CHARLOTTE

CRATER HYDROGEN AND REGOLITH LABORATORY ON TECHNICAL TERRAIN ENVIRONMENTS

Ashley Lepham, Undergraduate, Mechanical Engineering
Anjelica Salinas: Undergraduate, Graphic Design
Andrew Deros: Undergraduate, Industrial Design and Mechanical Engineering
Chandler Hutchens, Undergraduate, Aerospace Engineering
Connor Nail: Graduate, Robotics and Autonomous Systems
Elizabeth Arnold: Undergraduate, Computer Science
Gowan Rowland: Undergraduate, Electrical Engineering, Power Systems
Grayson Glazer: Graduate, Industrial Design
Julia Greteman: Undergraduate, Materials Science and Engineering
Jerina Gabriel: Undergraduate, Graphic Design
Kartik Paigwar: Graduate, Robotics and Autonomous Systems, Foreign National (India)
Kylel Scott: Graduate, Robotics and Autonomous Systems
Visnu Pisharam, Graduate, Robotics and Autonomous Systems, Foreign National (India)
Zach Smith: Undergraduate, Computer Science

Arizona State University
Arizona Space Grant Consortium
Space Grant Director Contact Information:
Tim Swindle: tswindle@lpl.arizona.edu

Faculty Advisors
James Bell, Professor, Arizona State University,
James Rice, Asst Research Scientist, Arizona State University
Joe DuBois, Engineer Sr, Interplanetary Initiative, Arizona State University
Tyler Smith, Director, The Luminosity Lab, Arizona State University

ASU Arizona State University

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QUAD CHART

Concept Synopsis

CHARLOTTE is a six-legged rover designed to carry advanced scientific payloads up and down steep rocky terrain using a rappel system. The rover consists of six legs: three with 1-degree of freedom (DOF) and three with 3-DOF which allow the rover to always maintain stable footing with three legs on the ground at all times. In addition, it is designed to carry the Mastcam-Z (Mars Perseverance Rover) multi-color stereo camera system to acquire high resolution images and Mini-NS (LunaH-Map) neutron spectrometer for detecting the presence of water ice.

Innovations

- CHARLOTTE's combination of 1-DOF and 3-DOF legs allow for ultra-stable operations in steep terrain.
- The shoes developed for CHARLOTTE are designed to maximize traction on various surfaces and directional orientations including Lunar regolith.
- Each leg is insulated from the ground using a thermal break that uses kevlar fiber to attach the foot to leg which eliminates any metal-metal conduction paths and also provides minimal shock absorption to each leg
- The tether system is designed to eliminate dust contaminated tether from re-entering the rover by using the tether slack basket. If the tether needs to be reeled into the rover, it uses the slack basket which is outside the carapace to store the slack tether so it doesn't renter CHARLOTTE's clean interior

Verification Testing Results & Conclusions

Strategic relevant environment and Earth analog testing were conducted throughout the duration of this development cycle. The Comprehensive Testing Plan (CTP) was used to complete all tests. Testing was broken down into Phase I (simulation) and Phase II (physical testing). Phase II testing included thermal cycling, thermal vacuum chamber testing, high voltage testing, abrasion testing, dust testing, darkness testing, and Earth analog locomotion testing.

Earth analog testing was conducted at Colton Crater in Flagstaff AZ. This test included locomotion testing in a realistic crater terrain environment, omnidirectional control testing, Hazcam and Navcam testing, day-to-night transition testing, and PSR analog testing created by the rim of the crater. These tests were conducted to advance CHARLOTTE to TRL 5 in preparation for future missions to the Moon and beyond.

EXECUTIVE SUMMARY

CHARLOTTE, the Crater Hydrogen and Regolith Laboratory for Observation on Technical Terrain Environments is a six-legged Lunar rover concept developed by Arizona State University designed to descend into steep and permanently shadowed regions (PSRs) of the Lunar south pole in search of water-ice and other Lunar volatiles.

CHARLOTTE's primary exploratory operation is to search for water-ice and other volatiles within Shackleton crater on the Lunar south pole. The mission begins with the voyage to the Lunar surface aboard the Astrobotic Griffin Lander. The lander is set to touch down on a nearly permanently sunlit region of the Lunar surface along the rim of Shackleton crater. This touchdown location is selected to maximize incident sunlight [1] within a region sufficiently close to the crater rim. Sunlight is a critical resource to this mission as it serves to power the rover for the duration of the mission. The Griffin Lander serves as the base station and electric power generator and storage for CHARLOTTE. Upon touchdown, the Griffin deploys a ramp similar to the original Viper deployment [2]. After successful egress, the rover begins its journey towards Shackleton crater to begin scientific data acquisition. A Medium Voltage Direct Current (MVDC) coaxial cable serves as both an electrical transmission line, data link, and mechanical rappel line between the base station and rover. Within the rover, CHARLOTTE is equipped with a Miniature Neutron Spectrometer (Mini-NS) and Mastcam-Z, a sophisticated imaging instrument used on the Mars Perseverance rover. These scientific instruments assist the rover in locating and mapping Lunar resources.

The design of verification testing for CHARLOTTE focused on testing the rover's custom components in relevant environment including thermal vitality, Lunar voyage survivability, tether power transfer and resilience, and the overall mobility functionality in several environments focusing on various aspects of Lunar terrain to achieve Technology Readiness Level (TRL) 5. The CHARLOTTE Comprehensive Testing Plan (CTP) was developed in Phase I prior to the detailed design and was used to drive design requirements for the rover. To maximize success during environmental testing, extensive simulation was conducted for each environmental test and used to inform the detailed design. During environmental testing, component level thermal cycling was conducted to ensure the rover would survive the thermal boundary into a PSR in tandem with thermal-vacuum (TVAC) validation tests for critical components including the rover's foot (which serves as a thermal barrier between the Lunar surface and the vehicle), the tether, and high-emissivity thermal radiator. Dusty abrasion mean-time-to-failure (MTTF) testing was conducted on the power transmission tether to measure the risk of critically damaged tether from rubbing against Lunar rocks with regolith as an additional abrasive media. The rover lighting system was subject to darkness to validate illumination of the hazard avoidance cameras (Hazcams) and navigation cameras (Navcams). To ensure CHARLOTTE's shoes provide sufficient traction in a Lunar environment, the shoes were tested while the rover remains partially suspended in a microgravity harness atop a bed of Lunar regolith simulant.

Through comprehensive laboratory and outdoor testing, the CHARLOTTE team was able to gather valuable insight and data on the performance of the rover under various environmental conditions. From this data it was determined that its mechanical, electrical, and thermal systems were capable of enduring extreme temperature variations, its traction shoes were effective in Lunar dust and other regolith simulants, and its mobility system is a simple and robust solution for traversing steep and rocky terrain.

PROBLEM STATEMENT & BACKGROUND

Mission Scenarios and Use Cases

Wheeled rover vehicles have several terrain limitations which make them unsuitable for PSR crater exploration. Typical state-of-the-art wheeled rover platforms can only descend slopes up to 30° [3]. The CHARLOTTE rover is designed to circumvent the technical challenges faced by wheeled rovers by altogether replacing wheels with an ultra-stable leg formation. Utilizing legs instead of wheels allows the rover to strategically climb with well-placed foot positions over rocky or fluffy regolith terrain. Although most of the Lunar surface is traversable by traditional rovers, some of the most geologically interesting and commercially important areas are guarded by steep, inaccessible areas. The leftward plot of Figure 1 below shows the relative density of slope gradients on the Lunar surface based on data collected about the Lunar south pole from -88.0 to -90.0 degrees North latitude [4][5].The corresponding surface height map and slope data used to create the density plot is to the right [6].

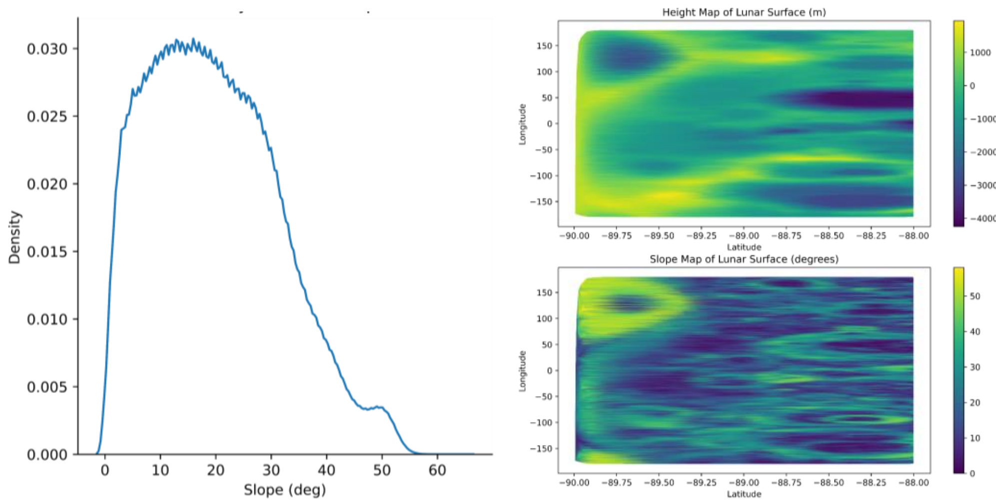
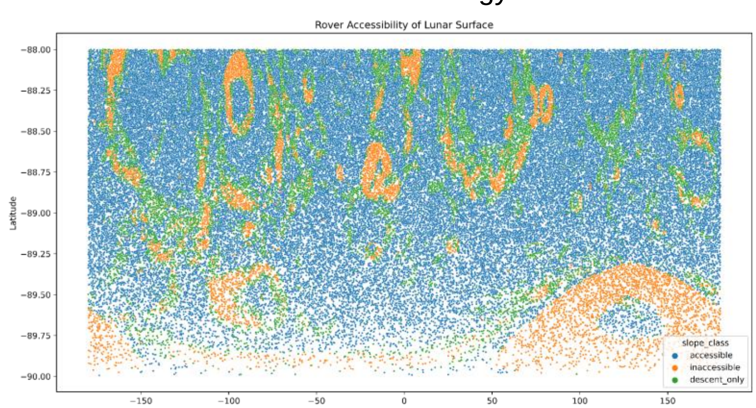


Figure 1. Density of slopes on Lunar south pole (left), Map of Lunar height and slopes (right)

To further illustrate the necessity for a rover platform that can traverse steep Lunar slopes, the Lunar surface data was categorized by accessibility based on the table in Figure 2 below. It is clearly visible that several areas are surrounded by slopes that render the area completely inaccessible to wheeled rover technology.



Slope	**Class**
0-25	Accessible
26-35	Descend
36+	Inaccessible

Figure 2. Map of wheeled rover accessibility (left) Accessibility classification table (right) [6]

In addition to steep terrain, the Lunar surface is subject to temperature swings exceeding several hundreds of degrees Kelvin over the Lunar day-night cycle. Additionally, the temperature change between the Lunar PSR and the sunlit region is thought to be an abrupt transition. These temperature extremes present major thermal challenges to any exploratory Lunar rover.

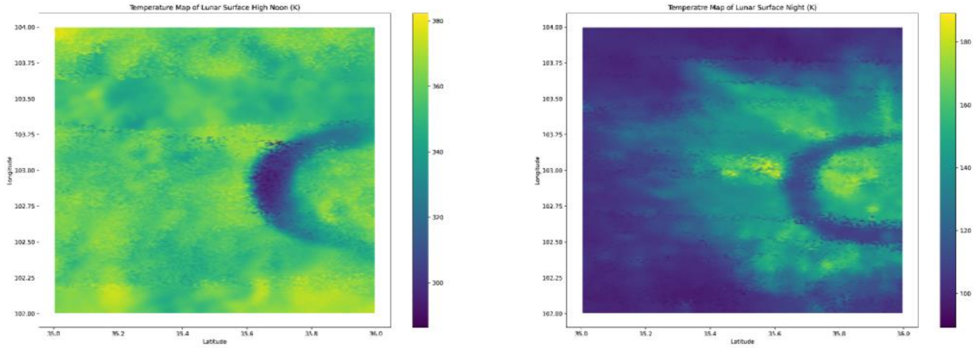


Figure 3. Temperature heat map of Lunar surface at high noon (left) and midnight (right) [6]

Overall Approach

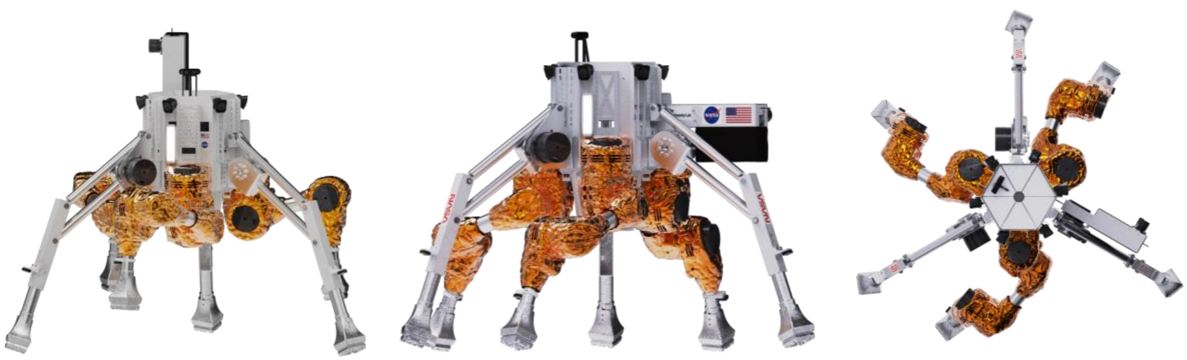


Figure 4. CHARLOTTE prototype rover front view (left), side view (middle), top view (right)

CHARLOTTE is inspired by the Dante II robot [7], which was designed to venture into volcanos using an eight-legged design. The research on Dante II, conducted in the late 1990's, proved that legged robots which alternate steps to ensure stability can effectively traverse steep slopes with a variety of surface terrain ranging from jagged rocks, to soft soil. The CHARLOTTE team utilized this research to inform their design while reducing the number of legs and increased mobility to allow omnidirectional movements.

CHARLOTTE's unique six-legged leg configuration ensures the rover is always stable with at least three feet on the ground while also providing the rover with omnidirectional translation, in-place rotation, and 6-DOF pose control for the Mastcam-Z and Navcam systems. To navigate extreme terrain, CHARLOTTE uses a rappel system which acts as a safety cable allowing it to safely descend into the crater. The rappel cord is anchored to the lander and serves as a power and data link between the rover and the lander at the top of the crater. During Lunar night when the solar generating station is shaded, the rover hibernates by raising three of its legs to reduce thermal conduction into the Lunar surface and uses its on-board battery to maintain thermal setpoints until power is restored through the transmission rappel. The core principle of

CHARLOTTE's thermal design is to remain robust and tolerant to heat fluctuations and implement several passive thermal control mechanisms alongside active heating to accomplish thermal homeostasis within the rover. To reduce complexity, mass, and risk, CHARLOTTE has no active cooling and no coolant circulation system. All thermally sensitive components, namely electronics and batteries, are close to the passive radiator panel to reduce the conduction path through thermal straps for heat shedding.

A core component of the rover's traverse strategy and science mission is its science payload which is housed inside the hexagonal carapace (body). CHARLOTTE was designed to carry the Mastcam-Z system which was developed at ASU for the Mars 2020 Perseverance rover mission, to image and characterize the surrounding Lunar geological features such as regolith, ridges, fissures, boulders, and small craters. In addition, the Mini-NS neutron spectrometer, which was also developed at ASU for the Artemis-1 LunaH-Map Cubesat mission, is mounted on the body of the rover for identifying concentrations of water ice on the Lunar surface.

CHARLOTTE was designed to perform its missions either via teleoperated control with the capability for autonomously using onboard sensing and navigation systems. The system is designed to conduct a traverse via a set of global waypoints from its starting location. These waypoints will be given to provide the best route for the rover based on previously-known remote sensing information about the terrain. If little information is known about the terrain and intermediate waypoints cannot be given, an end point will be supplied and the rover will attempt to use imaging and onboard autonomous navigation (based on past Mars rover experience) to find the best route. The rover can build a digital terrain model of its surroundings using stereoscopic Navcams in tandem with its six Hazcams. Although the Navcams and Hazcams primarily serve as engineering and navigation cameras, they can also be used for closely imaging the Lunar surface and extracting information about rock sizes and number density. This analysis can be performed as post processing on Earth with the images captured from the engineering cameras sent to mission control. The terrain below each leg can be analyzed prior to foot placement allowing the rover to choose stable footing.

PROJECT DESCRIPTION

Description of the Concept

CHARLOTTE's design concept is a 6-legged rover that prioritizes stability, safety, and reliability, while also aiming to minimize complexity and overall system mass. The rover accomplishes this by employing a simple walking philosophy which keeps at least 3 feet on the ground at all times. CHARLOTTE has a total of 6 legs of which three are single degrees of freedom (1-DOF), and three are 3 degrees of freedom (3-DOF). Using 1-DOF legs presents substantial weight and power savings over higher degrees of freedom, while the 3-DOF legs allow the rover to rotate in-place and translate in any direction. The 3-DOF legs also allow the rover to have more precise foot placement in rocky terrain.

Figure 5: CHARLOTTE CAD model render (left), CHARLOTTE during Environmental Testing at Hayden Butte

The concept for CHARLOTTE started with research of current and past state-of-the-art mobility platforms and ideation of new mobility platforms. Since the main goal was to have the rover transverse steep terrain of the Lunar craters, the concept for a 6-legged hexagonal rover was chosen to ensure that three legs would always be touching the ground and the center of mass is central and low to the ground to increase stability. To simplify the number of motors, three of the legs were chosen to be 1-DOF to raise and lower the rover while the remaining three legs were chosen to be 3-DOF to allow for omnidirectional movement. To further increase stability on steep terrain, a rappel tether was added to provide mechanical support and to provide the vehicle with power and data communications. The main design assumption for this rover is that CHARLOTTE will be tethered to the lander and it will be able to receive power and data communications.

CHARLOTTE is made up of seven main subsystems: carapace, 1-DOF legs, 3-DOF legs, foot, tether, cameras, and system control and user interface.

Carapace

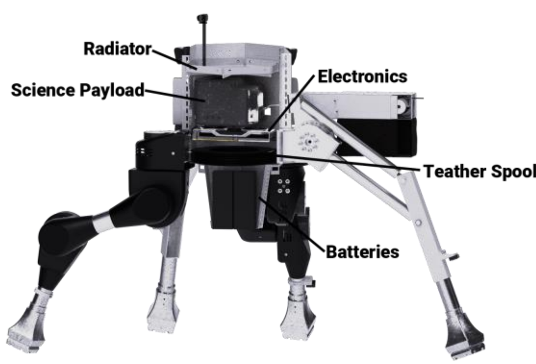


Figure 6. CHARLOTTE Carapace cross sectional view

The carapace is the main chassis of CHARLOTTE and is constructed with 5052 aluminum. It is based on a monocoque fuselage design with an outer skin and interior formers and bulkheads to stiffen the structure and is riveted together using aluminum rivets. The carapace houses the battery, tether spool, electronics, science payloads, and radiator. On the external surfaces of the carapace, the legs are mounted with fasteners to the bulk heads and DIN Rail payload mounts are attached to each side for cameras and lights. The thermal radiator is integrated into the top of the carapace and was designed to passively dissipate heat from the electronics while being optimized for Lunar South Pole operation by using walls of the carapace as shrouds to shield the radiator from the Sun.

1-DOF Leg

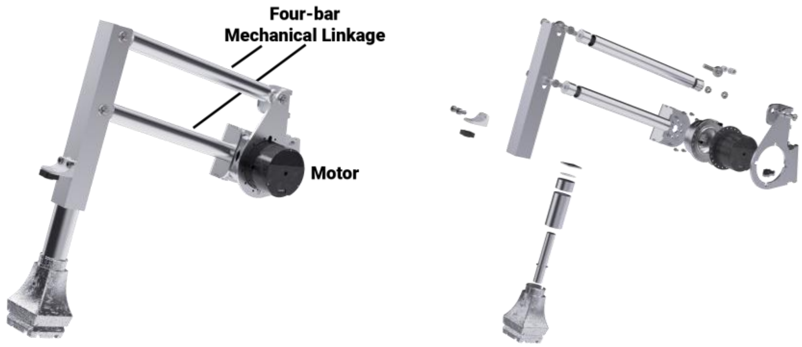


Figure 7. 1-DOF Leg (left), 1-DOF Leg exploded view (right)

The 1-DOF leg allows the robot to stabilize itself during locomotion while the 3-DOF legs are moving into the next position. The leg is made up of the motor and a four-bar mechanical linkage which allow a single motor to move the foot vertically during locomotion. The motor is manufactured by Umbratek motor and includes 280 Nm of torque, integrated 180:1 harmonic drive gearbox, encoder, and mechanical break. The four-bar linkage is made using 5052 aluminum sheet metal brackets and tubing.

3-DOF Leg

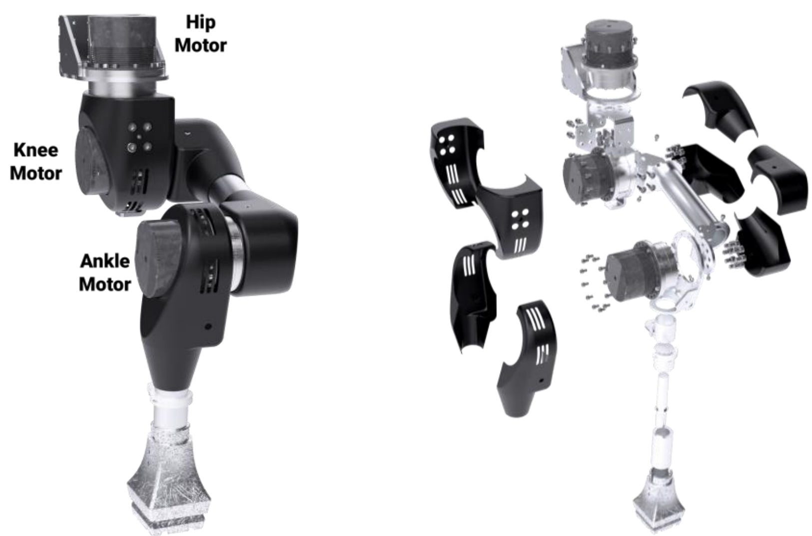


Figure 8. 3-DOF Leg assembly (left), 3-DOF exploded view (right)

The 3-DOF Leg is made up of three motors: hip, knee, and ankle. The 3-DOF leg is the primary means of locomotion and allows the rover to move in any direction and to dynamically adjust each leg for varied terrain. Each motor is connected using 5052 aluminum sheet metal brackets and tubular leg segments. The motor is manufactured by Umbratek motor and includes 280 Nm of torque, integrated 180:1 harmonic drive gearbox, encoder, and mechanical break.

Foot

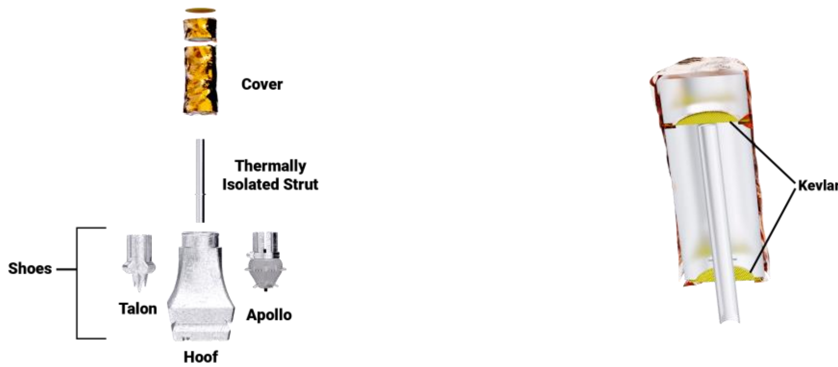


Figure 9. CHARLOTTE foot assembly exploded view and shoe designs (left), Insulator cross section (right)

The foot is made up of two components: the insulator and the shoe. The insulator was designed to create a thermal break between the foot and the leg to maximize thermal resistance while also maintaining structural rigidity. Numerous insulator concepts were evaluated, and the final design was constructed using kevlar weave to suspend the foot to eliminate any metal conduction path. The shoe was designed to maximize traction and stability. Various shoe designs were created as shown in Figure 8 above. The foot was designed such that a different shoe could be chosen for either the 1-DOF or 3-DOF legs as well as for specific terrain conditions encountered. For laboratory testing the shoe used was a simple tennis ball to reduce damage to hard flooring. For softer terrain, the mesh shoe inspired by the wheels on the Apollo Lunar Roving Vehicle (LRV) was chosen. For rocky terrain the hoof shoe which was inspired by the feet of mountain goats was chosen. For the 1-DOF legs the talon shoe was designed to provide maximum traction during locomotion.

Tether

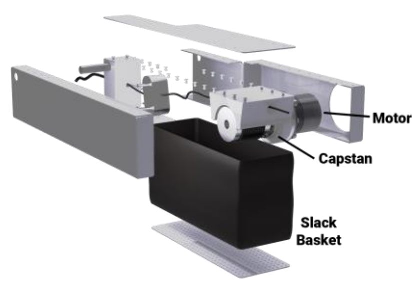


Figure 10. Tether Boom assembly exploded view

CHARLOTTE's Medium Voltage Direct Current (MVDC) cable serves as the exclusive power and data link between the rover and generating base station, as well as a mechanical tether for extreme steep terrain. Design decisions pertaining to the cable were made to minimize the linear density of the cable while maintaining sufficient electrical and mechanical properties. DC power transmission was selected over AC for several reasons. DC was selected to utilize all of the cross-sectional area of the electrical conductor and minimize skin-effects in power transmission. Additionally, with a DC link, power-factor correction equipment such as shunt reactors and capacitors will be minimized, and the mass and complexity of the system thereby reduced. For communications between the base station and rover, a radio frequency (RF) signal is injected into the shared coaxial cable within the tether via an RF bias tee on either end of the cable. Despite distortion harmonics in the MVDC power converter ripple, the injected RF signal is a high enough frequency that it will not encounter noise from the power transmission component of the line. A coaxial cable design study was conducted to compare combinations of conductor and dielectric materials. Using a fixed power transmission of 500W, the linear density of the cable was computed over a voltage sweep. Cross sectional area of the cable conductor and shield was determined by the material ampacity per circular mil, and the concentric dielectric ring thickness was determined based on the dielectric breakdown voltage of the dielectric material. These constraints create a relationship between linear density and operating voltage with a global optimum which was used to set the operating voltage and physical geometry of CHARLOTTE's tether coaxial cable.

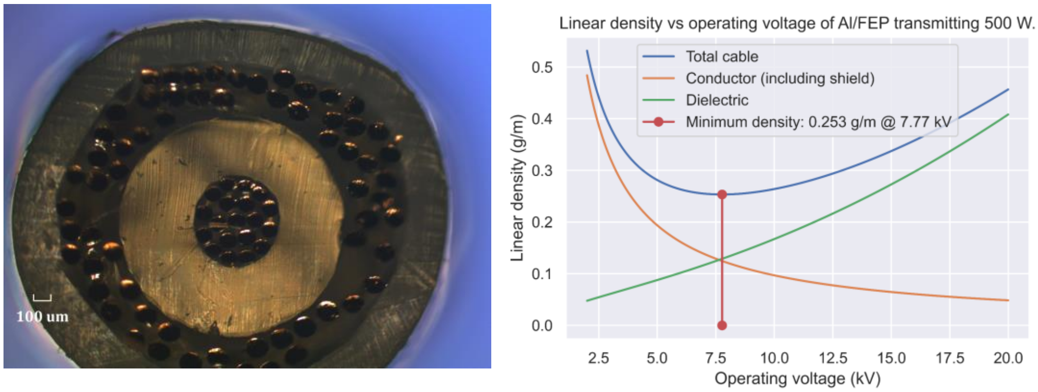


Figure 11. Microscope Image of tether DUT cross section (Left), Analytical results of tether voltage rating vs tether linear density (Right)

Figure 9 above shows a microscope image of the coaxial cable collected by the CHARLOTTE team on the cable used for testing, and the operating voltage sweep vs linear density of the optimal Lunar materials, Aluminum conductor and FEP dielectric, at 500 Watts of power transmission on the rightmost figure. Although the selected off-the-shelf coaxial cable [8] is close to the analytically ideal cable, it differs in several key areas.

	Optimal Coax	**Coax DUT**
Conductor	Silver plated Aluminum	Silver plated Copper
Dielectric	FEP	FEP
Rated Voltage	7.77 kV-DC	18 kV-DC
Conductor Diameter	172 micron	483 micron
Dielectric Thickness	78 micron	839 micron
Shield Thickness	21 micron	127 micron
Linear Density	0.253 g/m	17.81 g/m

Table 1. Coax Cable DUT Comparison

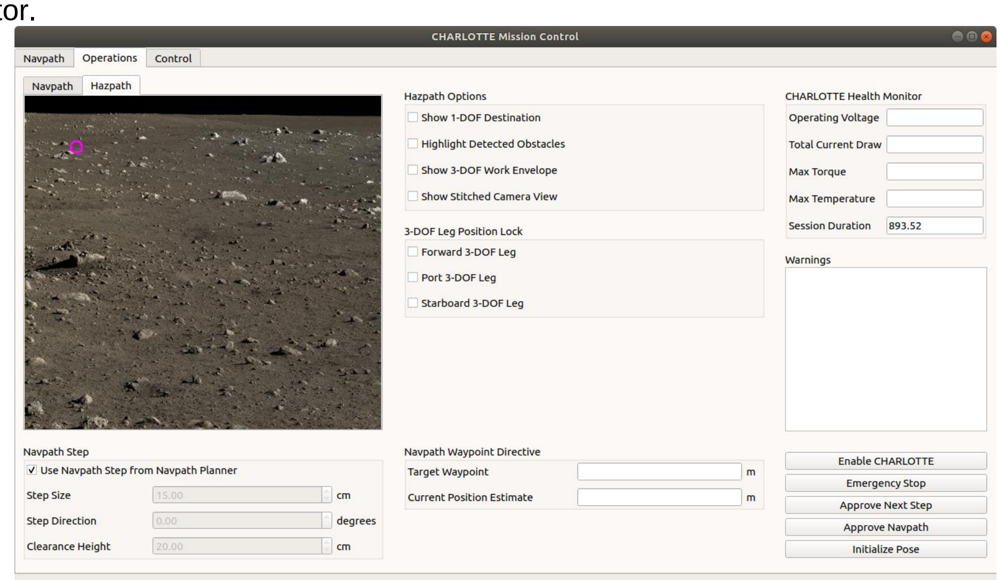
Cameras

Outside of the Mastcam-Z instrument, CHARLOTTE is outfitted with two types of imaging devices for mobility. Six hazard avoidance cameras (Hazcams) are mounted to each face of the hexagonal carapace and angled downwards to provide 360 degree visual feedback around the rover for the purpose of foot placement in extremely rocky terrain. A navigation camera (Navcam) is mounted in the front of the rover perpendicular to the carapace for long-distance navigation planning as shown in the figure below. Originally, the Navcam and Mastcam-Z were mounted to an elevated gimbal on a mast protruding upwards from the carapace's axis of symmetry. From vibrational analysis it was determined that this design would require significant structural support and therefore the design was modified for a simpler solution to mount the Mastcam-Z and Navcam in the carapace and controlled by adjusting the pose of the rover to direct the cameras and thereby reducing motors and actuators and making the design more robust for flight readiness.

Figure 12. Hazcam video feeds of each leg (left), Navcam video feed (right)

Control System and User Interface

The CHARLOTTE Mission Control is a custom desktop application built in C++ and Python for a Linux operating system which provides a command-and-control environment for the rover using Robot Operating System (ROS). On the Operations page, the operator can monitor the health status of the rover, control the step size, step direction, and clearance height. In addition, the operator can run CHARLOTTE step by step or can provide it with a Navpath which is a set of waypoints that the rover will follow. In addition, the Mission Control includes a Navpath planning page which allows the team to designate a set of waypoints for the vehicle to follow and the Control page which allows the team to monitor and control the position, velocity, and torque for each motor.



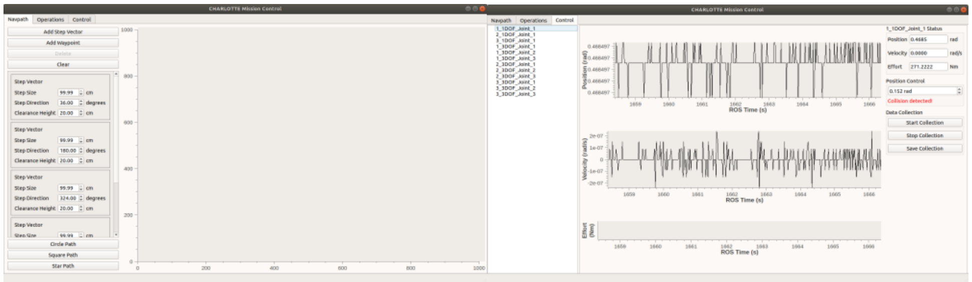
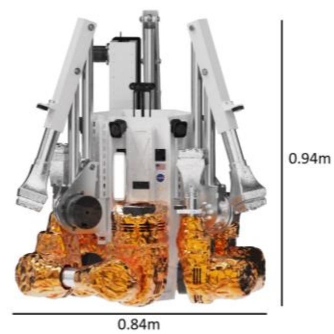


Figure 13. CHARLOTTE Mission Control Operations page (top), Navpath planning page (bottom left), Control page (bottom right)

Technical Specs
Earth Analog Mass: 102 kg
Volume: 0.79 m^3
Stowed Dimensions: height 0.94m, width, 0.84m
Power Requirements: 48V, Peak 147.5W, Average 89.4W
Processing Requirements: 62GB Ram, 6 cpus, 500GB hard drive
Max Translational Speed: 0.75 m/min



Integration with Existing Lunar Landers

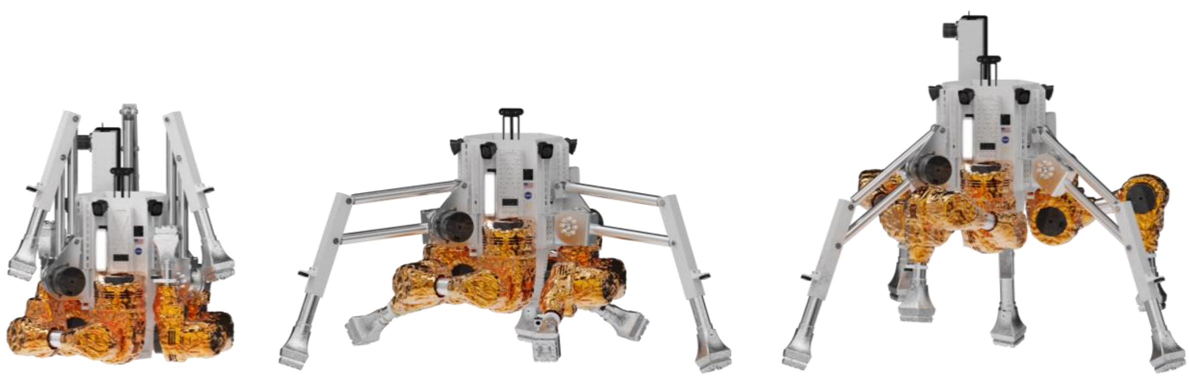


Figure 14: Fully stowed position for flight (left), Partial unfolded position (middle), Fully unfolded position (right)

CHARLOTTE is designed to operate with commercial landers such as the Astrobotics Griffin lander. The Griffin Lander is capable of carrying 500kg payload and can provide 1W/kg of payload [2]. This would allow the Griffin to easily carry CHARLOTTE and provide the necessary power to maintain it during its mission.

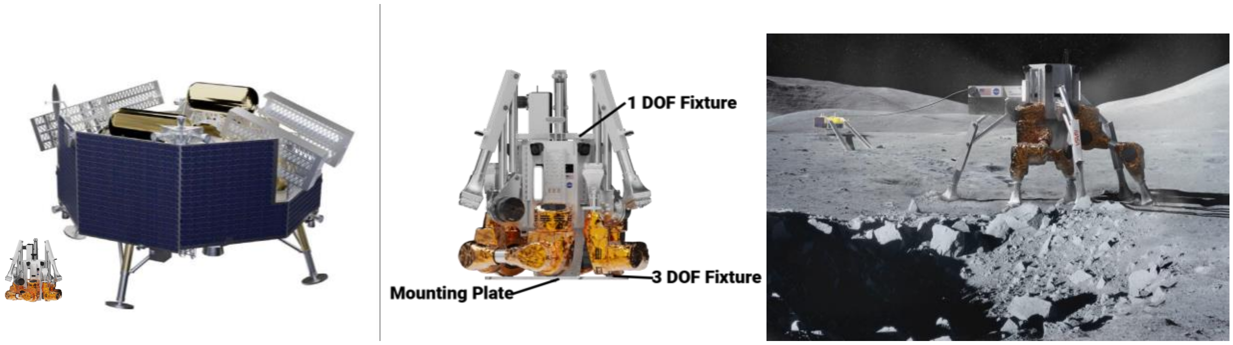


Figure 15. Astrobotic Griffin Lander with CHARLOTTE in stowed position for scale [2] (left) [2], CHARLOTTE flight ready fixtures and mounts, CHARLOTTE and Griffin CAD render (right)

Potential Stakeholders

CHARLOTTE is designed to traverse steep Lunar craters in search of Lunar volatiles such as water-ice. This capability is of great interest to various stakeholders including scientists and exploration teams to analyze the composition of the water and other volatiles for learning information about Lunar geology and commercial space providers who will rely on Lunar water-ice for life support and refueling for extended missions.

VERIFICATION TESTING ON EARTH

Summary

Strategic relevant environment and Earth analog testing was conducted throughout the duration of this development cycle. In keeping with the core values of NASA and space exploration at large, risk mitigation and management is a core tenant of CHARLOTTE's Systems Engineering (SE) team. Treating all doubts, concerns, and potential risks with the respect deserved is the foundation of CHARLOTTE's testing procedures.

In the early SE planning phases, a Comprehensive Testing Plan (CTP) was formulated as a living document to communicate testing procedures and plans to all CHARLOTTE stakeholders. Tests were evaluated and selected based on several factors including cost, timeline, and mission criticality. The team worked to identify as many mission and technology risks as possible and design an appropriate battery of tests to minimize risk and dispel major concerns. By building an intimate familiarity with the environmental hazards posed by the Lunar PSRs and identifying unique features of CHARLOTTE that could be susceptible to these conditions, the team filled the CTP testing tables and descriptions. Each potential susceptibility was broken down into a combination of preliminary simulations and corresponding laboratory and relevant environment tests.

Testing is subdivided into two Phases corresponding to the NIA BIG Idea Phases separated by the Mid-Project Report (MPR). Furthermore, the second phase is subdivided into Phase II-A, encompassing Earth analog tests, and Phase II-B, encompassing laboratory relevant environment tests. Each test was given a testing code which describes the test type with an identification number to help keep track of tests across facilities and researchers. For the sake of space, this section will be limited to a brief overview of the tests conducted including the test's purpose, design, and results. For more detailed information, please refer to the Comprehensive Testing Plan (CTP).

In this section, tests and relevant results will be presented by key category instead of exclusively by their phase and code designation. This is done to help contextualize the tests and their results.

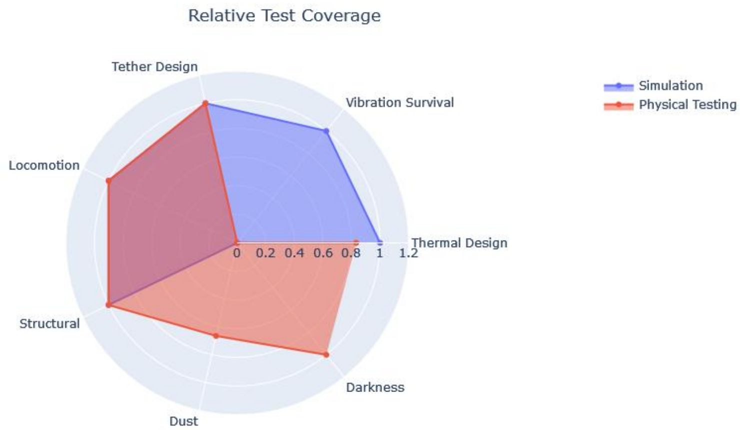


Figure 16. Radar plot describing the relative coverage of testing between computer simulation and physical validation testing

Thermal Design Testing

Thermal design is a fundamental challenge for Lunar exploration, especially in the context of PSR exploration. As such, thermal design was a high priority from the beginning of CHARLOTTE's design cycle. One of the key challenges identified early in the project was the transition between sunlit and permanently shadowed regions of the Lunar surface. If CHARLOTTE were to make the transition during the Lunar day, the vehicle could see a near instantaneous transition in the temperature of the Lunar surface from 400K to 30K [9][10]. Although this temperature drop would be minimized if the rover transitions into the PSR at the coldest time of Lunar night, the thermal divide will persist and could cause critical mechanical failure by way of thermal expansion and contraction. To address this issue, a total of eight computer simulation tests were performed (CHT-SM-001 to CHT-SM-008) as well as two physical validation thermal cycling tests. (CHT-TC-002 & CHT-TC-003) The thermal cycling tests were performed on the 1-DOF (CHT-TC-002) and 3-DOF (CHT-TC-003) legs with motor stand-ins. These tests were performed to meet MIL-STD-1540 (7.3.3) Acceptance criteria with minor alterations to tailor the test to mirror Lunar conditions and deviations due to limitations of the test design.

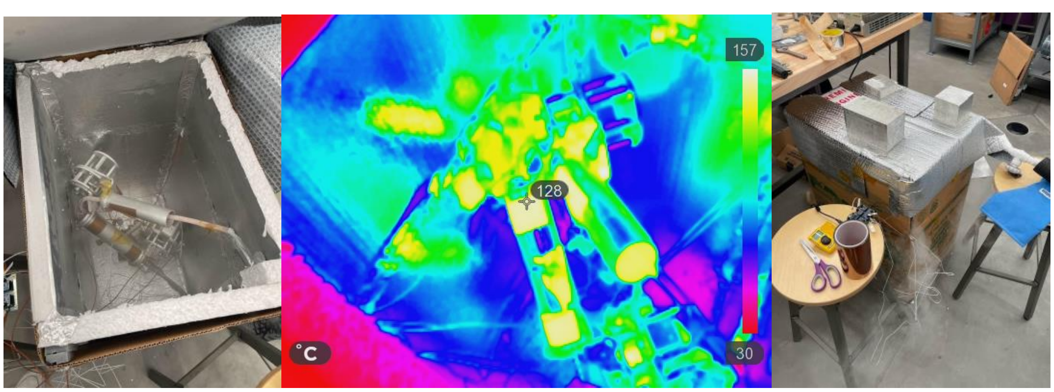


Figure 17. 3-DOF leg during cryogenic cycle (Left), 3-DOF leg thermal image during cycle heating (Middle), Custom large-format thermal cycle chamber (Right)

Each test was conducted in a custom insulative chamber because the DUTs for this test exceeded the capacity of our existing laboratory equipment. Several Kapton heaters were adhered around each DUT to deliver heat during the heating cycle and copper tubing interweaved through the DUT served as a means of fluid transport for the liquid nitrogen (LN2) during the cryogenic stages of the cycle. The 3-DOF leg was exposed to over 34 hours of cycling and the 1-DOF leg endured over 33 hours. A combination of eight K-type thermocouples were placed around each DUT, on the chamber LN2 inlet, and on the exterior of the chamber. Figure 18 below visualizes the collected thermocouple data. The leg temperature trace corresponds to the average temperature of the leg while the shaded bands surrounding the leg temperature trace show the standard deviation of the measured temperatures.

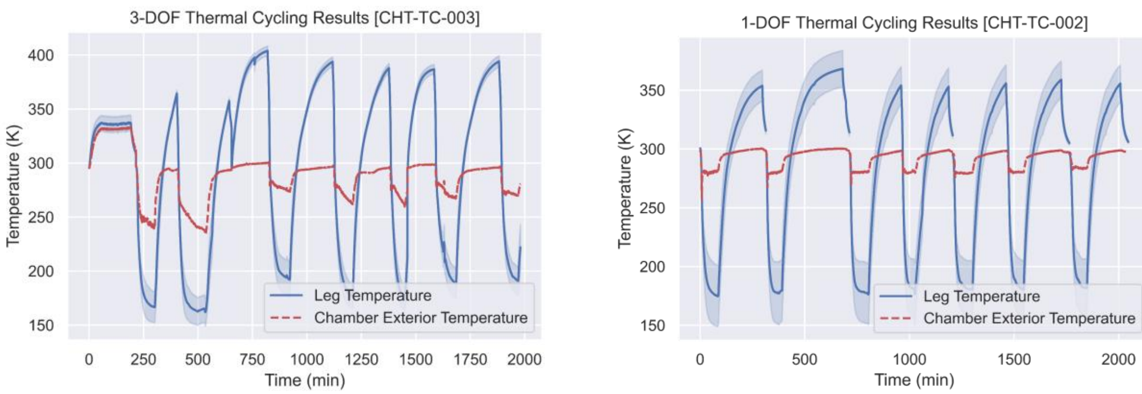


Figure 18. Results of CHT-TC-003 (Left), Results of CHT-TC-002 (Right)

Device Under Test	1-DOF Leg	3-DOF Leg
Test Code Designation	CHT-TC-002	CHT-TC-003
Thermal Cycles	7	7
Test Sessions	5	5
Total Test Minutes	2046	1980
Heater Power	82 W	104 W
Max Temperature	387.15 K	410.65 K
Min Temperature	146.15 K	143.4 K
Max Temperature Swing	229 K	267.25 K
Mean Temperature Swing	194.45 K	221.75 K

Table 2. Thermal Cycling Test Results

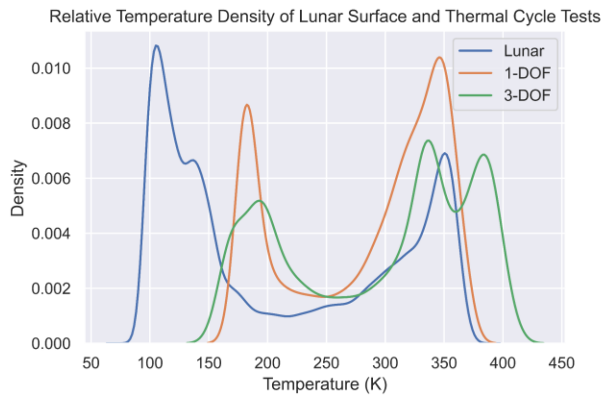


Figure 19. Comparative temperature density of Lunar surface vs thermal cycle DUTs

Figure 19 above shows the relative kernel density estimate of temperatures comparing thermal cycling test data results with data collected from the Lunar south pole by Willimas et al. via the Diviner probe. This plot gives context to the thermal cycling in a Lunar environment in addition to the strength of MIL-STD-1540 (7.3.3) acceptance criteria for component-level thermal validation. Thermal cycling tests (CHT-TC-002 & CHT-TC-003) were able to reach the upper bound of expected Lunar temperatures, but unable to reach the extreme cryogenic temperatures that the Lunar night would provide. This discrepancy is partially due to the use of liquid nitrogen (~77 K) as a cryogenic cooling agent instead of liquid hydrogen (~20 K), and also due to limitations of the thermal cycling chamber constructed for the oversized DUTs. The chamber limitations are clearly indicated by the ambient temperature probe placed on an exterior surface of the chamber which is a visible trace in Figure 19. The exterior temperature of the chamber drops substantially in the cooling cycles due to inadequate insulation.

Another consideration of the thermal design was that of thermal isolation between the rover and the Lunar surface. In order to minimize the effect of the variant temperatures of the Lunar surface and ensure simple control over the rover’s thermal homeostasis, CHARLOTTE’s foot insulator assembly was tested to ensure the kevlar-membrane design would provide sufficient thermal isolation. This test (CHT-TO-001) was conducted in a thermal vacuum chamber (TVAC) to simulate the Lunar environment.

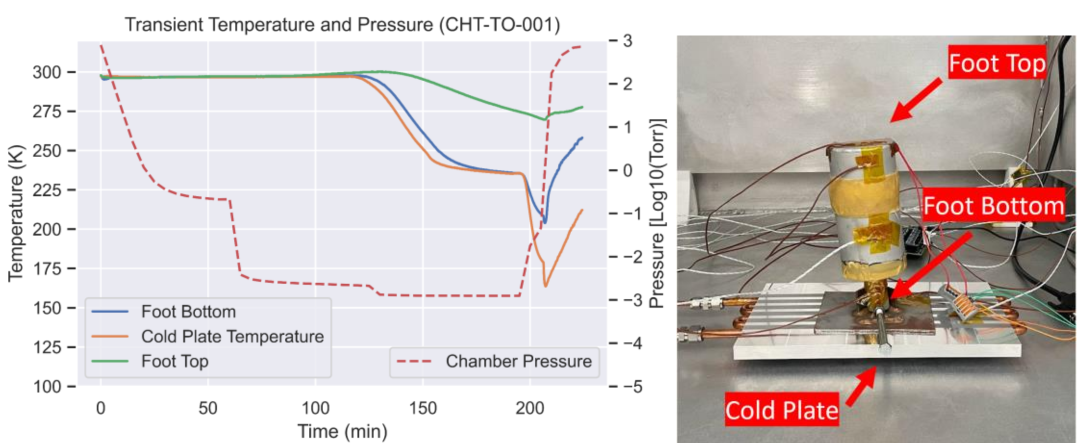
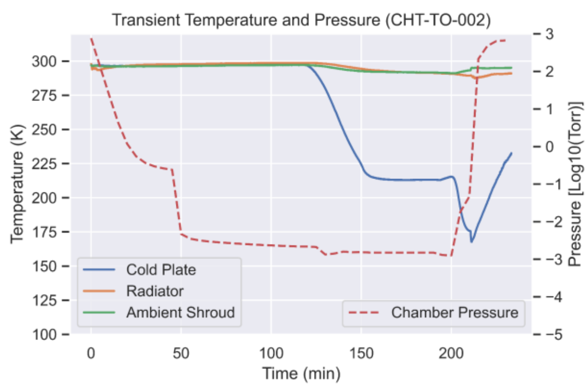


Figure 20. Transient temperature and pressure data for thermal break test (Left), Corresponding sensor positions on thermal break DUT (Right)

CHARLOTTE's primary mechanism for shedding excess heat is through the six symmetrical radiator panels that make up the radiator assembly atop the vehicle. This system passively radiates excess heat to deep space. The radiator panels are coated with Aeroglaze A276 white polyurethane coating to control absorptance and emittance parameters. For radiator testing (CHT-TO-002), a single radiator slide DUT was suspended with thin nylon strings directed to face an LN2 cold plate coated with Aeroglaze Z306 black polyurethane coating. Controlled power was injected into a Kapton heater on the radiator, and the cold plate was cryogenically cooled to validate the thermal design of the radiator panel.



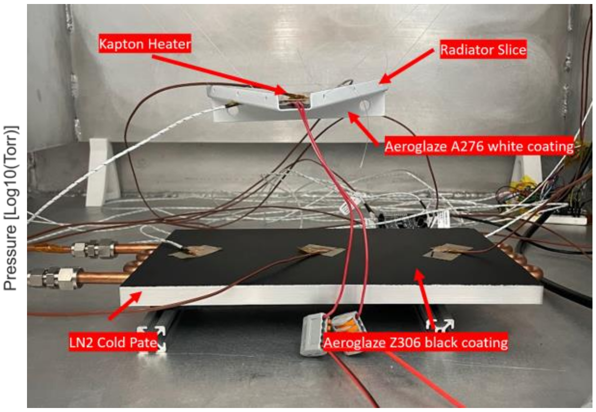


Figure 21. Transient temperature and pressure data for CHT-TO-002 (Left), Test apparatus for CHT-TO-003 (Right)

To validate the stable operation of the tether as a power transmission line across the sunlit and PSR boundary, a thermal operation test was performed in vacuum conditions with the tether split between a heated and cooled side in extreme proximity to each other. This test is to determine if an extreme thermal gradient would degrade the dielectric properties by causing thermal cracks to form. The DUT from this test was electrically tested at the operational current delivery (66 mA) for the duration of the test to simulate cable self-heating from Ohmic losses. After this test, the DUT was tested for a second round of MVDC testing (CHT-EE-002) to check for dielectric breakdown degradation.

Parameter	Test Value	Simulated Value
Foot Thermal Conductivity	17.8 mW/K	13.4 mW/K
Radiator Thermal Transmittance	3.32 W/Km^2	1.21 W/Km^2

Table 3. Extracted parameters vs simulation results

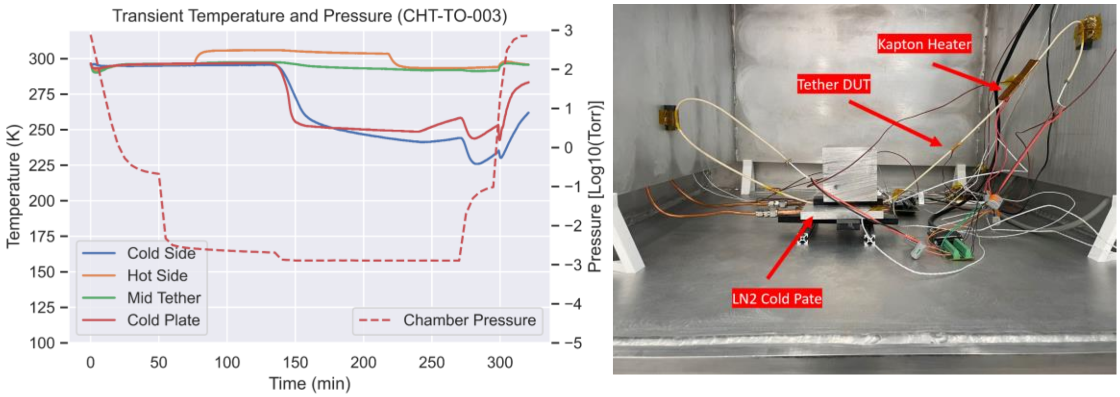


Figure 22. Transient temperature and pressure data for CHT-TO-003 (Left), Test apparatus for CHT-TO-003 (Right)

Device Under Test	**Foot**	**Radiator**	**Tether**
Test Code Designation	CHT-TO-001	CHT-TO-002	CHT-TO-003
Tether Transmission Current	N/A	N/A	66 mA
Heater Power	750 mW	3.2 W	487 mW
Hot Side Max Temp	300.15 K	303.15 K	305.9 K
Cold Side Min Temp	203.9 K	212.9 K	225.9 K
Maximum Temp Delta	65.75 K	79.5 K	68.0 K
Vacuum Pressure	1.24 mTorr	1.26 mTorr	1.27 mTorr

Table 4. Thermal operation test highlights

Tether

Dust abrasion testing was conducted on the tether. This test (CHT-DT-003) was performed using Lunar Regolith Simulant to abrade the tether performing an oscillatory translational motion of 8in of the tether across a rock submerged in the LMS-1 Lunar Mare Simulant from Exolith Labs. The test provides insight into the durability of the tether during CHARLOTTE's mission. From this test it was found that the mean time to failure was 54 cycles. It is recommended that better abrasion resistant materials are found for the tether system for Lunar operation to reduce risk.

Figure 23: Tether dirty abrasion test chamber (Left), Resultant condition of tether DUT after CHT-DT-003 (Center), Custom tether abrasion test machine (Right)

Power to the rover is transmitted via a medium voltage direct current (MVDC) coaxial cable operating at approximately 8 kV. With the high operating voltage, dielectric breakdown becomes a consideration which these tests aim to address. The coaxial MVDC conductor was first tested to 8kV for dielectric breakdown and then placed in a thermal vacuum chamber for thermal operation testing. Following the thermal operation testing, the conductor was retested with 8kv for dielectric breakdown. The coaxial cable successfully passed all tests and was found to be a sufficient solution for providing power to CHARLOTTE for Lunar operation.

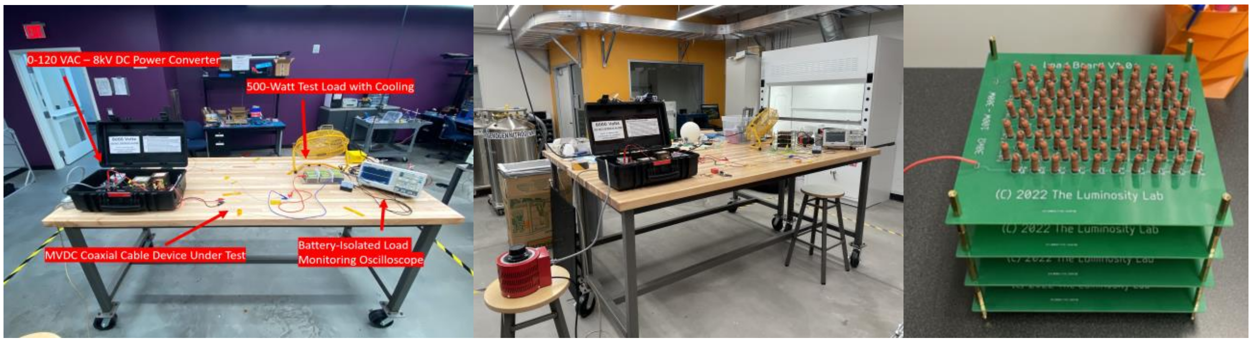


Figure 24. MVDC power test setup for CHT-EE-001 (Left), Test setup for CHT-EE-002 (Middle), 500 W 8kV resistor load bank for test (Left)

Structural

For the purposes of this project, the team designed an Earth Analog (EA) prototype of CHARLOTTE's mobility platform as well as Lunar components unique to CHARLOTTE. Because of the excessive gravity of Earth compared to the Moon, there are several design deviations between the EA prototype and what would be a Lunar model. For one, the motors driving CHARLOTTE's joints and even the limbs themselves must be much heavier to overcome Earth's gravity whereas these components would be substantially lower mass when designed exclusively for Lunar gravity. As Lunar gravity is approximately a third of Earth gravity, the torque experienced by the rover's leg joints will be reduced by a factor of three which leads to a motor with substantially less mass and power consumption. With that in mind, the EA prototype of CHARLOTTE serves as a demonstration of the locomotion platform and its capabilities without the need for a gravity harness for testing in steep terrain. Using the EA prototype's mass and power consumption parameters must be analyzed knowing the implications of Lunar micro-gravity and its effects at miniaturizing many of the mechanisms aboard CHARLOTTE.

Vibration Survival

Vibration analysis was conducted in-lieu of physical vibration testing because the CHARLOTTE prototype built was designed for Earth gravity. Therefore, physical vibration testing of the heavier Earth analog prototype was determined to be of low value and high risk and therefore computer simulation was chosen to evaluate the prototype with motor masses which would be used in a Lunar prototype. This allowed the team to evaluate the structural integrity of the rover design and the flight fixtures which were designed to secure CHARLOTTE during flight as specified by GSFC-STD 7000. From the vibration analysis it was found that the max stress exceeded the yield strength of 5052 Aluminum in the carapace. From this analysis, it's recommended that the regions of high stress be reanalyzed and redesigned to ensure the max stress satisfies an Ultimate Factor of Safety (FOSULT) of 1.5 [11].

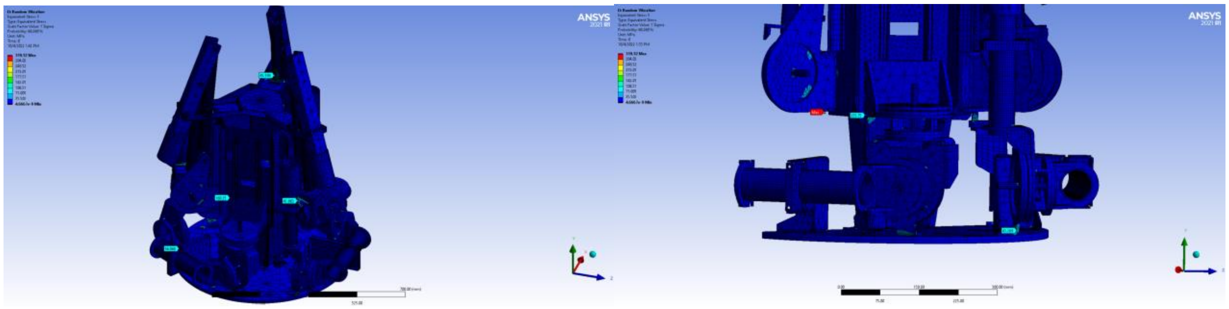


Figure 25. Vibration Simulation Results

Dust

Dust testing (CHT-DT-001) was conducted in the Interplanetary Initiative Lab using a custom designed sandbox which held 100kg of LMS-1 Lunar Mare Simulant along with 300kg of crushed granite (¼ minus) separated into separate containers. This allowed the team to test the shoe designs on Lunar and Earth analog regolith. The sandbox dimensions are 8ftx8ftx12ft and include a gantry to act as a gravity harness and for moving CHARLOTTE in and out of the sandbox during testing.

Figure 26. CHARLOTTE Dust Testing without gravity harness (left), with gravity harness (right)

Lunar Shoe Test

During dust testing both the hoof and Apollo shoe were tested on Exolith Lab's LMS-1 Lunar Mare Simulant. The hoof shoe performed highly in these conditions due to its inner chamber and outer form design. Its middle cavity was found to catch and compact regolith forming stable ground, while the exterior form reaches max width just above the inner cavity and an additional outer catch. The Apollo shoe was found to maintain its wire form through Earth and Lunar gravity testing and showed less slip as compared to feet with tennis balls which were used for indoor laboratory testing.

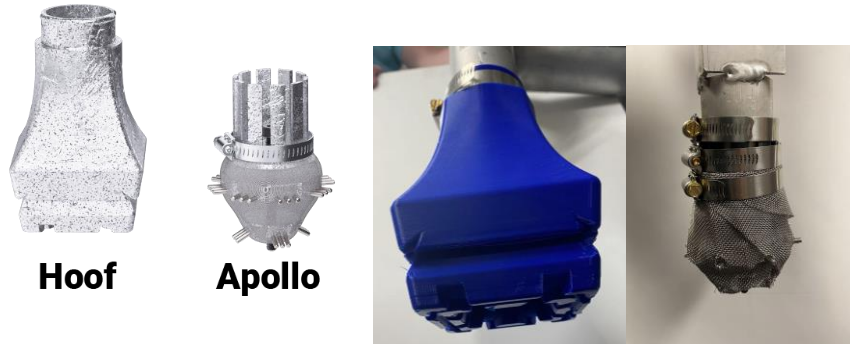


Figure 27. CHARLOTTE shoe prototypes, CAD renders (left), physical prototypes (right)

Darkness

Laboratory Darkness testing was conducted at the ASU Drone Studio which is a 10,000 sq.ft indoor facility with the ability to shut off all light sources. The facility was used to test the rover's lighting systems in a controlled dark environment. Two tests were performed: the first test was of the lighting systems while the rover is stationary to determine the beam distance and spread, the second test was to conduct a series of maneuvers and record the data from the cameras to determine the ability of the cameras to identify objects in a dark environment. From these tests it was found that the lights were capable of illuminating objects as far 20ft from the rover. This was found to be satisfactory for the Hazcams for the 3-DOF legs which have a max field of view of 7.5ft from the rover and for the Navcam which has a range of 9ft for depth sensing. Potential improvements would be to add additional lighting to better illuminate the 1-DOF legs and a long range lighting solution for the Navcams. In addition to laboratory testing, darkness testing was conducted at Colton Crater. This allowed the team to fully test CHARLOTTE's lights and camera systems in a crater analog with terrain features.

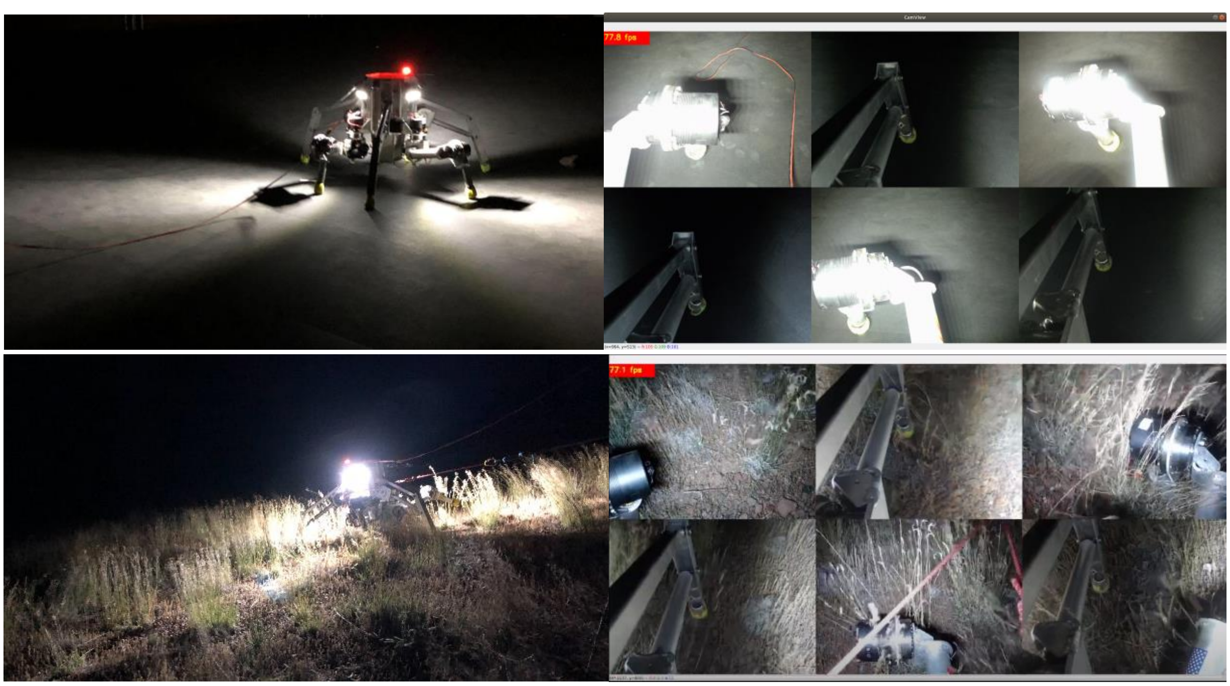


Figure 28. Darkness Testing, Indoor Testing (top left), Indoor Hazcams video feeds (top right), Outdoor testing at Colton Crater (bottom left), Outdoor Hazcam video feeds at Colton Crater (bottom right)

Locomotion

Locomotion testing was conducted at Hayden Butte on the ASU campus as well as at Colton Crater near Flagstaff Arizona. The location of each test is shown in Figure 30 below.

Figure 29. Earth Analog Testing Sites, Hayden Butte, Tempe AZ (left), Colton Crater, Flagstaff AZ (right) yellow line shows rover path during testing

Locomotion testing at Hayden Butte allowed the team to test varied terrain conditions which included large rocks (20cm diameter) and small gravel (0.5cm in diameter). The rover was tested ascending and descending a max slope of 20 degrees from horizontal. It was found that the combination of the three 1-DOF legs and the three 3-DOF legs is a very stable configuration for traversing this terrain.


Figure 30. Earth Analog Testing at Hayden Butte

Locomotion testing at Colton Crater provided an analog crater environment for traversing from the rim into the crater. CHARLOTTE successfully traversed approximately 350 linear feet in 4 hours which included estimated 275ft downhill traverse, 25ft horizontal traverse, and 50ft uphill traverse over slopes ranging from 5-25 degrees unassisted (without reppel tension).


Figure 31. Earth Analog Testing at Colton Crater

SAFETY PLAN

The goal of this safety plan was to properly identify any potential testing hazards and plan accordingly to eliminate potential risks during testing. This plan outlines facilities and testing hazards, planned mitigations, and required personal protective equipment used during testing.

Laboratory Testing

Vacuum cryogenic testing, high voltage tether testing, and Lunar regolith testing were conducted by certified lab technicians in a laboratory environment following required safety measures. Students assisting with testing were required to complete the following safety training: Fire safety, Lab safety, Hazardous Waste management, Liquid nitrogen safety, and Compressed gas training. All laboratory testing was conducted under ASU lab safety guidelines by designated lab technicians in the ASU Interplanetary Initiative Lab located in Sun Devil Hall Room #160.

Outdoor Environmental Testing

For environmental testing of the system, the team conducted outdoor testing of the rover's mobility system in accordance with ASU Environmental Health and Safety (EHS) department Standard Operating Procedures (SOP) for field testing and in accordance with local and state jurisdiction. Prior to testing, the area was surveyed by the team to determine the specific locations for the testing sites. Prior to testing, the weather and environmental conditions were assessed to maintain safe testing conditions. During incline testing, the rover was tethered at all times to the ground to prevent any unintended slippage on the terrain and the rover was equipped with dual redundant emergency stops mechanisms for safe operation.

Medium Voltage Safety Procedures

A subset of electrical testing was conducted with a medium voltage (MVDC) converter in order to test the dielectric breakdown properties of a coaxial power transmission cable. Measuring equipment was isolated from the mains power with a battery pack to mitigate the risk of a fault occurring due to incorrect measuring. The converter was enclosed in a protective case with two locks keyed separately. Each key was given to a different member of the team to ensure that at least two people must be present in order to open the equipment case. During medium voltage testing, all test facilitators were required wear safety glasses and stand at least one meters away from the “Device Under Test” (DUT) and test equipment at all times. A single qualified instrument operator was allowed within the three meter radius in order to facilitate the test safely. Testing bystanders were equipped with a rescue hook and ABC Fire Extinguisher in the event that the operator was exposed to high voltage. The voltage converter case was equipped with appropriate warning symbols and relevant instructions and labeling and the converter source plug was locked with a separate key for additional safety.

Personal Protective Equipment

Electrical PPE

The operator was grounded during testing and was required to wear electrical/arc flash PPE, Class 2 rubber gloves which are to meet both ASTM D120 and NFPA 70E standards, electrical compliant shoes, and was prohibited from wearing synthetic fabrics or blended acetate in accordance with OSHA guidelines.

Shop/Lab PPE

For testing conducted in laboratory environments, PPE was used in accordance with ASU laboratory requirements. For outdoor testing, protective eyewear was provided and required at all times for individuals conducting rover operation, assembly, or fabrication. All individuals in proximity to the rover during operation were required to wear closed-toed shoes. During machining, fabrication, and welding, individuals were required to wear steel-toe industrial boots and were prohibited from wearing metal rings or loose clothing or lanyards.

Figure 31. Lunar Regolith Simulant Test (Left), Student with rescue hook for MVDC tests (Right)

Rover Safety

The rover was equipped with several features for relevant environment testing in the presence of people. Both hardware breaker and software e-stop switches were integrated on the rover to cut power from the battery and stop all movement respectively. A bright orange safety light is used to ensure that everyone in proximity to the vehicle knows when it is powered on. Test facilitators were instructed to never put their hands within 1 meter of the rover while the rover is operating as indicated by the safety light. All motors on the vehicle were individually fused with automotive blade-style fuses in case a ground fault occurs to mitigate risk. The rover was powered with commercial off the shelf (COTS) lithium-polymer batteries with an internal battery management system (BMS) to keep the battery within safe operating limits.

PATH-to-FLIGHT

To prepare CHARLOTTE for a Lunar mission by 2026, the rover will need to be advanced from TRL 5 to TRL 8 with critical modifications such as designing the rover for a low-gravity environment. To reach TRL 6 the current prototype can be used with modifications to include full autonomous navigation systems, thermal control systems, and egress system in a relevant Earth-analog environment. To reach TRL 7, the Earth-analog design will need to be modified for a low-gravity environment. In addition, the prototype will need to be made with flight ready hardware which includes batteries, motors, cameras, and compute models to test the system in a low-gravity environment.

Key components which need additional qualification for are the tether and deployment system, the feet and thermal insulators, and the systems vibration survival. Physical validation testing for vibration survival (CHT-VB-001, CHT-VB-002) were left incomplete due to the Earth analog prototype being significantly heavier than the Lunar analog prototype. CHARLOTTE needs to pass the full battery of vibration tests in order to be cleared for flight. These are critical systems and will need qualification for flight-readiness.

The team intends to patent all novel inventions and continue development on CHARLOTTE to prepare it for submission to The NASA Innovative Advanced Concepts (NIAC) 2023 Phase I and or Space Technology Research, Development, Demonstration, and Infusion-2023.

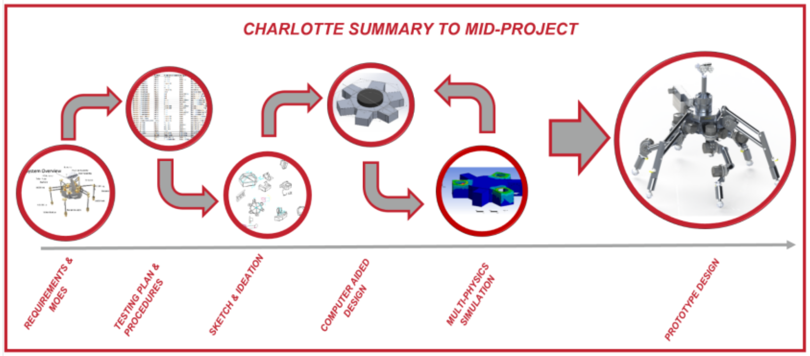
RESULTS AND CONCLUSIONS

CHARLOTTE was designed to carry advanced scientific payloads up and down steep terrain of the Lunar PSRs. Over the course of this project, the CHARLOTTE team successfully designed, built, and tested a six-legged rover which has been validated through Relevant environment testing, System requirements, and Measures of Effectiveness (MOEs) for each critical component to achieve TRL5. The objective of this project was to create a rover which can traverse Lunar craters. This was demonstrated through laboratory testing which included thermal operation, thermal cycle, dust, and electrical testing of critical components. This included testing of the 1-DOF and 3-DOF legs, radiator panel, tether, foot insulator, and shoes. All tests were successfully conducted, and valuable data was collected, analyzed, and documented in the Comprehensive Testing Plan for future development.

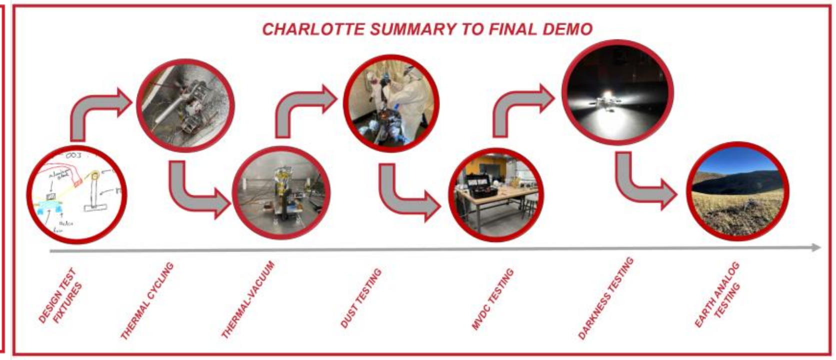
In addition to laboratory testing, Earth analog testing for darkness, locomotion, and teleoperation was conducted at Colton Crater in Flagstaff Arizona. From this test, the team successfully demonstrated the rover’s ability to omnidirectionally traverse an Earth analog crater and collect data via the onboard Hazcams and Navcams during daytime, nighttime, and into an analog PSR.

From the verification testing in the lab and in Earth analog environments, it was demonstrated that CHARLOTTE is capable of operating in dusty, steep/rocky, and thermally extreme environments. This capability will allow CHARLOTTE to be used to carry advanced scientific payloads for a wide range of mission scenarios on the Moon or Mars.

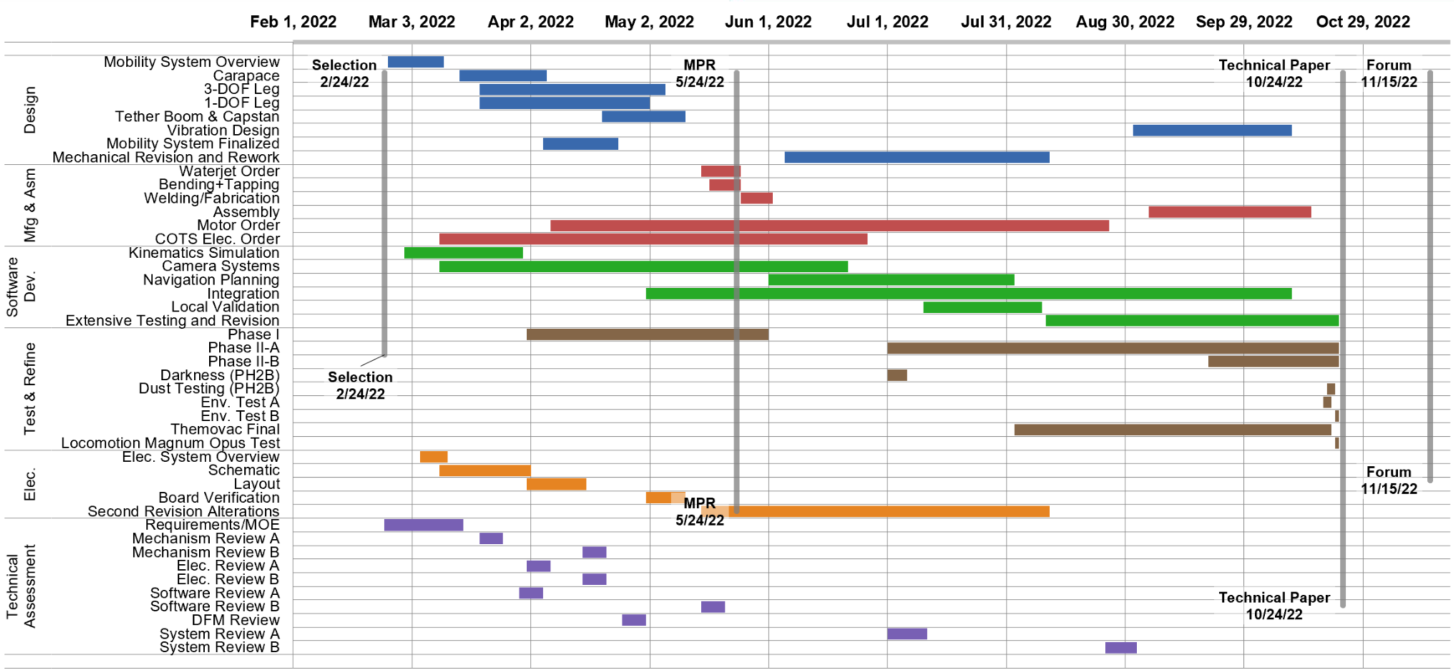
TIMELINE



CHARLOTTE SUMMARY TO MID-PROJECT
REQUIREMENTS & MOES
TESTING PLAN & PROCEDURES
SKETCH & IDEATION
COMPUTER AIDED DESIGN
MULTI-PHYSICS SIMULATION
PROTOTYPE DESIGN



CHARLOTTE SUMMARY TO FINAL DEMO
DESIGN TEST FIXTURES
THERMAL CYCLING
THERMAL-VACUUM
DUST TESTING
MVDC TESTING
DARKNESS TESTING
EARTH ANALOG TESTING



Feb 1, 2022
Mar 3, 2022
Apr 2, 2022
May 2, 2022
Jun 1, 2022
Jul 1, 2022
Jul 31, 2022
Aug 30, 2022
Sep 29, 2022
Oct 29, 2022
Selection 2/24/22
MPR 5/24/22
Technical Paper 10/24/22
Forum 11/15/22
Design
Mobility System Overview
Carapace
3-DOF Leg
1-DOF Leg
Tether Boom & Capstan
Vibration Design
Mobility System Finalized
Mechanical Revision and Rework
Mfg & Asm
Waterjet Order
Bending+Tapping
Welding/Fabrication
Assembly
Motor Order
COTS Elec. Order
Software Dev.
Kinematics Simulation
Camera Systems
Navigation Planning
Integration
Local Validation
Extensive Testing and Revision
Test & Refine
Phase I
Phase II-A
Phase II-B
Darkness (PH2B)
Dust Testing (PH2B)
Env. Test A
Env. Test B
Themovac Final
Locomotion Magnum Opus Test
Elec.
Elec. System Overview
Schematic
Layout
Board Verification
Second Revision Alterations
Technical Assessment
Requirements/MOE
Mechanism Review A
Mechanism Review B
Elec. Review A
Elec. Review B
Software Review A
Software Review B
DFM Review
System Review A
System Review B

BUDGET

Primary Proposing University Name: Arizona State University
Project Title: Charlotte – Crater Hydrogen and Regolith Laboratory for Operation on Technical Terrain Environments
2022 BIG Idea Challenge

Budget Period of Performance: February 22 - November 18, 2022

Description	Rate	2/22/22 - 6/30/22	Phase I Budget Remaining	Rate	Phase 2 7/1/21 - 11/18/22	Phase II Budget Spent	Phase II Budget Remaining	Total
A. Direct Labor - Key Personnel								
PI Tyler Smith		$ 1,031.50	$ -		$ 1,031.50	$ 803.88	$ 227.62	
Subtotal Salary		***$ 1,031.50***	$ -		***$ 1,031.50***	***$ 803.88***	***$ 227.62***	***$ 227.62***
Direct Labor - Other Personnel								
Graduate Hourly Students		$ 5,894.00	$ -		$ 11,786.00	$ 2,100.00	$ 9,686.00	***$ 9,686.00***
Undergraduate Hourly Students		$ 5,894.00	$ -		$ 11,786.00	$ 9,482.50	$ 2,303.50	***$ 2,303.50***
Subtotal Other Personnel		***$ 11,788.00***	***$ -***		***$ 23,572.00***	***$ 11,582.50***	$ 11,989.50	***$ 11,989.50***
B. Fringe Benefits								
Staff	34%	$ 346.38	$ -	34%	$ 346.38	$ 987.32	$ (640.94)	***$ (640.94)***
Students	2%	$ 206.29	$ -	2%	$ 412.51	$ 189.68	$ 222.83	***$ 222.83***
Subtotal Fringe		**$ 552.67**	**$ -**		**$ 758.89**	**$ 1,177.00**	**$ (418.11)**	***$ (418.11)***
Total Labor Costs (A+B)		**$ 13,372.17**	**$ -**		**$ 25,362.39**	**$ 13,563.38**	**$ 11,799.01**	***$ 11,799.01***
C. Direct Costs - Equipment (any individual item over $5,000)		**$ -**			**$ 5,000.00**	**$ 5,000.00**	**$ -**	***$ -***
D. Direct Costs - Domestic Travel		**$ -**			**$ 31,004.00**	**$ 14,884.64**	**$ 16,119.36**	***$ 16,119.36***
E. Other Direct Costs								
Materials and Supplies		$ 35,650.00	$ -		$ 5,998.15	$ 1,900.00	$ 4,098.15	***$ 4,098.15***
Testing Costs or Facilities Rental		$ -			$ 17,783.00	$ 9,415.04	$ 8,367.96	***$ 8,367.96***
Consultants		$ -			$ -			$ -
Services		$ -			$ -			$ -
Subcontracts/Subawards		$ -			$ -			$ -
Miscellaneous		$ -			$ -			$ -
Total Other Direct Costs (E)		***$ 35,650.00***	***$ -***		***$ 23,781.15***	***$ 11,315.04***	***$ 12,466.11***	***$ 12,466.11***
F. Total Direct Costs (A+B+C+D+E+F)		**$ 49,022.17**	**$ -**		**$ 85,147.54**	**$ 44,763.06**	**$ 40,384.48**	***$ 40,384.48***
Modified Total Direct Costs, if applicable		$ 49,022.17	$ -		$ 80,147.54	$ 39,763.06	$ 40,384.48	***$ 40,384.48***
G.i. University Indirect Costs (Required for Phase I & Phase II)	57%	$ 27,942.64	$ -	57%	$ -			
G.ii. Space Grant Indirect Costs (Phase II only)				0%	$ -			$ -
H. Total Direct and Indirect Costs (F+G)		**$ 76,964.80**	**$ -**		**$ 85,147.54**	**$ 44,763.06**	**$ 40,384.48**	***$ 40,384.48***
% of Total Budget (Phase I should be ~46%; Phase II should be ~54%)								

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