(S), regardless of geologic formation.

TLS:

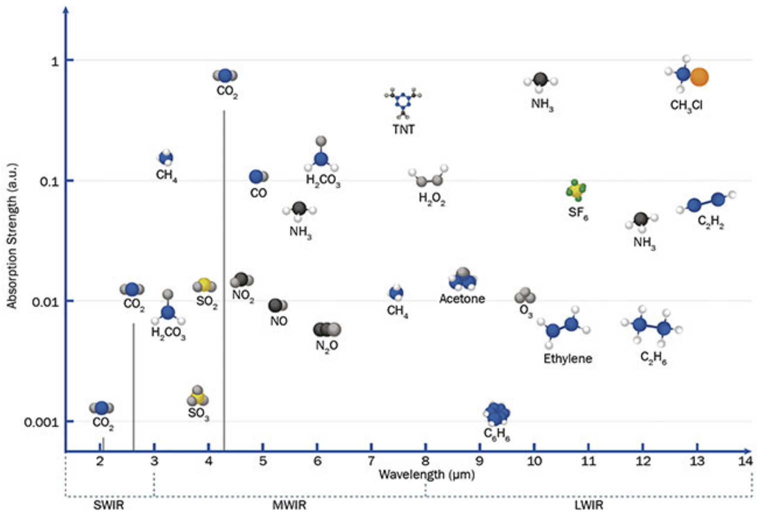


Figure 4.2.7.2. (TLS Structure Graph)

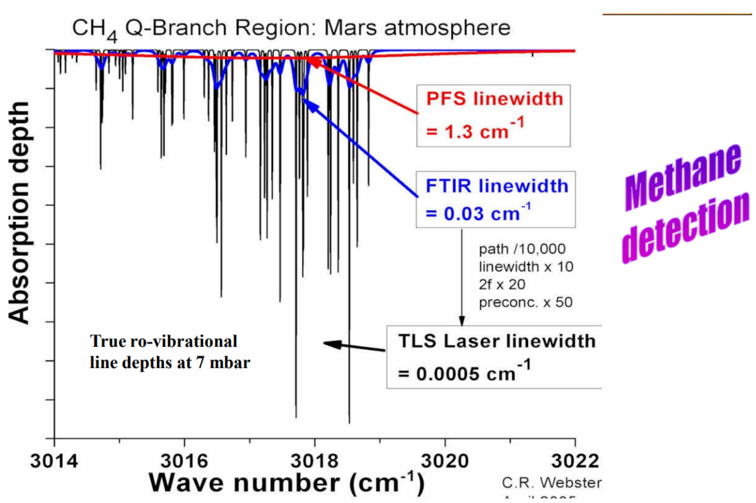


Figure 4.2.7.3. (TSL Methane Concentration)

The TLS picks up the wavelengths of various chemical compounds, methane is the one that is TLS' main goal. Within the Mars atmosphere methane has been detected, however the potentially changed conditions of the cave should give different, more abundant results.

ChemCam:

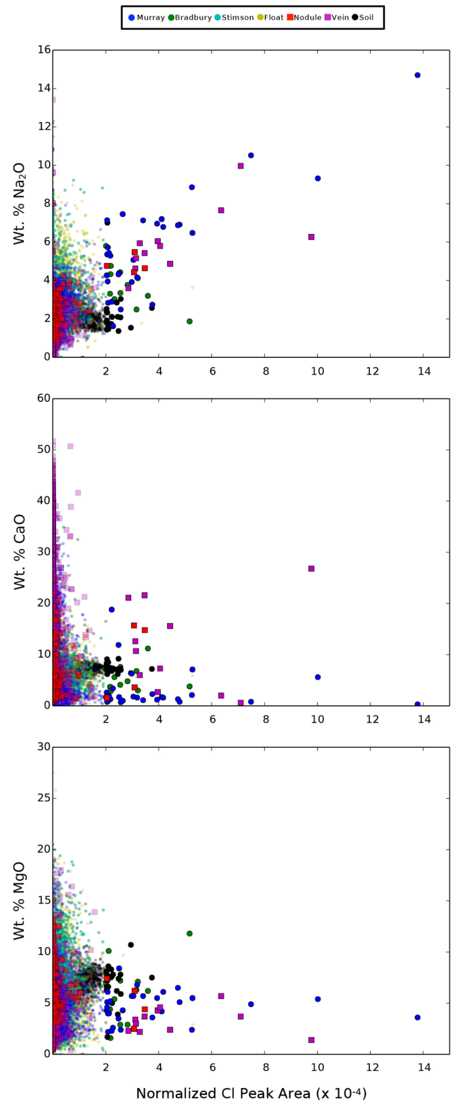


Figure 4.2.7.4. (ChemCAM Cl Detection)

Normalized Cl peak area versus wt.% Na2O, CaO, and MgO from ChemCam. The opacity indicates the significance of the Cl observation. Fully opaque data points are three-sigma Cl detections (≥ 2x10-4 Cl peak area). No correlation is seen for CaO and MgO. Pictures gathered from ChemCam would be of the same quality as any past explorations. A light may be needed to aid in quality.

REMS:

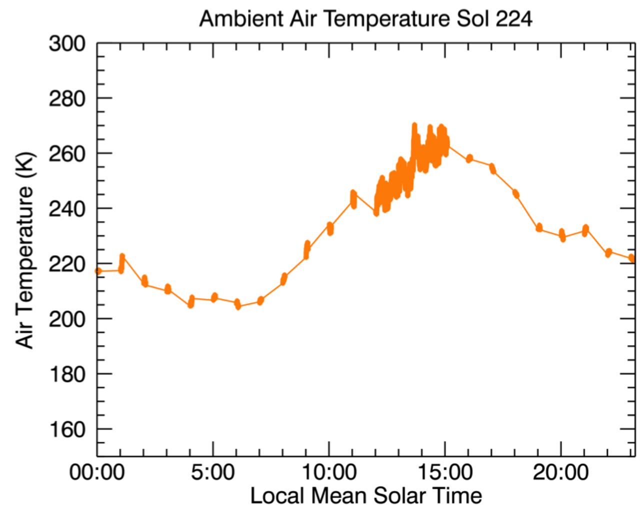


Figure 4.2.7.5. (REMS Temperature Graph)

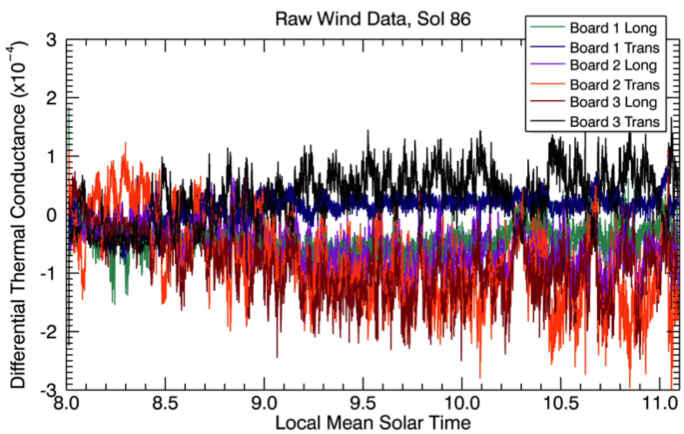


Figure 4.2.7.6. (REMS Wind Data Graph)

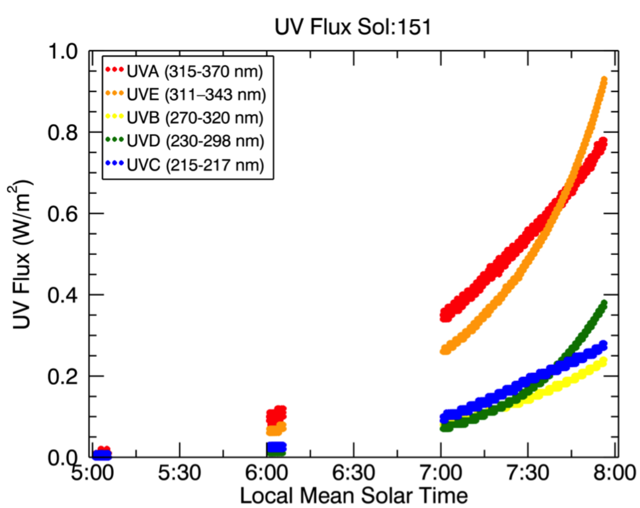


Figure 4.2.7.7. (REMS UV Flux Graph)

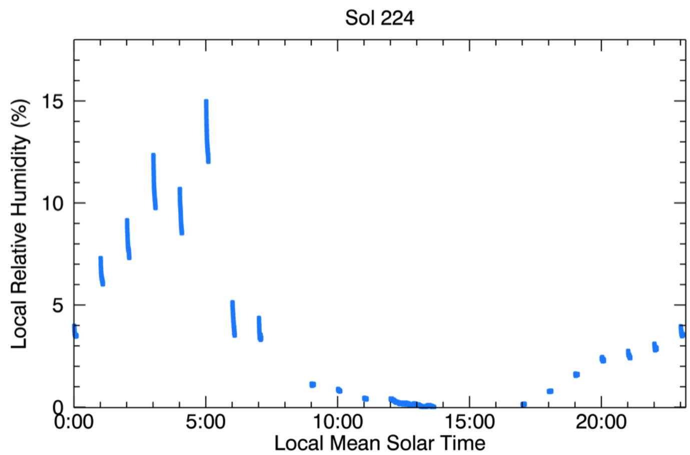
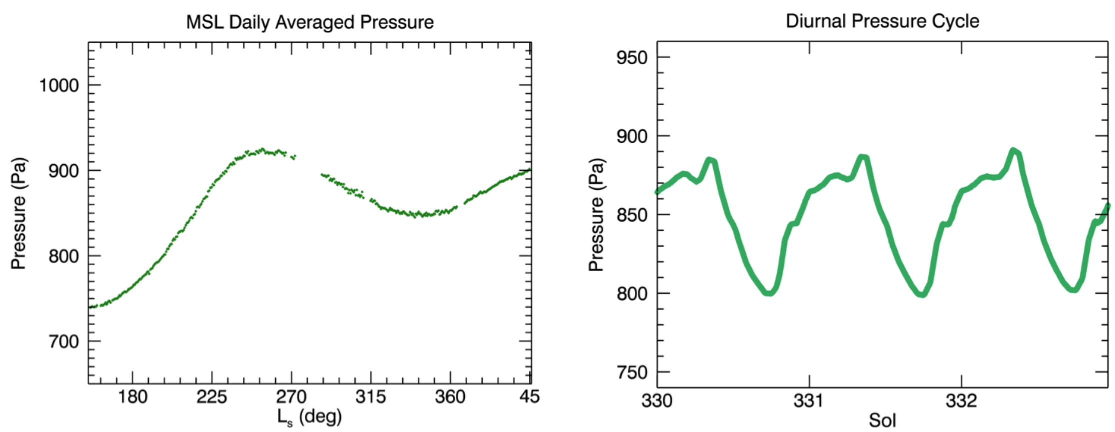


Figure 4.2.7.8. (REMS Humidity Graph)



Figures 4.2.7.9. And 4.2.7.10. (REMS Pressure Graphs)

Mars undergoes various fluctuations in temperature and pressure throughout its days and cycles. The weak atmosphere of Mars possibly contributes to that, so testing the atmospheric conditions of a cave, an area on the same planet with relatively sheltered conditions should show changed and altered conditions compared to day to day surface conditions.

Section 5: Safety

5.1. Personnel Safety

5.1.1 Safety Officer

The Safety Officer, Abraham Chavarria, bears responsibility for the health and safety of all employees in order to provide a safe and healthful work environment for engineers and scientists. This includes avoiding loss of life, personal injuries and illnesses, property loss or damage, or environmental harm. The primary duties and responsibilities of the safety team include:

- Serves as safety program focal point (expert)
- Provides regulatory and agency requirements interpretation
- Facilitates safety training and awareness
- Supports all levels of safety review
- Coordinates emergency preparedness

Research conducted lists and resolved hazards found during the manufacturing, integration, and testing phases of the mission. This is done by using sources from the Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), the Electronic Code of Federal Regulations (eCFR), and the Environmental Protection Agency (EPA).

5.1.2. Personnel Hazards

Workplace injuries, illnesses, deaths, and suffering pose a threat towards the safety of team members and the success of the mission. Therefore, identification of hazardous environments and/or operations while working on the mission is essential for success. Personnel hazards that could threaten the safety of team members during the manufacturing, integration, and testing phase of the mission have been identified in the following categories: Biological, Chemical, Safety, Ergonomic, Work Organization, and Physical hazards.

Manufacturing/Machining Hazards

a. Hazardous motions such as rotating machine parts, reciprocating motions, and transverse motions (Machine guarding : introduction - hazardous motions/actions).
b. Points of operations such as areas where the machine cuts, shapes, bores or forms the stock being fed throughout.

c. Pinch and shear points such as areas where a part of the body can be caught between a moving part and a stationary object.
d. Protruding devices such as levers, cranks, hooks, and controls located where they pinch, snag, and could cut.
e. Mechanical devices capable of storing and releasing energy such as springs and torsion bars.
f. Personal harm as a result of improper use of equipment, whether it be improper training or negligence.
g. Failure of equipment due to negligence of maintenance.
h. Burred corners and edges

Electrical Hazards

a. Hazardous/critical event where crew is subject to electric shock.
b. Lack of use of safety (green) wire, bonding, insulation and barriers around electrically energized surfaces and conductive surfaces.
c. Exposed electrical conductors and terminations are not insulated.
d. Equipment does not have grounded/nonconductive protective covering.
e. Lack of a ground fault interrupter (prevents electric shock by interrupting a household circuit when there is a difference in currents in wires).
f. No consideration for leakage current design control.
g. Equipment design presents moisture collection.
h. Equipment does not protect from static charge buildup.
i. Switches/controls do not prevent unplanned hazardous manual or automatic operation.

Fire Hazards

a. Lack of fire protection system including detection, warning, and extinguishing devices.
b. Design of the vehicle does not have rapid access to fire fighting equipment.
c. Lack of in-flight fire detection system with signaling, reset and self test capabilities.
d. Lack of air filtration system to remove air-borne flammable particles.

Explosive Hazards

a. Hazards associated with lithium batteries, such as:
    i. Decomposition of electrolyte
b. Lack of air filtration system to remove air-borne combustible particles.

Lab Testing / Cleaning Hazards

a. Non-ionizing or ionizing radiation (either direct or indirect exposure).

b. Infectious agents such as bacteria and viruses from sampling tests.
c. Cleaning solutions such as isopropyl alcohol, ultra pure water, and hydrofluoroether.
d. Improper clothing protection from various chemicals.
e. Improper disposal of hazardous material.
f. Improper storage and handling of chemicals.

General Safety Hazards

a. Heavy equipment or materials suspended above ground level
b. Tall equipment unanchored with risk of falling during an earthquake or vibrations
c. Minimal exits in an event of a fire
d. Running/speed walking around equipment within the facility

Ergonomic Hazards

a. Repetitive activities related to a long-term stationary position such as arthritis, back and knee pain, etc.
b. Harsh manual handling results in joint pain, etc.
c. Repetitive loud noises may cause hearing problems

Work Organization Hazards

a. Lack of communication between team members when carrying materials around corners.
b. Lack of communication between team members and upper management causing a disconnect between what is intended and what is executed.

5.1.3. Hazard Mitigation

In order to successfully mitigate hazards, proper training and supervision is necessary.

Manufacturing/Machining Hazard Mitigations

a. Proper maintenance of equipment and working area.
b. Wear appropriate Personal Protective Equipment (PPE).
c. Proper training in equipment being used.
d. Proper disposal of lubricant, chips, and excess material.

Electrical Hazard Mitigations

a. Proper maintenance of equipment and working area.
b. Wear appropriate Personal Protective Equipment (PPE).
c. Proper training in equipment being used.

d. ESD strap to ground electrical equipment.

Fire Hazard Mitigations

a. Proper fire protection system to detect, warn, and extinguish fires.
b. Fire-fighting equipment such as fire blankets and extinguishers are accessible.
c. Active air-filtration system to remove air-borne flammable particles and the build-up of dust.

Explosive Hazard Mitigations

a. Proper handling and storage of lithium-ion batteries.
b. Active air-filtration system to remove air-borne combustible particles and the build-up of dust.

Lab Testing / Cleaning Hazard Mitigations

a. Proper handling and storage of chemicals and infectious agents.
b. Wear appropriate Personal Protective Equipment (PPE) against chemicals and radiation.
c. Proper disposal of hazardous and non-hazardous chemicals and materials.

General Safety Hazard Mitigations

a. Proper signage and notice of dangerous zones.
b. Adequate sick and vacation days to reduce illness transmission.
c. Access to germ-removing supplies like hand sanitizer, antibacterial wipes, etc to reduce illness transmission.
d. Proper air-conditioning and heating to reduce temperature-related illnesses and comfort.

Ergonomic Hazard Mitigations

a. Breaks to stretch and exercise to reduce joint-related pain and mental break.

Work Organization Hazard Mitigations

a. Corner dome mirrors to reduce chance of human collision
b. Ensuring upper management requests have a dedicated avenue to directly communicate or intervene with lower divisions and vice versa.
c. Ensuring for cleanliness of the area to diminish risk from debris, dust, and tripping hazards.

Section 6: Activity Plan

6.1. Budget

	Additional Information						
	# People on Team	FTE Year 1	FTE Year 2	FTE Year 3	FTE Year 4	FTE Year 5	FTE Year 6
Science Team:	5	1	1	1	1	1	1
Engineering Team:	7	1	1	1	1	1	1
Administrative Team:	6	1	1	1	1	1	1

NASA L'SPACE Mission Concept Academy Budget - *Astrobiology in Martian Caves*

Year	Yr 1 Total	Yr 2 Total	Yr 3 Total	Yr 4 Total	Yr 5 Total	Yr 6 Total	Cumulative Total
			PERSONNEL				
Science Team	$ 400,000.00	$ 400,000.00	$ 400,000.00	$ 400,000.00	$ 400,000.00	$ 400,000.00	**$ 2,400,000.00**
Engineering Team	$ 560,000.00	$ 560,000.00	$ 560,000.00	$ 560,000.00	$ 560,000.00	$ 560,000.00	**$ 3,360,000.00**
Administrative Team	$ 480,000.00	$ 480,000.00	$ 480,000.00	$ 480,000.00	$ 480,000.00	$ 480,000.00	**$ 2,880,000.00**
Total Salaries	$ 1,440,000.00	$ 1,440,000.00	$ 1,440,000.00	$ 1,440,000.00	$ 1,440,000.00	$ 1,440,000.00	**$ 8,640,000.00**
Total ERE	$ 401,904.00	$ 401,904.00	$ 401,904.00	$ 401,904.00	$ 401,904.00	$ 401,904.00	**$ 2,411,424.00**
TOTAL PERSONNEL	$ 1,841,904.00	$ 1,841,904.00	$ 1,841,904.00	$ 1,841,904.00	$ 1,841,904.00	$ 1,841,904.00	**$ 11,051,424.00**
			TRAVEL				
Total Flights Cost	$ -	$ 6,600.00	$ -	$ -	$ -	$ -	**$ 6,600.00**
Total Hotel Cost	$ -	$ 21,000.00	$ -	$ -	$ -	$ -	**$ 21,000.00**
Total Transportation Cost	$ -	$ 3,000.00	$ -	$ -	$ -	$ -	**$ 3,000.00**
Total Per Diem Cost	$ -	$ 8,460.00	$ -	$ -	$ -	$ -	**$ 8,460.00**
Total Travel Costs	$ -	$ 39,060.00	$ -	$ -	$ -	$ -	**$ 39,060.00**
			OUTREACH				
Total Outreach Materials	$ 600.00	$ 600.00	$ 6,600.00	$ 6,600.00	$ 6,600.00	$ 6,600.00	**$ 27,600.00**
Total Outreach Venue Costs	$ 300.00	$ 300.00	$ 300.00	$ 300.00	$ 300.00	$ 300.00	**$ 1,800.00**
Total Outreach Costs	$ 900.00	$ 900.00	$ 6,900.00	$ 6,900.00	$ 6,900.00	$ 6,900.00	**$ 29,400.00**
			OTHER DIRECT COSTS				
Total Outsourced Manufacturing Cost	$ 50,500,000.00	$ 290,000.00	$ 68,000,000.00	$ -	$ 10,000.00	$ -	**$118,800,000.00**
|> Science Instrumentation	$ 50,500,000.00	$ -	$ -	$ -	$ -	$ -	**$ 50,500,000.00**
|> Other COTS Components	$ -	$ 290,000.00	$ 68,000,000.00	$ -	$ 10,000.00	$ -	**$ 68,300,000.00**
Total In-House Manufacturing Cost	$ 106,250.00	$ -	$ -	$ -	$ -	$ -	**$ 106,250.00**
|> Materials and Supplies	$ 106,250.00	$ -	$ -	$ -	$ -	$ -	**$ 106,250.00**
Total Equipment Cost	$ -	$ 4,000,000.00	$ 4,000,000.00	$ 11,000,000.00	$ 11,000,000.00	$ 7,000,000.00	**$ 37,000,000.00**
|> Manufacturing Facility Cost	$ -	$ 4,000,000.00	$ 4,000,000.00	$ 4,000,000.00	$ 4,000,000.00	$ -	**$ 16,000,000.00**
|> Test Facility Cost	$ -	$ -	$ -	$ 7,000,000.00	$ 7,000,000.00	$ 7,000,000.00	**$ 21,000,000.00**
In-House Manufacturing Margin	$ 53,125.00	$ 2,000,000.00	$ 2,000,000.00	$ 5,500,000.00	$ 5,500,000.00	$ 3,500,000.00	**$ 18,553,125.00**
Total Direct Costs	$ 52,502,179.00	$ 8,171,864.00	$ 75,848,804.00	$ 18,348,804.00	$ 18,358,804.00	$ 12,348,804.00	**$185,579,259.00**
Total MTDC	$ 52,502,179.00	$ 2,171,864.00	$ 69,848,804.00	$ 1,848,804.00	$ 1,858,804.00	$ 1,848,804.00	**$148,579,259.00**
			FINAL COST CALCULATIONS				
Total F&A	$ 5,250,217.90	$ 217,186.40	$ 6,984,880.40	$ 184,880.40	$ 185,880.40	$ 184,880.40	**$ 13,007,925.90**
Total Projected Cost	$ 57,752,396.90	$ 8,389,050.40	$ 82,833,684.40	$ 18,533,684.40	$ 18,544,684.40	$ 12,533,684.40	**$198,587,184.90**
Total Cost Margin	$ 17,325,719.07	$ 2,516,715.12	$ 24,850,105.32	$ 5,560,105.32	$ 5,563,405.32	$ 3,760,105.32	**$ 59,576,155.47**
Total Project Cost	$ 75,078,115.97	$ 10,905,765.52	$ 107,683,789.72	$ 24,093,789.72	$ 24,108,089.72	$ 16,293,789.72	**$258,163,340.37**

Figure 6.1.1. (Budget Chart)

Travel costs were dictated by average flights from the major airports in California, San Francisco International Airport and Los Angeles International Airport to Orlando International Airport which in the median range is about $550. Accounting for 12 members of the team the total is $6600 for travel to Florida. Getting to Cape Canaveral will be done using rental cars. If the team each uses a car, using a median price of 48 dollars for 5 days it is $2880; $3000 will be dedicated to personnel travel around launch. Housing will be done in hotels; $21,000 dollars will be allocated to the team as a whole, giving $350 per day over 5 days.

Outreach has many varying costs. The website will be used in conjunction with NASA and be built in-house by the outreach officers using Wix which will cost $300. Social media will also be run by the outreach officers to keep expenses low. The team's school outreach will consist of a variety of programs. Outreaching to geology and engineering programs will require money for travel and resources for presentations totaling $300 each being dedicated to materials and for venue and travel costs. The travel campaign will take place for the entirety of the mission and two years afterwards, totaling $3600. For the winner of the middle school challenge, expenses will be paid for by outreach, including hotels and travel costs, totaling $2500. Finally the college data analysis project will give a team of 3-4 students a $1500 scholarship. The program will take place every year for 4 years, meaning $24,000 will be allocated to this. Outreach total costs will be $29,400.

For the rover itself, the estimated cost of the extruded aluminum frame from Johnson Bros. Rolling Forming Co. can be upwards of $20,000 for 14 feet of space-grade aluminum. At the NASA Sheet Metal Center, the estimated cost for 1.5 square meters of space-grade sheet metal can be upwards of $50,000. The reason for this is that other metals like gold, titanium, and nickel are used to further enhance the thermal insulation and to protect the insides. The cost of material needed to construct the suspension and wheels are fairly cheap when compared to the manufacturing costs. The cost of material is expected to upwards of $5000 for Aluminum Alloy AA6061 with a cost of $130 per kg for 4 kg and not including any anodizing and extra coating, and for Titanium 6A1-4V, the estimated cost is upwards of $10,000 with a cost of approximately $200 per kg for 5 kg and not including any extra coating needed. Fasteners can be estimated to be 25% of the total raw material cost.

The 1m^2 surface solar panels on the primary payload from SolAero can be estimated up to $280,000, but the price may vary as noted on their website. The battery pack is made of 18650s batteries which are highly accessible and commercial. The expected cost of the pack is $10,000 and will be made in-house as heritage hardware.

A brushless motor system from NASA based on heritage hardware can be estimated to upwards of $10,000,000.

A radioisotope heating unit (RHU) and heat rejection unit (HRU) from NASA can be expected to be $50,000,000 due specificity of the part and that it must be specifically designed for the team's use-case. Other thermal-related components will be purchased from AZ Technology like AZ-3700-LSW Low Thermal Emittance, Electrostatic Dissipative Paint / Coating. This coating will help reflect light and ultimately, heat; the cost of the coating is unknown due to vendor price not being released to the public. The projected cost of the coating will be conservatively estimated to $10,000.

The rover will be tethered to the primary payload which communicates with the base and sends its data back to mission control using the Deep Space Network. This costs $10,000 a day to maintain and the mission, which lasts approximately a year, will take $8,000,000 to maintain. The Jet Propulsion Laboratory is in charge of the DSN, and works by having 3 equidistant deep space satellites send radio signals through space. Many other space missions like the Double Asteroid Redirection Test or DART and the Europa Clipper Mission.

Multiple manufacturing facilities will be used and the exact cost cannot be closely estimated, as a result, four million over four years will be used.

Testing facilities are similar and seven million will be used over three years due to specialized testing equipment, totalling $21 million.

In order from least expensive to most, there is TLS at $7.5 million to create. Next is Chemcam at $9 million. PIXL is $10 million. Finally REMS is $24 million.
The total of the 4 science instruments is $50,500,000.

This leads the total cost of the rover to be $258,163,340.37

6.2. Schedule

Astrobiology in Martian Caves

Team Number: #33

Project Team Members: Jeffrey Callaway, Rabhat Chaiprapa, Abraham Chavarria, Jonathan Cordova, Roger Nguyen, Hong Joo Ryoo, Brandon Tabata, Daniel Ponce, Daisy Salmeron, Yiyu Chen, Karen Lin, and Joshua Kozlowski

ID#	TASK	ASSIGNED TO	PROGRESS	START	END	DAYS	MARGIN
1	Conceptual Development		100%	5/24/22	7/4/22	42	28
1.1	Concept Studies	All	Complete	5/24/22	5/31/22	8	
1.2	Instrument Identification	Engineering	Complete	6/1/22	6/20/22	20	
1.3	Define Scientific Objectives	Science	Complete	6/22/22	7/4/22	13	
1.4	Preliminary Budget	Admin	Complete	6/1/22	7/4/22	34	
1.5	Schedule Margin			6/7/22	7/4/22	28	
1.6	◆ SRR: System Requirements Review Completion		Complete	7/4/22	7/4/22	1	
2	Preliminary Design and Analysis		0%	7/12/22	8/15/22	35	12
2.1	Finalize science objectives	Science	Not complete	7/12/22	7/22/22	11	
2.2	Begin CAD Design	Engineering	Not complete	7/11/22	7/18/22	8	
2.2	Create Concept of operations	Admin	Not complete	7/11/22	7/18/22	8	
2.3	Establish Budget	Admin	Not complete	8/26/22	9/5/22	11	
2.4	System Review (KDP B)	Engineering	Not complete	9/5/22	9/30/22	26	
2.5	Schedule Margin			9/30/22	10/11/22	12	
2.6	◆PDR: Preliminary Design Review Completed		Not complete	8/1/22	8/15/22	15	
3	Verification and Validation		0%	10/12/22	4/10/23	181	32
3.1	Finalize CAD design	Engineering	Not complete	10/12/22	1/1/23	82	
3.2	Instrument analysis	Science	Not complete	11/24/22	1/11/23	49	
3.3	Subcomponent analysis	Engineering	Not complete	1/11/23	3/10/23	59	
3.4	Begin supplier requests for quotes	Admin	Not complete	3/10/23	3/10/23	1	
3.5	Schedule Margin			3/10/23	4/10/23	32	
3.6	◆ CDR: Critical Design Review Completion		Not complete	4/10/23	4/10/23	1	
4	Begin Manufacturing		0%	4/10/23	1/5/24	271	66
4.1	Submit purchase orders	Admin	Not complete	4/10/23	5/4/23	25	
4.2	Begin manufacturing	Engineering	Not complete	5/24/23	8/10/23	79	
4.3	Subcomponent V&V	Engineering	Not complete	8/10/23	11/1/23	84	
4.4	Instrument V&V	Science	Not complete	8/10/23	11/1/23	84	
4.5	Schedule Margin			11/1/23	1/5/24	66	
4.6	◆ ORR: Operational Readiness Review Completion		Not complete	1/5/24	1/5/24	1	
5	System Assembly and Testing		0%	1/8/24	12/2/24	330	64
5.1	System Assembly/Manufacturing	Engineering	Not complete	1/8/24	3/1/24	54	
5.2	System Testing	Engineering	Not complete	2/8/24	4/16/24	69	
5.3	Readiness Review	Engineering	Not complete	5/15/24	6/19/24	36	
5.4	Integration with primary payload, launch vehicle	Engineering	Not complete	6/19/24	10/17/24	121	
5.5	Schedule Margin			10/17/24	12/19/24	64	
5.6	◆ Launch Date	Primary Payload	Not complete	12/2/24	12/2/24	1	
6	Cruise Stage		0%	12/5/24	8/13/25	252	N/A
6.1	Launch vehicle performance analysis	Primary Payload team	Not complete	12/5/24	2/12/25	70	
6.2	Monitor vehicle health	Engineering	Not complete	12/6/24	8/13/25	251	
6.6	◆ Landing Date		Not complete	8/13/25	8/13/25	1	
7	Science Mission		0%	9/18/25	7/3/26	289	90
7.1	Cave movement and entry	Primary payload/Engineering	Not complete	9/18/25	2/19/26	155	
7.2	Obtain scientific data	Science	Not complete	2/19/26	3/18/26	28	
7.3	Ensure data transmission	Engineering	Not complete	3/18/26	4/5/26	19	
7.5	Schedule Margin			4/5/26	7/3/26	90	
7.6	◆ Robot Completes Science Mission		Not complete	7/3/26	7/3/26	1	

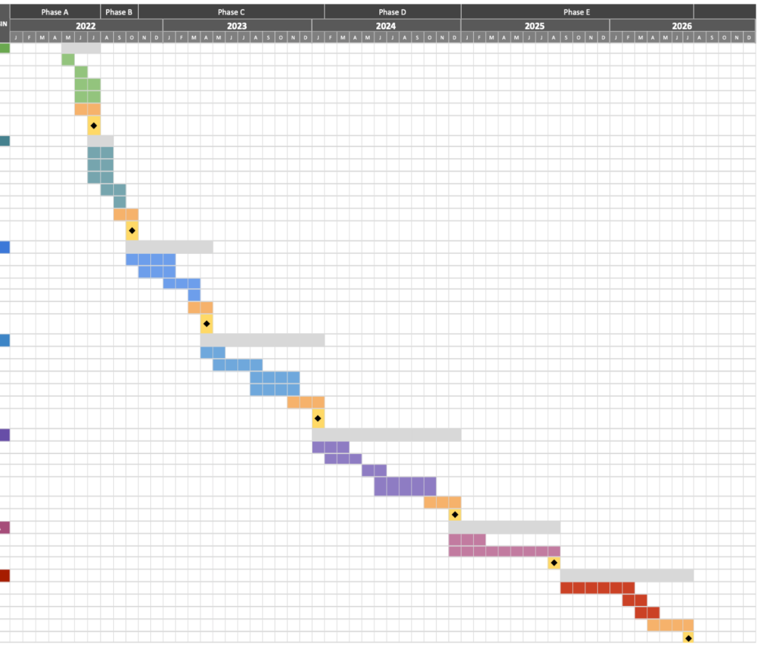


Figure 6.2.1. (Mission Schedule Gantt Chart)

The mission schedule begins with Phase A in January 2022, and is completed with the Mission Concept Requirements Review as the mission's Systems Requirements Review. Missions that require landing on the Martian surface utilize the Sun's gravitational force to save fuel when leaving Earth. As a result, missions are often spaced 26 months apart. This can be seen in the InSight and Mars 2020 mission. A tentative launch date chosen is December 2nd, 2024. With a notional launch date of 2024, this provides 2 years to coordinate with the primary payload for project phases B-D. Phase E begins with primary payload launch to Mars in the December 2024 transfer window. Assuming a 8-month low energy Hohmann transfer, the primary payload will undergo Entry, Descent and Landing in the Tharsis region in August 2025. Upon primary payload arrival on the edge of cave CC0068, Phase E continues with deployment of the system from the primary payload, cave egress, and fulfillment of the science objectives. The projected duration of the science mission inside the cave is 2 weeks, after which the robot shall be raised out of the cave and separated from the primary payload.

6.3. Outreach Summary

Internet and Social Media Presence Timeline

- Website: The team plans to create a dedicated website to the mission including the mission statement, plans, updates, interviews, information, background, and more. NASA and other applicable websites will have a dedicated tab to redirect to the mission website to help increase the page rank and spread awareness. Members of the team will contribute to content.
- Social Media: Photographs and images will be posted to the missions dedicated Instagram and Facebook profiles that will be launched in conjunction with the mission. Videos such as updates and Q&A's will be featured on the mission's Youtube and Twitter pages. The outreach officers will maintain these pages spending 2 hours every week maintaining, editing, and posting content.

School Outreach Timeline

- The scientists will partner with pre-collegiate schools and educate students on geology and cave formation. Universities such as California Institute of Technology, Massachusetts Institute of Technology, and University of Colorado, Boulder will be partnered with the mission scientists to give interactive presentations to college students through an 8 week internship. This internship will teach students on the future of cave formations on Mars and finding geological locations as well as writing a research paper.
- The engineers will partner with collegiate student organizations relevant to the mission like Students for Exploration and Development of Space (SEDS) to talk about the mission, the effect of Martian dust on wheels, treads, and legs, and how they can prepare for dust in their designs. Colleges such as University of California - Berkeley and Georgia Institute of Technology will be the targeted schools with the clubs: Space Technologies at California and ExplOrigins. These clubs are student run organizations that incorporate engineering projects by developing space tools.
- Present a middle school challenge on NASA's STEM Engagement Page to build a model robot which can explore Martian caves. The winner will be chosen by the outreach team on design and accessibility and will win a tour of the mission center.
- Work with First Robotics Competition (FRC) of which NASA is already a sponsor to create a cave exploration robotics competition. Through meeting with FRC, high schoolers build a rover that is specific to one of the mission's scientific goals.
- A challenge to all community college students to analyze mock data similar to what is predicted for the mission that is given to them in teams of 3-4. The team that analyzes the data the fastest and most accurately will receive a $1500

scholarship. The challenge will be created with the researchers on the science team and run through NASA's STEM Engagement Programs.

6.4. Project Management Approach

At the beginning of the project, the team would gather for main meetings together. Tasks would be led by individuals that volunteered to advise and take on leading responsibilities. Tasks themselves would be completed in groups where people worked on both writing and revision. When organizing the team into an organized structure, roles were distributed based on major and interest; secondary roles were also filled in the same manner. The leadership positions of Project Manager, Deputy Project Manager, Lead Systems Engineer, and Chief Scientist were decided using single-winner plurality voting by all the members after candidates nominated themselves for the position. Weekly meetings consisting of all personnel would be held for announcements, updates, and discussion that was applicable to all team members. In addition, sub-team meetings were created for the science and engineering team to hand out tasks when necessary and work as progress checks. The main method of communication between the team was through organized Discord channels and voice chats.

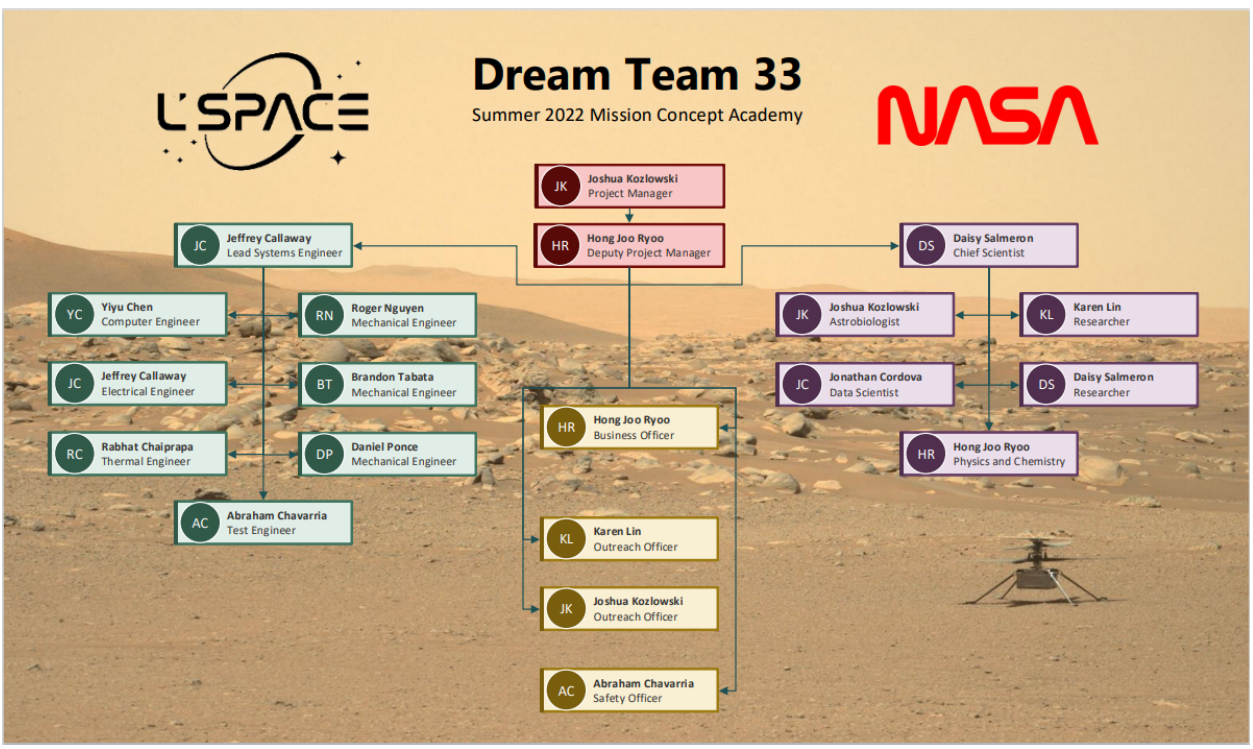


Figure 6.3.1. (Team Organizational Chart)

One decision that was made was to appoint an interim safety manager to the position until a candidate was selected. This compromise streamlined the process and led to a more efficient meeting. Another decision was to vote to select team leads. This democratic process led everyone to have an opinion. Specific sub-roles were chosen by specific sub-team members that wanted them. During the decision making process, candidates for the Chief Scientist position had other commitments that would make having the position restricted, less available, and encumbered with responsibilities. The Project Manager and Deputy Project Manager encouraged a qualified candidate from the science sub-team to hold the position until a permanent solution was presented. The situation was resolved when the qualified candidate took the position and extended their responsibilities to the permanent position. When an issue arose and the general team could not come up with a decision, the team leads would decide on a temporary resolution until a more permanent decision was made.

Section 7: Conclusion

In conclusion, the purpose of this mission is to further human understanding of the Martian cave environment by gathering information pertaining to the topics of astrobiology, especially whether life could have existed in the past and if life can exist in the future. A tethered rover is the primary method for exploring the cave network. This allows simple ingress into the cave network utilizing the tether system for stability. The rover itself utilizes many of the same computing elements as the MSL and Mars 2020 missions, achieving a high amount of flight heritage in the overall mission design. Several instruments were selected to achieve the mission science objectives. For example, the instruments selected were REMS, Chemcam, TLS, PIXL, and DAN. Each instrument either analyzes the temperature, tests the soil, releases X-rays to identify chemicals on the rocks, tests for methane, carbon dioxide, and water vapor, and measures the ground temperature, humidity, and atmospheric pressure inside the cave. If there is more time, additional safety features and possibilities could have been addressed.The team will be working towards the Critical Design Review. The steps to getting to this point will be finalizing all CAD designs and instrument integration. More engineering time will be spent refining the tether system and testing cave entry methods. All instruments and subcomponents will be fully fleshed out in capabilities and expectations. After the CDR has been submitted, materials and supplies will begin to be requested and shipped to facilities as design will be finalized. Partners, associate facilities, and companies will be operational for the mission to begin fabrication, manufacturing, and assembly.

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