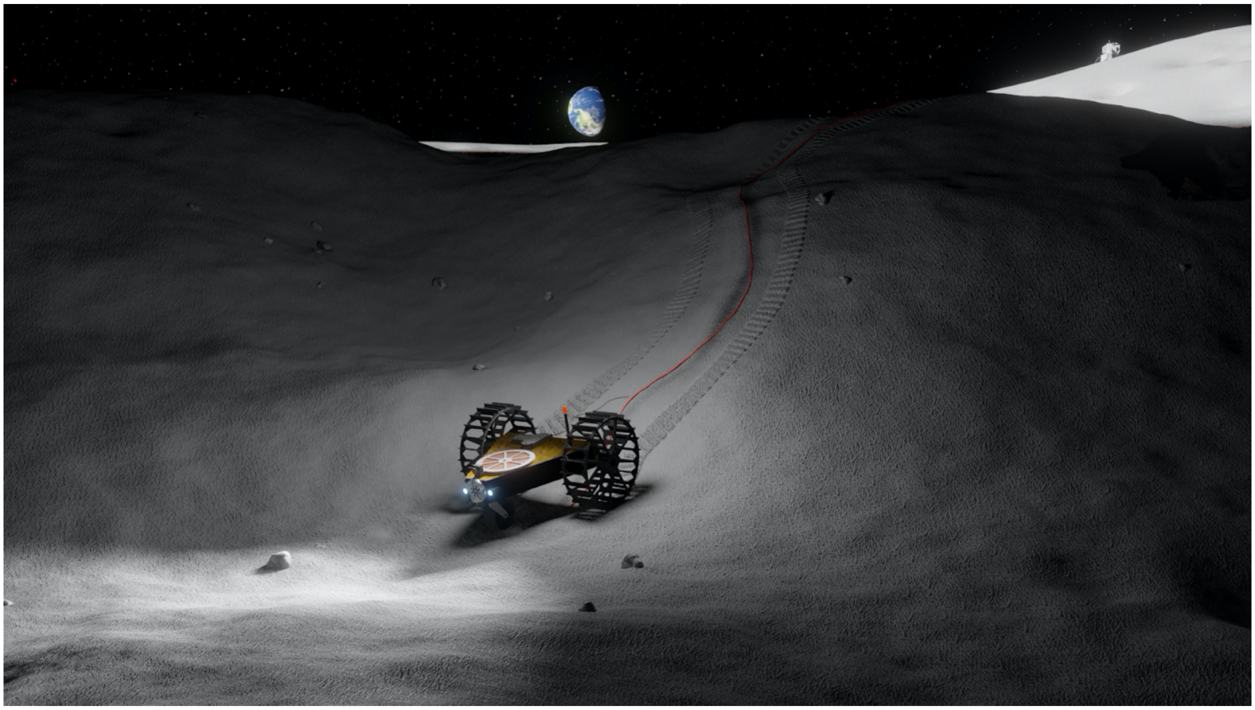
The Tethered permanently shadowed Region EXplorer (T-REX)



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Tethered-permanently shadowed Region EXplorer (T-REX)*

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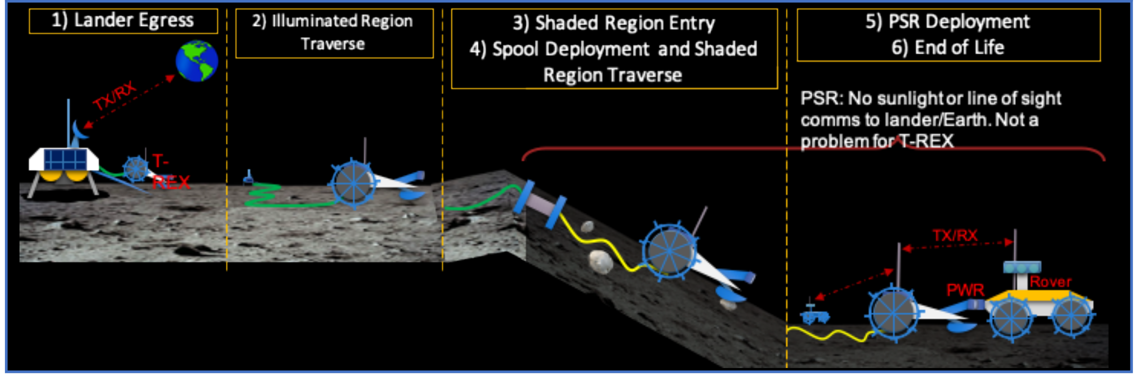
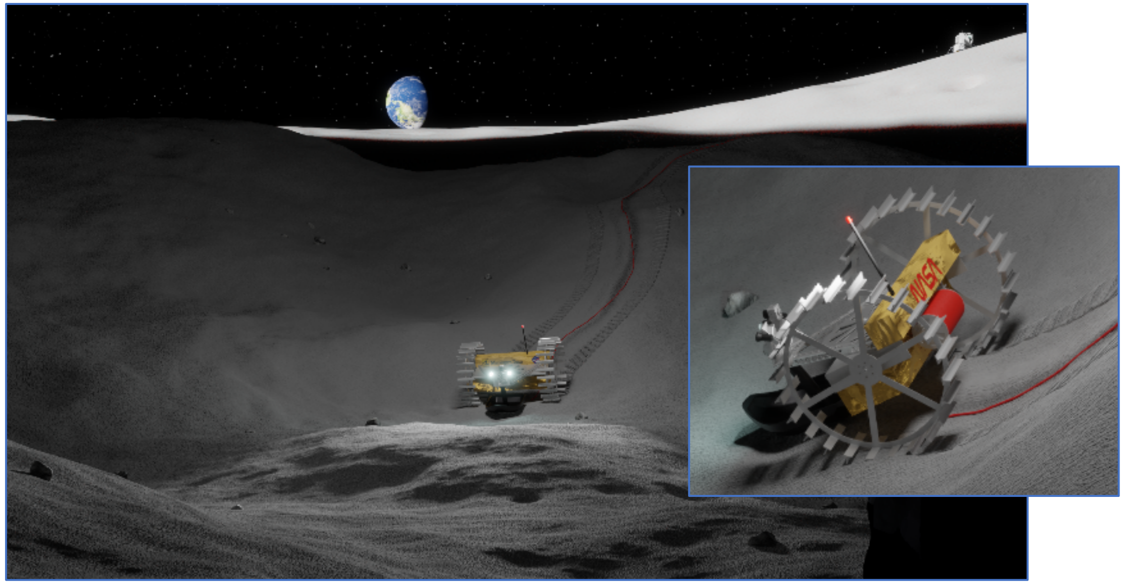
Mission Statement

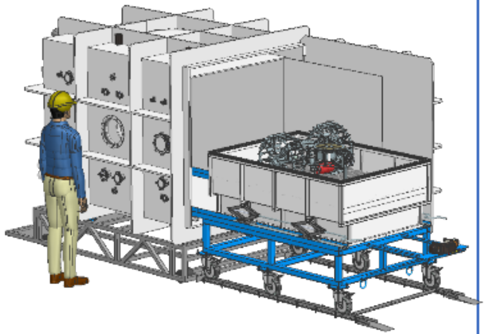
T-REX is an infrastructure technology demonstrator mission whose goal is to provide reliable power and data to other operations within Permanently Shadowed Regions (PSRs) of the Moon, where conventional line-of-sight radiofrequency (RF) communications and solar power generation is limited.





Research Team and facilities

- The mission is being developed by a team of 11 interdisciplinary students from Michigan Tech for the BIG Idea challenge.
- The atmospheric test facilities have been built, the vacuum testing facilities are being shipped currently. The Dusty Thermal Vacuum Chamber (DTVAC) will be used for high-fidelity environmental testing. It is 60in by 60in by 80in, can reach 10e-5 Torr, and temperatures from 76K to 470K.
- A 6ft by 16ft lunar simulant sandbox will be used for slope traverse and mobility testing using a gravity offloading gantry.



Payload Overview

1) T-REX is tethered to a CLPS lander for power provision and data passthrough.
2) A conventional tether in series with a superconducting tether (SCT) is used for power and data transfer. The SCT is passively cooled by the ambient cold trap temperature.
3) The rover relays wireless data to other rovers within the PSR and can recharge them via a detachable charging interface.

- Rover mass: ~30kg
- Rover size: ~50cm x 50cm x 50 cm
- Conventional tether length: 275m
- Superconducting tether (SCT) length: up-to 2km
- Communication protocol: VDSL-2
- Tether data rate: 1.82Mbps up, 11.65 Mbps down**
- Max power from CLPS lander: 50W
- SCT max allowable current: ~75A
- SCT cross section: 4mm x 0.3mm
- SCT operating temperature: ~<77K

*This mission will be renamed to L-SABRE if selected for next phase of development
**This value may be as high as 100Mbps up/down if there are proven to be negligible losses in data transfer in the SCT

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Executive Summary

The technology undergoing development as part of the T-REX tethered-rover mission will leverage the extreme cold environment within PSRs to use a superconducting tether for providing power and data to nearby missions. Other missions leveraging the local comms and charging services offered by T-REX can allocate more onboard space to payloads, reducing the Size Weight and Power (SWaP) cost of dedicated power and long-range comms subsystems. It can demonstrate a solution to a critical need to get power and communication down into the PSRs for future operations and ice mining as part of the ARTEMIS program or commercial operations.

The T-REX rover is in the second of three major iterations for the engineering model. This prototype system is nearing complete integration of individually tested subsystems. Rover testing is ongoing in an atmospheric environment with lunar regolith simulant and gravity offloading. The Dusty Thermal Vacuum Chamber (DTVAC) facility will arrive at Michigan Technological University and begin commissioning as atmospheric testing of the T-REX rover completes. Subsequent DTVAC testing will raise the technology which enables the T-REX mission to TRL-5/6. After the conclusion of the BIG 2020 Challenge, the T-REX rover will be modified to partake in the Watts on the Moon Centennial Challenge.

This report describes the concept of operations, design overview, current testing efforts, and programmatics. Additional documents to supplement this report are as follows:

- Compilation of video media taken during testing
- Compilation of all current testing documents
- Compilation of test facility images
- Requirements Verification Matrix
- Detailed T-REX system block diagram

1 PROBLEM STATEMENT AND BACKGROUND

1.1 Background

NASA's Artemis program has the goal of returning humans to the lunar surface and subsequently preparing for missions to Mars in a sustainable manner. To create a sustainable program, the goal is to confirm the presence, properties and distribution of the water ice detected in the permanently shaded regions (PSRs) at the lunar poles and then mine and process the water ice into LH2 and LOX to be used as propellant. Orbital measurements are limited in being able to measure the properties and the needed resolution of the horizontal and vertical distribution of the ice. Determining the in-situ properties and distribution will allow the ice deposits to be quantified as a reserve if they are found to be accessible, have sufficient quantities and are extractable. This process is optimally done via surface operations.

Extracting significant quantities of water ice from PSRs requires long-duration industrial scale operations. One of the largest challenges besides extreme environmental conditions is limited power generation and line-of-sight (LoS) communications. Large PSRs in polar craters will have both sunlight and LoS comms to Earth blocked. This necessitates an intermediary step to relay either resource to missions within the PSR. These infrastructure gaps in the polar regions of the moon prevent any substantial excavation effort and limit capabilities and duration of smaller exploratory missions. To maximize the science potential of long-duration PSR missions, precursor communications and power architecture must be established. During manned operations on the Moon, a resilient communications and power system is paramount to ensure safety of astronauts.

1.2 Mission Overview

1.2.1 Mission Statement

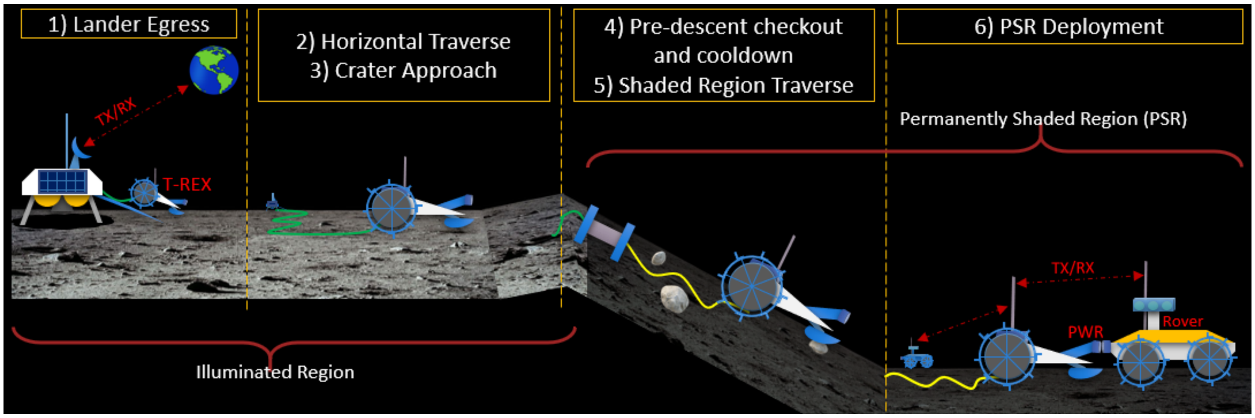
MS-01	Mission Statement	The Tethered permanently-shadowed Region EXplorer (T-REX) is an infrastructure technology demonstrator mission whose goal is to provide reliable power and data to other operations within Permanently Shadowed Regions (PSRs) of the Moon, where conventional line-of-sight radiofrequency (RF) communications and solar power generation is limited.

1.2.2 Mission Objectives

MO-01	Mission Objective 1	The T-REX rover shall utilize a direct connection to a CLPS lander to provide continuous power and communications to itself within a lunar PSR.
MO-02	Mission Objective 2	The T-REX rover shall provide power recharging and communications relaying for other compatible missions operating within a lunar PSR.

2 PROJECT DESCRIPTION

2.1 2.1 Concept of Operations



Lander Deployment and Checkout: Once touchdown is complete, the T-REX will initiate a checkout prior to deployment to confirm functionality of all subsystems. Once this is completed, the rover will egress from the lander. Egress method will vary based on the selected CLPS lander for the mission. During egress, the T-REX rover will begin deploying conventional conductor tether from the onboard secondary spool. Movement by the T-REX is done via remote commands sent via the Deep Space Network (DSN) and relayed via the CLPS lander to and from T-REX with feedback received as rover diagnostics and onboard video camera feed.

Illuminated Region Traverse: T-REX will traverse from the lander towards the rim of the PSR. While the landers will land a nominal 125m straight-line distance from a crater rim, extra tether is brought for landing location error and deviations from the direct path. The rover possesses the spooling capacity to hold 250m of conventional tether as margin. The conventional tether is deployed without power using tension between T-REX and the lander initially, then between the friction of the deployed cable and T-REX as unspooling progresses. Temperatures in this region will reach 127C by direct solar radiation from the sun. The illuminated surfaces on T-REX and the tether are designed to operate within this temperature.

Shaded Region Entry: The rover will descend into the edge of the crater and begin descent into the PSR. Upon reaching a sufficiently shaded region, the T-REX lander will halt movement until the primary spool stored on top of the lander has reached near the ambient cryogenic temperature of the PSR.

Unlike the more conventional cable deployed by the secondary spool, the primary spool will use a flat 4 conducting-path tape-like Superconducting Tether (SCT) which requires temperatures under 77K (-173C) to become superconducting. The SCT enables T-REX to store 2 km of tether with a cross-sectional area 0.2mm x 4mm. With passive cooling provided by the PSR environment, the currently installed SCT deployed by T-REX can conduct 75 amperes of power and data with minimal signal integrity losses. The cable and tether can be customized for higher amp applications as needed.

Spool Deployment and Shaded Region Traverse: Once the operators on Earth have determined that the primary spool has reached superconducting temperatures, the secondary spool will be commanded to detach from the T-REX rover onto the surface of the PSR. This action reduces the mass which T-REX must carry downhill and protects the SCT. The spool is used as a thermal conductivity inhibitor between the conventional conductor and SCT by radiating heat transferred by the tether from the illuminated regions, while maintaining a direct electrical connection. This interface is required so that excess heat does not raise the temperature of the SCT out of the desired cryogenic operating temperature.

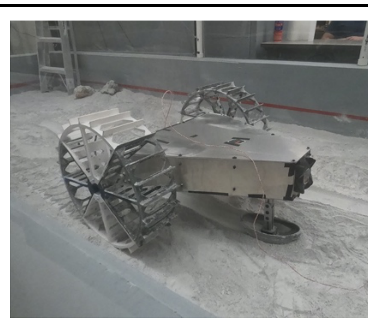
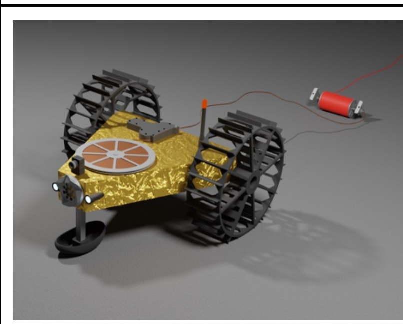
The SCT is connected to the detached secondary spool via a slip ring at one end of the spool and begins unspooling utilizing a control system with environmental feedback to ensure minimal tension in the system. While the SCT is strong enough to suspend the T-REX rover above the lunar surface, tension is minimized at all times to account for slippage and reduce the chance of damaging the tether. The primary spool and control system continue SCT deployment for up to 2 km or until the basin of the PSR is reached. Longer cables are possible, depending on the lander location.

PSR Deployment: Once deployed, in a stable location, T-REX enters service as a power and comms hub for other missions within the PSR. A HOTDOCK detachable, coupling interface is activated on the rover. This connector then provides power to any rover which moves to the T-REX rover and mates coupling mechanisms. After recharging is complete, client rovers can then detach and continue their missions. Communications in the PSR between the T-REX and client missions are performed using a full duplex RF communication system. Commands are sent from Earth to the CLPS lander, through the tether, into T-REX and are broadcasted in the PSR to client missions. Return video feed and telemetry follows the opposite route back to Earth.

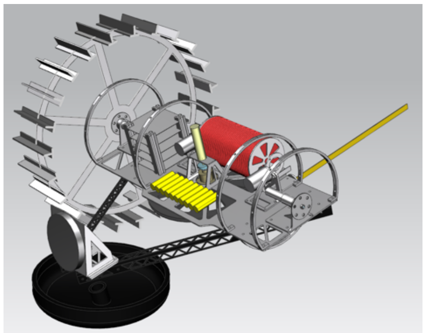
Two-way communication is done using the Very-high-speed Digital Subscriber Line (VDSL) protocol. While the bit rate is lower compared to optical fiber, speeds offered by VDSL are an order of magnitude faster than current high-TRL wired communication protocols like RS-482, at long range. Data rates are currently bottlenecked by the current ~10 Mbit/s connection between the DSN and the CLPS lander. Gigabit connectivity does not add value to the mission for the increased complexity introduced with fragile optic fiber cables when the full capacity of optic fiber cannot be utilized. VDSL retains signal integrity up to 5km and can use the existing SCT substrate to transfer power. The VDSL protocol is an ideal balance between simplicity, TRL, durability, and transfer rate.

End of Life: The T-REX demonstration mission will last 12-14 Earth days. This time span is the duration where the CLPS lander is continuously illuminated by the Sun in the poles of the Moon. The lander will no longer be able to provide power to T-REX when eclipsed and is not designed to operate during the lunar night. T-REX will have completed all mission objectives by the time the CLPS lander is no longer illuminated.

2.2 Design Overview

Mark 1	Mark 2	Mark 3
		

2.2.1 Mark I Rover

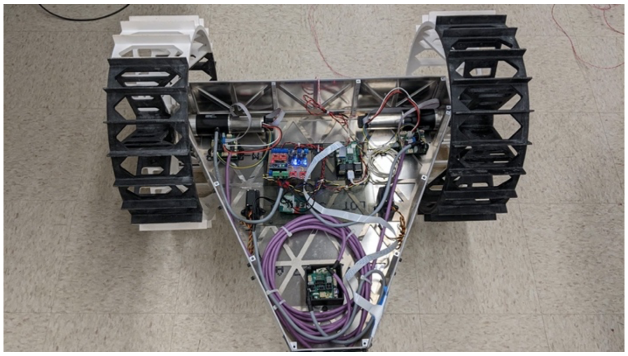


The mark 1 rover was based largely on the model created by the senior design team (right) who first approached this project but more optimized for being a basic test platform to test mobility and to discover physical problems such as the center of gravity. The rovers structure consists of one flat sheet of aluminum with L shaped extrusions to create a mounting point for the Sled. This made mounting different subsystems in different locations very easy and quickly allowed for testing in sand at a local beach. These mobility tests involving mark 1 quickly identified a center of gravity problem and gave us good empirical data about the design of the Sled

The "Boat" Design seen in the above figure proved to be the most effective for the terrain that we plan on encountering during our mission by giving the rover good stability on steep downhill slopes as well as not impeding movement on flat terrain or small slopes. Further mobility testing will be conducted with the mark 2 rover to confirm these results with numerical data for the different center of gravity. The wheels for this version and future ones were 3D printed using PETG filament for ease of manufacturing. On the space ready version of the rover these wheels would be machined and designed for use in low gravity. Creating such a wheel was outside of the capabilities we had in house and was determined to not be an effective use of resources because RVM requirements could be confirmed without them. Although the superconducting tether subsystem was mounted to this version of the rover to accurately represent the center of gravity most of the tuning for this subsystem was still done off of the rover.

"Boat" Design	"Ski" Design	"Wide" Design
		

2.2.2 Mark II Rover

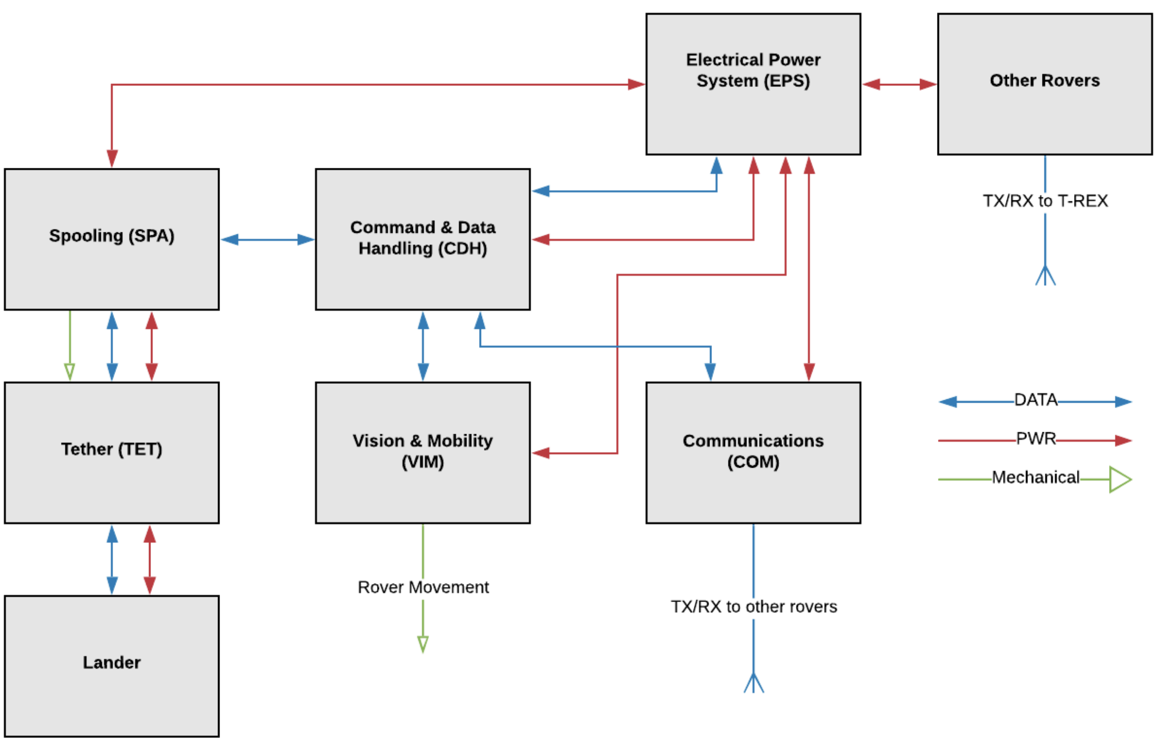


The largest difference between the mark 1 and 2 rovers is the environments they were designed for. The Mark 2 frame was constructed to be a completely sealed system to compensate for the extremely dusty environment of the lunar surface. Weather stripping was used at the seams of the outer panels to create a dust proof seal. This would later be changed to an interface that doesn't require compliant materials for cryogenic vacuum conditions but was not necessary for the atmospheric testing conducted with this rover. To solve the center of gravity problems encountered in the mark 1 rover, the wheels were moved to the very rear of the rover and all subsystems that added significant mass to the rover, such as, the two spools that make up the tether and the electronics were moved between the 3 points of contact with the ground to prevent the motors lifting up the front end of the rover instead of driving forward. Although this rover has not yet been tested at cryogenic vacuum conditions the position of the superconducting spool and electronics have been specifically positioned inside the frame to allow the superconducting tether to reach its operating temperature when in the PSR. These locations were based on a thermodynamic simulation conducted earlier in the project. Also included in the mark 2 rover is larger drive motors. During mark 1 testing the team found that scaling 10 cm rocks as described in the RVM was very difficult for the rover. The new motors allowed the rover to scale these obstacles with relative ease without the use of a gravity offloading device. Motors would likely be scaled back down for a final version due to the reduced gravity of the moon. Tests were run with these motors while a gravity offloading device was in place, but the results were determined to be inaccurate due to the device not being able to maintain the same center of gravity for the rover as it traversed obstacles. The different panels used on the mark 2 rover were also optimized for weight and use an iso-grid pattern to reduce weight while maintaining stiffness. This was backed with a thin sheet of aluminum to prevent dust from entering the rover. The iso grid faces inside to allow for easier cleaning of the rover after tests.

2.2.3 Mark III Rover

The mark 3 rover will be very similar to the mark 2 with a few key differences to make it more tolerant to a cryogenic, high vacuum environment. All of the electronics will be exchanged for versions that are rated for high vacuums. Electronics will also be contained in a stack at the center of the rover which will make them more efficient to heat in cryogenic temperatures. The side panels will also be replaced with ones that are completely machined, as of now they are two sheets bonded together which was done for ease of manufacturing. As mentioned before, compliant materials will also be replaced with alternative solutions such as u-channels to prevent dust from reaching the electronics. Most structural analysis to flip requirement gates will be done on this version due to planned similarity to the flight model.

2.3 Subsystem Overview



The T-REX rover consists of seven major subsystems: Command and Date Handling, Communications, Software, Vision and Mobility, Electrical and Power Systems, Spooling Assembly, and Structures. Each subsystem is responsible for certain aspects of the rover's functionality. However, several subsystems are contained within a single on-board computer in order to accelerate development during the prototyping process. Below are overviews of each major subsystem on the current Mk.2 rover.

2.3.1 Command and Data Handling (CDH)

The command and data handling subsystem on the T-REX mission has largely been consistent throughout different physical design iterations. On the mark one design, there existed separate boards for COM, CDH, and VIS. However, through debugging issues, the T-REX team found it much easier to have a single board for as many subsystems as we could. As the processing power needed for mark 1-2.5 is relatively low, we found a Raspberry Pi 4 to be sufficient as our main on-board computer.

2.3.1.1 Command Implementation

The T-REX CDH subsystem has a custom implementation of an event handling system. Messages are all formatted the same way regardless of the subsystem they are intended for. This allows for a uniform packet structure and the ability to quickly adapt our system. One can think of the command implementation as a two-sided conversation between nodes where each side can "implement" and "invoke" a subset of commands from our global command dictionary.

2.3.1.2 Subsystem Daemons

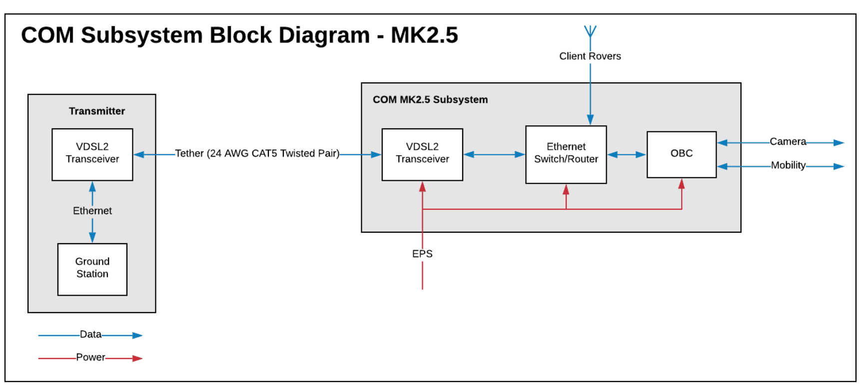
The COM, CDH, and VIS subsystems are all running on the main on-board computer. Instead of each subsystem running on its own computer, they are all running together as system daemons. Running these subsystems on the same computer makes it easier to control error handling and reliability because they are simply running through the built in Linux daemon management system which provides many helpful programs for running environments and logging.

2.3.1.3 Communications Integration

The CDH subsystem is tied very closely to the COM subsystem. They are both running under the same process. When COM receives external messages it immediately passes them to the CDH daemon that parses and routes them to their designated subsystems. Having these two vital components so closely tied together provides the T-REX with a simpler topology that focuses on what is important.

2.3.2 Communications (COM)

2.3.2.1 Topology



The COM subsystem and connected nodes consist of an integrated ethernet switch, the main on-board computer, and any active ground control software instances. Communication between the rover and ground control instances can be achieved via WLAN or via LAN through the tether. Once connected to the T-REX's internal private network, all subsystems can be accessed. The T-REX operates as a server which provides the necessary access points to communicate with multiple active ground control instances at the same time. All messages originating from the T-REX are sent to all active ground control instances.

2.3.2.2 *Physical Protocol*

The T-REX COM subsystem utilizes the VDSL2 protocol for long-range communication over the tether. As the second iteration of Very high-speed Digital Subscriber Line technology, VDSL2 was chosen for its full-duplex capability, impressive bit-rate performance, and adaptability to various RF noise environments. The protocol divides its occupied 30 MHz bandwidth into equally spaced upstream and downstream channels through Frequency Division Duplexing, allowing for full-duplex communication. Therefore, a lower latency is achieved, and data transfer efficiency is increased considerably. The standard modulation scheme of VDSL2 is Discrete Multitone, analogous to Orthogonal Frequency-Division Multiplexing, where the baseband is separated into many QAM-encoded subchannels over the total bandwidth. Thus, bit-rate performance is greatly improved by allowing data to be transferred in a parallel fashion. A bit-loading algorithm determines the QAM constellation size on each subchannel based on the present SNR of the received signal to the transceiver, enhancing signal integrity even under various RF noise conditions.

2.3.2.3 *Network Protocol*

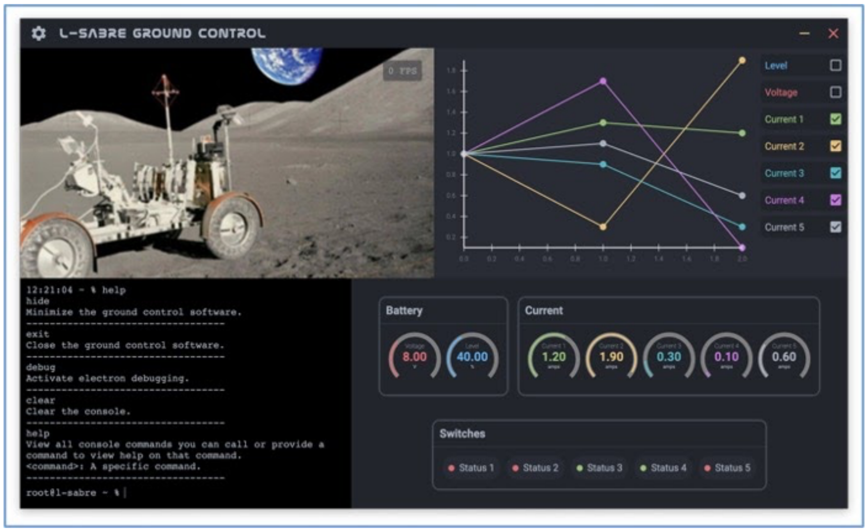
The T-REX COM subsystem uses the WebSocket network protocol to communicate with external nodes. The WebSocket protocol was selected as it provides a useful abstraction over base TCP sockets. Including features like automatic message framing, heartbeats, and much more, this protocol allowed the T-REX team to accelerate the development of the COM subsystem relying heavily on its feature set.

2.3.3 Software (SFW)

2.3.3.1 *Rover Software*

Although it may not be very traditional to have some of our subsystems running in the NodeJS runtime, it has proven to be very successful. The adaptability of TypeScript and its strict type-safety has enabled our team to focus on developing our rover. Our CDH, COM, and VIS subsystems are written in TypeScript and run under the NodeJS runtime. Internal communication to other subsystems occurs via different methods but mostly consists of named pipes, allowing for the easy integration of different programming languages. The MOB, TMS, and EPS subsystems are written in C/C++ to provide tighter integration with the hardware.

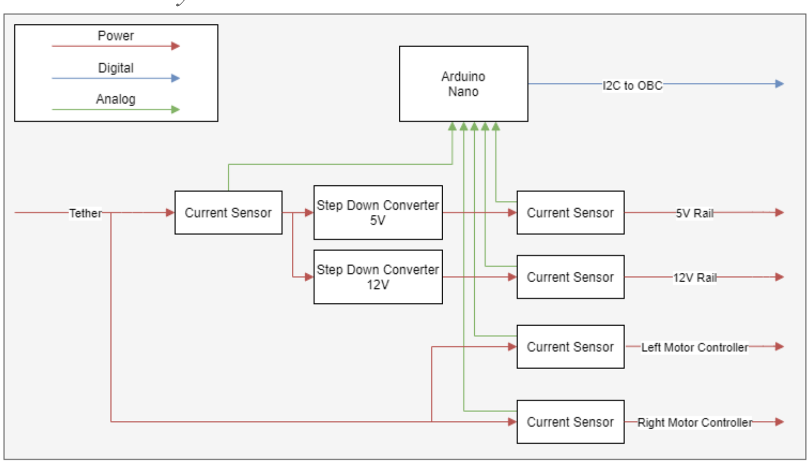
2.3.3.2 *Ground Control Software*

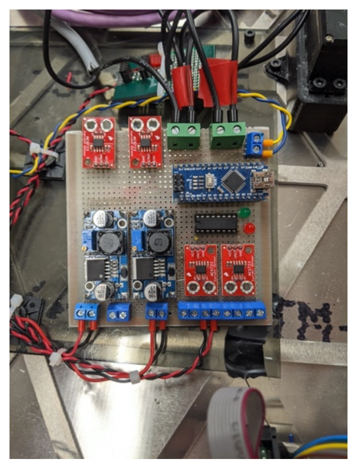


The rover is controlled by a custom piece of software the T-REX team developed. Written in TypeScript, the ground control software uses the latest web technologies to present a desktop application accessible on any platform. The ground control software is a web-application that is run in a controlled environment using a popular library called Electron. This provides hardware and software APIs to all system resources. On startup, our ground control system initiates a handshake with the COM daemon on the rover's OBC. The ground control software provides telemetry, a camera feed, a simulated terminal, and controls for issuing movement commands to our MOB subsystem.

2.3.4 Electrical Power System (EPS)

2.3.4.1 *Subsystem Overview*





2.3.4.2 *Hardware Overview*

The Electrical Power System (EPS) takes the incoming power from the tether (roughly 24 VDC), steps the voltage down and distributes it to the various subsystems on the rover. Using five ACS723 current sensors, the currents leaving and entering the EPS subsystem are measured and reported to the OBC using an Arduino Nano. This helps to ensure safe operation of the rover and minimizes the risk of damaging hardware due to a possible overcurrent. Future iterations of the EPS hardware will include the ability to electro-mechanically disconnect the rover from the tether to prevent current draw before the SCT has cooled to its operating temperature in the PSR.

2.3.4.3 Firmware Design

The EPS firmware flashed to the Arduino Nano is designed to act predictably with the intent of being the last system to fail on the rover. Written in the Arduino language, the firmware periodically reads values from each of the five current sensors. If an event is detected on the I2C bus, an interrupt is triggered to begin communication with the OBC. Once communicating with the EPS subsystem, the OBC is able to either request the current value on a single line or the value of current on each line. These values are then relayed to the ground station to be displayed. To improve the reliability of the subsystem, the watchdog timer of the Arduino is enabled by default to four seconds. If the timer is not reset each loop iteration, the microcontroller will reset, preventing a hang. The OBC has the ability to enable, disable, reset and change the time by requesting an event over I2C.

2.3.5 Spooling Assembly (SPA)

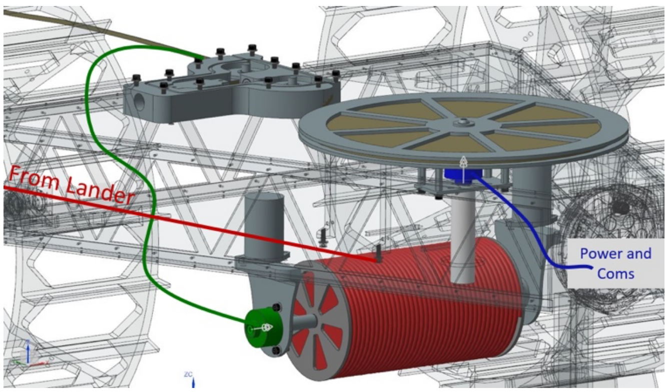


Figure 1: Path of tether (red >> green >> blue)

The spooling assembly manages the deployment of the superconducting and conventional-conducting tether (CCT) and measures the tension in the cable as it deploys. The purpose of this system is to verify the requirements shown in the RVM marked as SPA in section 3.2.3.5. The entire tether is made up of multiple sections that, in order from the lander to electronics of the rover, are: 200 meters of the CCT, CCT spool which acts as a heat break for the superconductor, a slip ring, 2 km of the superconductor, and finally a slip ring attached to the CDH board. The figure below shows a visual of how these different elements are connected within the rover.

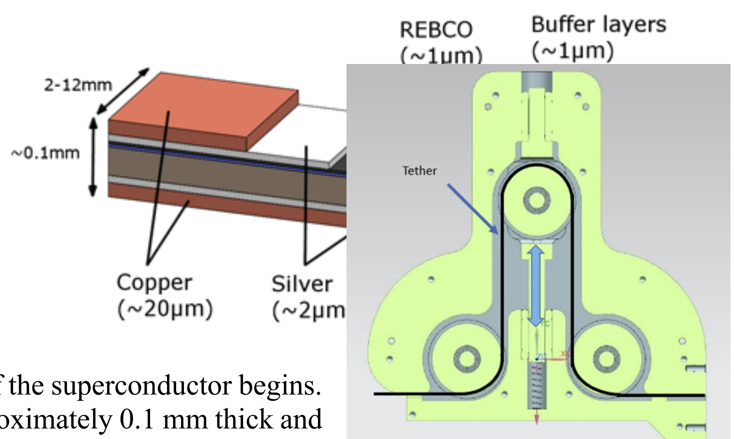
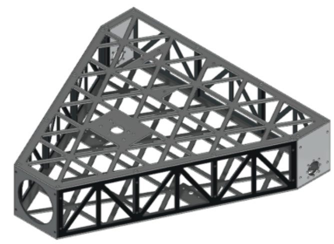


Figure 1 shows the path of the cable as it passes through the rover with the red cable representing the conventional conducting tether (CCT) and the brown/bronze representing the superconducting tether (SCT). As described in the concept of operations the rover will first enter the PSR and then deploy its CCT spool onto the surface of the moon using two separation nuts which hold the spool on the rover. With the CCT spool acting as a heat break for the SCT the deployment of the superconductor begins. The SCT is a very fragile cable that is approximately 0.1 mm thick and 4 mm wide with maximum tensile strength and a minimum bend radius that when exceeded can create a fracture or loss in performance within the cable. Because of these risks, the tension measurement system (TMS) was created to measure the tension in the SCT as it is deployed and ensure that the minimum bend radius of the SCT is not exceeded. The TMS works by using a series of pulleys to allow the cable to displace a central pulley when the tension in the cable is increased. This displacement works against a spring of known spring constant which allows for the measurement of the tension in the cable as it leaves the rover. The displacement of the central pulley is measured by an analog device which serves as feedback for a PID loop which actively controls the SCT spool via a motor. All of the surfaces that SCT comes into contact with while passing through the TMS have Teflon inserts to reduce rubbing and all corners are well above the minimum bend radius. Although the TMS has not been fully integrated into the latest mark 2 rover, the subsystem has undergone preliminary tests using a conventional wire to ensure that the concept could be effective.

2.3.6 Structures (STR)

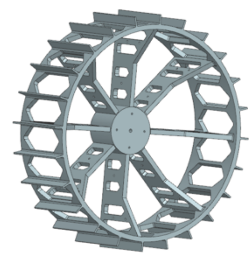
2.3.7 Chassis Design

The current iteration of the T-REX rover uses a chassis design which consists of a top and bottom plate connected together with standoffs capped with side panels. This design was chosen due to its simplicity of manufacturing. The top and bottom plate as well as the side panels are constructed of aluminum cut with a water jet. Triangular cut outs were designed to make the rover as light as possible without sacrificing much strength. In order for the robot to be resistant to dust, very thin aluminum sheets are adhered to the outside faces of the top, bottom, side, and back panels.



2.3.8 Wheel Design

The wheels for T-REX were designed to be 3D printed for convenience of manufacturing. The wheels were printed in four separate pieces then bolted and epoxied together. The design of these wheels allows for good traction in regolith thanks to the use of growsers, and the holes allow regolith to pass through the wheel and not get trapped.



2.4 External Relevance

2.4.1 External Interfaces

The current iteration of the T-REX rover is designed to interface with a CLPS lander that is capable of carrying a payload of at least 30kg and have the dimensions specified earlier. The CLPS lander would be tethered to the T-REX rover and be able to supply power and allow data passthrough to Earth via the lander communication system. The lander should also be capable of allowing the T-REX rover to egress smoothly from the lander deck to the surface via a ramp or lowering platform.

Client-side, the rover would physically interface with any other hardware which has the active end of a Space Application Systems HOTDOCK connector. A client mission would connect to the front of the T-REX rover and detach based on application. T-REX can connect other rovers much like a wireless hotspot. If the right credentials are presented, client missions can then interface with each other and the lander on the local T-REX-provided network.

2.4.2 Science and Exploration Goals

The T-REX project due to its nature falls in many NASA taxonomy categories. The rover will deploy a superconducting tape from the CLPS lander down into a PSR and thus providing power and communication from the CLPS lander into the crater where other rovers or systems can dock and recharge as well as communicate via a local wireless node. This solves one of the major issues for PSR exploration and ISRU: getting sufficient reliable power down into the PSRs. This covers the following goals in NASA's technology taxonomy map:

- TX03 Space Power and Energy Storage; 3.3 Power Management and Distribution
- TX04 Robotics and Autonomous Systems; 4.1 Sensing and Perception; 4.2 Mobility
- TX05 Communication, Navigation, and Orbital Debris Tracking and Characterization Systems; 5.3 Internetworking
- TX07 Human Exploration Destination Systems; 7.2 Mission Infrastructure, Sustainability, and Supportability
- TX10: Autonomous Systems; 10.1 Situational and Self Awareness
- TX13 Ground, Test, and Surface Systems; 13.2 Test and Qualification
- TX14 Thermal Management Systems; 14.2 Thermal Control Components and Systems

2.4.3 Potential Stakeholders and Funders

The technology utilized by the T-REX mission can easily be applied to most applications that operate within PSRs and scales easily. Other missions leveraging the local comms and charging services offered by T-REX can allocate more onboard space to payloads; reducing the Size Weight and Power (SWaP) constraints inherited from larger, dedicated electrical power and communication systems will enable client missions to maximize science data-gathering potential. T-REX will serve as a proving ground for later iterations that could provide increased power and bandwidth to support more power and data intensive operations within PSRs for industrial use. These operations could include mining or in-situ resource utilization infrastructure located within the PSRs. Successor technology can connect habitats, telescopes, antennae, and kilowatt power plants into a unified grid.

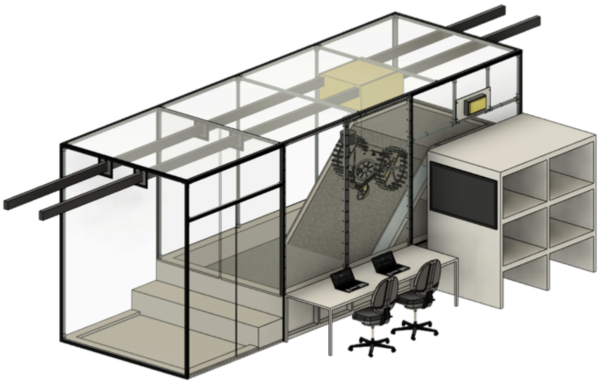
The T-REX mission (and successors) is not intended to be the only type of communication and power method available on the moon. Cabled power and comms will augment other proposed systems such as reflected solar power and laser comms/power. All systems have advantages and drawbacks. However, simultaneous use of all systems will provide a failure-tolerant architecture to all manned and unmanned operations on the Moon.

3 VERIFICATION PROCESS

3.1 Facilities

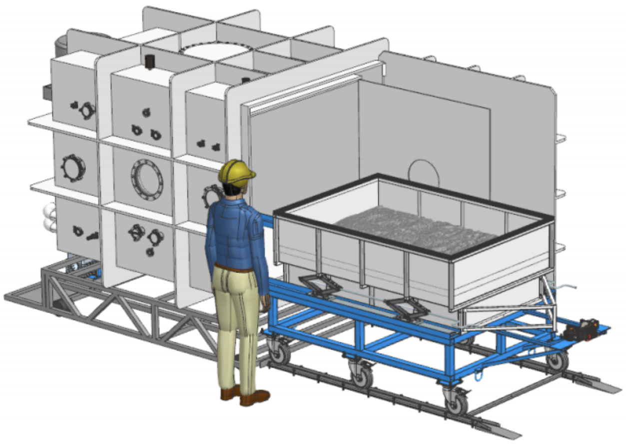
The verification of the T-REX technology was enabled by the use of the PSTDL's facilities including an enclosed lunar simulant sandbox with a gravity offloading system, as well as our Dusty Thermal Vacuum Chamber. Access to these facilities allowed for the verification of the different subsystems of the T-REX rover by simulating realistic environments that would be experienced by the rover on the moon.

3.1.1 Sandbox



The PSTDL Sandbox encompasses a 6ft x 20ft x 9ft volume in the PSTDL lab facilities with all faces save for the bottom enclosed with a vinyl shroud as shown in Figure 4. A 6'x6'x9' area adjacent to the sandbox serves as an airlock between the laboratory and the Sandbox. A gravity-offloading gantry runs the length of the Sandbox facility. This system tracks the movement of the vehicles under test with VIS/IR cameras and continuously centers itself over the target in the X-Y axis. A counterweight currently adjusts for lunar gravity and is currently under retrofit to utilize a powered winch in the Z-axis. A 14ftx6ft regolith bed holding up to 3800 kg of simulant allows for testing in terrain up to 30 cm deep. A removable ramp can be installed in the sandbox for terrain testing at varying grades.

3.1.2 DTVAC



After validation testing in the sandbox, vehicle or system testing is then continued in the PSTDL Dusty Thermal Vacuum Chamber (DTVAC). This vacuum chamber consists of an internal usable volume of 50x50x70in, removable regolith beds, and a rectangular layout to maximize testing area within the thermal shroud and pressure vessel. The encompassing thermal shroud operates from -196°C up to 200°C to simulate temperature ranges and cycles found in most illuminated and shaded areas of the Moon. Combined utilization of the DTVAC and Sandbox will provide an effective means to rapidly develop, test and raise the TRL of new technologies and lunar hardware. The DTVAC facility production has been delayed many months by Covid but is now fully integrated and tested and ready for shipment to be installed at Michigan Tech in early December 2020.

3.2 Requirements Verification Matrix

A Requirements Verification Matrix (RVM) was used to track the overall progress of the engineering model T-REX rover while keeping the development path in the context of a realistic lunar CLPS mission. This matrix has most of the standard identification and traceability features while also leveraging a 2-tier gate verification system. A requirement can be "yellow-gated" if it is proven by design or analysis for the engineering model. The same requirement can then be "green-gated" when the verification method has been shown to be similar enough to what would be a "flight model" T-REX rover. This two-tiered process is used to have more granularity when tracking engineering model rover development. Requirements that are currently undergoing verification are described in the next section. The entire RVM can be found in the additional file uploads.

"Green gate"	Verified on flight model or by similarity to flight model via engineering model and or verified in DTVAC testing facility
"Yellow gate"	Verified on Engineering Model and or verified in atmospheric testing facility
	Unverified

4 PROOF OF CONCEPT TESTING

4.1 Command and Data Handling

4.1.1 Health Data

REQ ID	Name	Verification method	Test data folder name
CDH-01	Health Data Collection	Test	GitHub Repo
CDH-02	SOH Storage	Test	GitHub Repo

Test Description: In order to ensure continued nominal operation, the T-REX rover will need to keep detailed information about the health of its components so that the conditions of the craft can be monitored from the ground. This will be tested by purposefully causing faults in the system, and verifying that these faults are correctly detected, stored, and transmitted to ground if need be.

Results: This test has not yet been performed, the software diagnosing and recording system health is still in development.

Path forward: In order to move forward, the desired health data for each subsystem must be more accurately defined, the infrastructure needed to poll it must be created, and the control processes to periodically request it must be written. Then, the test to verify the requirements can be performed.

4.1.2 Subsystem Control

REQ ID	Name	Verification method	Test data folder name
CDH-03	Subsystem Control	Test	GitHub Repo

Test Description: The design of the T-REX rover's CDH system centers around the use of an on-board computer to handle the control of each subsystem through a connection to ground. As a result, the OBC must be capable of communicating with each applicable subsystem. This requirement has been yellow gated by demonstration of connectivity with the EPS, VIM, SPA, and COM subsystems, but needs a formal test procedure demonstrating active connections allowing for telemetry, SOH collection, and control for each.

Results: A formal test has not yet been performed.
Path forward: In order to move forward, a connection-test script should be created, verifying the connection to each subsystem. Successful completion of the test script will green gate this requirement.

4.1.3 Data Transmission

REQ ID	Name	Verification method	Test data folder name
CDH-04	Data Downlink	Test	GitHub Repo

Test Description: Because the T-REX rover is designed to operate largely with direct control from the ground during the traversal phases of its mission, telemetry data collected by CDH must be capable of being downlinked through the use of the COM system. This requirement has been yellow gated by demonstration of EPS telemetry downlinking but needs a formal test procedure demonstrating that the telemetry and health information for each subsystem is received by the ground correctly and accurately.
Results: A formal has not yet been performed.
Path forward: In order to move forward, more telemetry gathering infrastructure will need to be created, and a formal test procedure comparing the data received by the ground to that produced by each subsystem will need to be performed.

4.2 Communications

4.2.1 Wireless Communications

REQ ID	Name	Verification method	Test data folder name
COM-02	Communications Routing	Test	TP-COM-002

Test Description: Acting as a communication beacon to nearby client rovers is a central function of T-REX. To fulfill this requirement, the rover's network infrastructure must be capable of routing data both upstream to a client endpoint and receiving data downstream at the ground station endpoint. This requirement is being yellow-gated by the demonstration of sending and receiving data through the T-REX communication pipeline. To green-gate this requirement, more information needs to be known about the client rover's bandwidth requirements, the T-REX data budget, and the bandwidth capabilities of a flight-model wireless transceiver.
Results: A formal has not yet been performed.
Path forward: To move forward, more information needs to be known about the connection properties of the client rovers. This will dictate our hardware requirements, however, the networking software implemented on the T-REX should maintain forward compatibility with future iterations.

4.2.2 Tether Video Streaming

REQ ID	Name	Verification method	Test data folder name
COM-03	Conventional Conducting Tether Data Transfer	Test	TP-COM-001
COM-04	Superconducting Tether Data Transfer	Test	TP-COM-001

Test Description: The tether must support the transfer of various data, among those with the highest priority is video streaming. It is thus imperative that both conventional conducting and superconducting portions of the tether support video streaming from the rover to the ground station. These tests ensured this requirement was met. To simulate lunar conditions as well as keep in an operable temperature, the superconducting tether was dipped in a liquid nitrogen bath, in which a VDSL2-encoded video stream was sent from a raspberry pi and displayed on a laptop running the ground station software, while the conventional conducting tether was tested at room temperature. To green-gate this requirement, a full section of conventional conducting and superconducting tether needs to be tested in an RF noise-environment similar to that of the specified lunar PSR.
Results: Video was successfully transmitted from the raspberry pi over both the conventional conducting and superconducting portions of the tether, then displayed on the ground station.

Path Forward: Considering the increased effects of RF noise on longer lengths of conducting material, it is necessary to test a full length of superconducting tether in a lunar-like RF (noise) environment, where data loss/retransmission and video quality can be assessed more accurately.

4.3 Electrical Power System

4.3.1 SCT Battery Charging

REQ ID	Name	Verification method	Test data folder name
EPS-04	Tether Charging	Test	TP-COM-001

Test Description: Charging the T-REX on-board batteries is a key requirement of the tether. The purpose of this test was to determine whether the superconducting portion of the tether is capable of supporting a current large enough to charge the rover's batteries. This was done by submerging a section of superconducting tether in liquid nitrogen, connecting one end to a benchtop power supply and the other to the rover's batteries, then providing current through the submerged tether.
Results: The rover's batteries charged successfully over the superconducting tether.
Path forward: Charging the batteries over a full length of superconducting tether using flight hardware is the next step. However, there are no foreseen obstacles using a full length of superconducting tether given the electrical properties of the superconducting tether.

4.3.2 HOTDOCK Power Transfer

REQ ID	Name	Verification method	Test data folder name
EPS-05	HOTDOCK Power Transfer	Test	

Test Description: The HOTDOCK is how the T-REX will accomplish power transfer to other rovers within the PSR. To accomplish this task, another rover with a HOTDOCK unit must attach itself to the T-REX HOTDOCK unit located in the front of the rover. Once docked, the two units lock themselves together and power transfer can begin.
Results: Using the HOTDOCK units provided by Space Application Services, power was able to be transferred from one unit through the other.
Path forward: Further testing with additional units will involve doing a similar test in a vacuum and a dusty environment to TRL levels.

4.3.3 CCT Power Transfer

REQ ID	Name	Verification method	Test data folder name
EPS-06	Conventional Conducting Tether Power Transfer	Test	TP-COM-001

Test Description: With one section of the tether being conventional conducting, it is necessary that the rover receives adequate power for all of its functions through the CCT.
Results: Over multiple sessions testing the mobility and other various functions of T-REX, it has been proven that the CCT can reliably transfer power to the system.
Path forward: Further testing will be done with a longer length of CCT.

4.4 Software

4.4.1 Data Collection

REQ ID	Name	Verification method	Test data folder name
SFW-01	Execution Logs	Inspection	
SFW-03	Periodic SOH	Test	

Test Description: A variety of data collection and logging will be essential to monitoring the operation of the T-REX rover as a remote system, and as a result the system needs to keep detailed execution logs and

health data. The SFW-01 requirement has been yellow-gated through demonstration of the output of execution from varying system processes such as the EPS telemetry system, and the VIM subsystem's drive controller. A more formal test needs to be performed operating the rover in a variety of modes similar to the described operation described in the mission CONOPS and verify that the logs and SOH data contain the expected content describing system operation.
Results: A formal test has not yet been performed; our logging system is under ongoing development.
Path forward: A more centralized and controlled logging system, utilizing UNIX's built-in log capabilities should be developed, and each subsystem's control process should be modified to include on-action logging. Then the test can be performed.

4.4.2 Remote Control

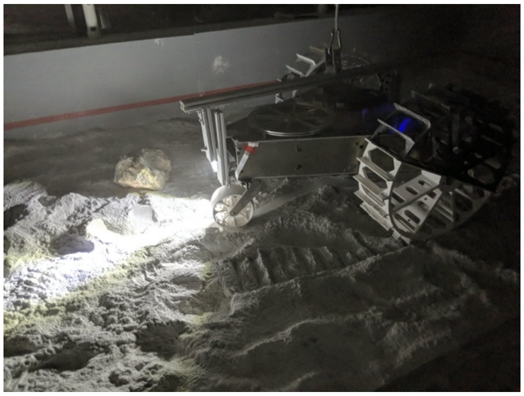
REQ ID	Name	Verification method	Test data folder name
SFW-02	Remote Control	Test	GitHub Repo
SFW-05	Drive Motor Control	Test	GitHub Repo
SFW-06	SCT Spool Motor Control	Test	GitHub Repo
SFW-07	Spool Detachment Motor Control	Test	GitHub Repo

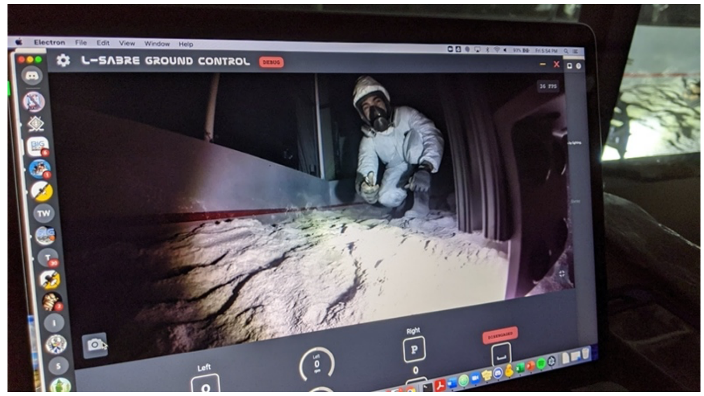
Test Description: In order for the T-REX rover to operate in a lunar environment, subsystem commands must be able to be issued, and the system must be able to be driven remotely. SFW-02, SFW-05 and SFW-06 have been able to be yellow-gated by demonstration in the sandbox testing of each system iteration so far. A more formal test will need to be performed that involves placing the T-REX rover in the sandbox and DTVAC, operating in environments similar to those described in the mission's CONOPS in order to green gate these requirements. Additionally, each subsystem command in our command dictionary will need to be individually issued, and the effective action of each command will be verified.
Results: A formal test has not been performed, the command, drive, and spool system software us under ongoing development.
Path forward: A more concise and centralized command issuing control system will need to be developed on the rover side, and the capability to issue commands linked to the dictionary will need to be developed on the ground control side. Then the test can be performed.

4.4.3 Vision

REQ ID	Name	Verification method	Test data folder name
SFW-04	Camera Feed	Test	GitHub Repo
SFW-09	Light Control	Test	GitHub Repo

Test Description: In order to be accurately controlled from the ground, the T-REX rover will need to be able to buffer and downlink a live camera feed and control an on-board system of lights for visibility within a PSR. The SFW-04 requirement has been yellow-gated using a Raspberry-Pi compatible camera to provide a live camera feed to the ground station. In order to green gate these requirements, a more formal test will need to be performed to verify sufficient control of each of the on-board lights from the ground station, that the camera feed operates with minimal latency both in its own operation, and that placed on the system, as well as verify the ability to take high-quality still pictures. These parameters will be tested both in a high and low-light environment similar to the lighting conditions expected in the environments described in the mission's CONOPS.
Results: A formal test has not yet been performed; our vision system software is under ongoing development.
Path forward: A higher-quality camera system needs to be chosen and integrated into the VIM subsystem, as well as the capability to re-orient the camera in a variety of viewing angles. Control capability for the lighting system must be added to the EPS subsystem and the previously mentioned command control system must be implemented. Then the test can be performed.





4.4.3.1 4.4.4 PSR Operation Functionality

REQ ID	Name	Verification method	Test data folder name
SFW-08	Base Service	Test	GitHub Repo

Test Description: In order to ensure proper operating within a PSR and fulfill the requirements of its mission, the T-REX rover must be capable of providing a wireless link through its COM system to the ground for any other rovers within range. In order to green-gate this requirement, a test will need to be performed by operating a small and simple faux rover using the T-REX system as a wireless passthrough.
Results: A format test has not been performed; our base service application is under ongoing development.
Path forward: A small test rover must be developed and given the capability to wirelessly connect to the COM system, then the test can be performed.

4.4.3.2 4.4.5 Thermal System Control

REQ ID	Name	Verification method	Test data folder name
SFW-10	Cooldown State	Test	GitHub Repo
SFW-11	Thermal Control	Test	GitHub Repo

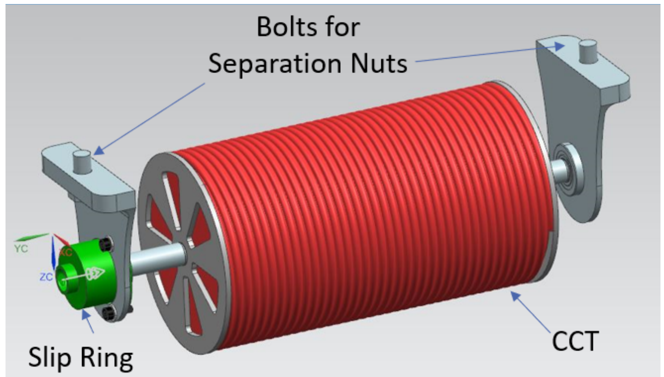
Test Description: In order to keep the system operating within the thermal environments of a PSR, it must be able to monitor and control the thermal conditions of its on-board components. In order to green gate these requirements, a more formal test must be performed to ensure that the system is capable of operating in a cool-down state to allow its SCT to reach cryogenic conditions, must be able to monitor the temperatures of the SCT and other subsystem, as well as switch on necessary warming for subsystems that cannot operate in the thermal environment of a PSR.
Results: A formal test has not been performed and our thermal system software is under ongoing development.
Path forward: Temperature probes must be acquired and integrated with the CDH subsystem, heating elements must be chosen and integrated into the EPS subsystem, the operation of each subsystem in the cooldown state must be more precisely defined and implemented, and the previously mentioned command control system must be developed. Then the test can be performed.

4.5 Spooling Assembly

4.5.1 CCT Spool General Mechanical Test

REQ ID	Name	Verification method	Test data folder name
SPA-03	Deploy CCT Spool	Test	N/A
SPA-05	Conventional Conductor Cable Storage	Analysis	N/A

Test Description: The T-REX rover is expected to carry at least 250 m of conventional conducting cable capable of power and data transmission in order to enter the PSR, after which the CCT spool will be dropped using separation nuts. This is replicable through calculation and atmospheric testing.



Results: Using the on-board computer, the T-REX was able to activate the separation nuts and drop the CCT spool. Through calculations, the CCT spool is able to carry approximately 300 meters of 5 mm diameter cable. See section 10.1 for calculations.

Path forward: The path forward to bring these requirements to TRL level will be to do the same test in the vacuum chamber with rated components.

4.5.2 CCT Spool General Mechanical Test

REQ ID	Name	Verification method	Test data folder name
SPA-06	Superconducting Cable Storage	Analysis	[5] Testing/Cable Single Wrap Calculations
SPA-07	Tether Capabilities	Test	

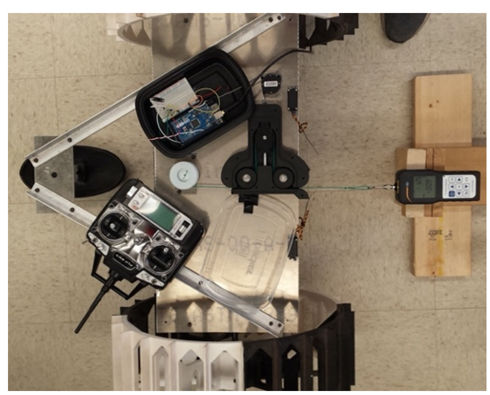
Test Description: The superconducting cable storage tests is an analysis to confirm that 2km of cable can be stored on the rover. The analysis shows that a 400 mm diameter spool is required to store the superconductor assuming that the cable is single layer wrapped. Note that the rover currently has a 1.5 km capacity spool mounted to it due to manufacturability however it can accommodate the slightly larger 2km spool. This requirement is still yellow because the multi-channel cable has not been fabricated but in theory its thickness should not change meaning that it should only require a taller spool. The tether capabilities test sets a requirement for the amount of power and data that the cable is able to transfer, however, the quantity of each is still being determined due to its reliance on the size of motors used which may be subject to the mobility testing along with the number of cameras and lights that are determined necessary during dark mobility tests.

Results: The rover has the capability to contain 2km of superconducting cable

4.5.2.1 4.5.2 Tension in Superconducting Cable

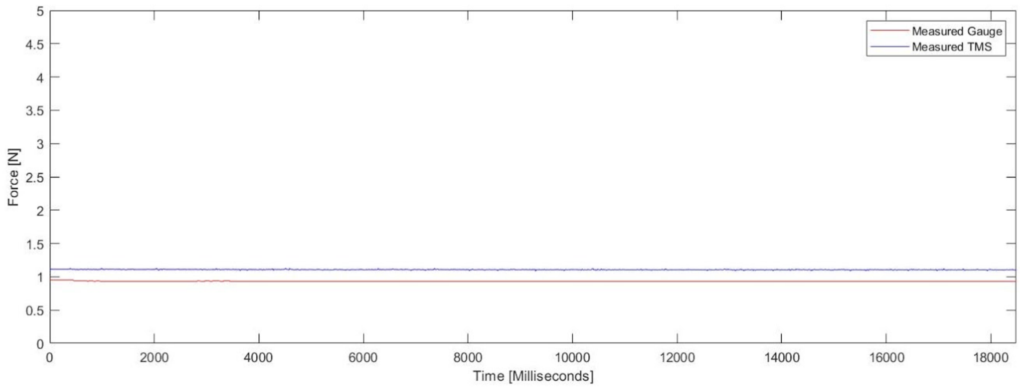
REQ ID	Name	Verification method	Test data folder name
SPA-01	Measure Tension in Superconducting Cable	Test	SPA -01
SPA-04	Manage Tension in Superconducting Cable	Test	SPA -01
SPA-08	Minimum Bend Radius	Test	N/A

Test Description: Measuring and managing the tension in the superconducting cable is handled by the TMS and the motor that drives the SCT spool. The requirements are verified by putting the SCT sub assembly through two tests. First a static test where the cable is held by a force gauge at a constant distance away from the rover and the TMS and motor are activated which holds the SCT at a specific tension, using the known tension from the force gauge and the measured from the TMS the TMS can be calibrated. Once calibrated, the TMS can undergo dynamic testing where the cable is still held by the gauge, but the rover moves across the sandbox and the real tension and the measured tension in the TMS are compared



The above figure shows an early static test setup used for calibrating the TMS. The cable used in this test is a normal cable that is used to tune the control loop before the expensive superconductor is implemented. The minimum bend radius of the cable is also considered in managing the superconducting cable however no formal tests have yet been performed. Despite this, the actual super conductor has been run through the TMS before by hand to ensure its fit and no damage was observed afterwards.

Results: Preliminary static and dynamic tests shows promise but many were conducted with simulated superconductors outside of the sandbox containing the lunar regolith. The TMS is able to hold the cable steady without significant oscillation in the system and tracks the tension in the cable well within the nearest newton and can keep it under the newton requirement.



The above figure shows data from the most recent TMS static test. The system still needs calibration at this state but the TMS manages to hold the cable at a very consistent tension for the duration of the test which is very close to its target tension of 1 N

Path Forward: Although these preliminary tests are encouraging, a test has not yet been run where the real superconducting cable is used in the regolith sandbox. Once the system has been thoroughly tested in this environment then the requirements SPA-01 and SPA-02 can be green gated.

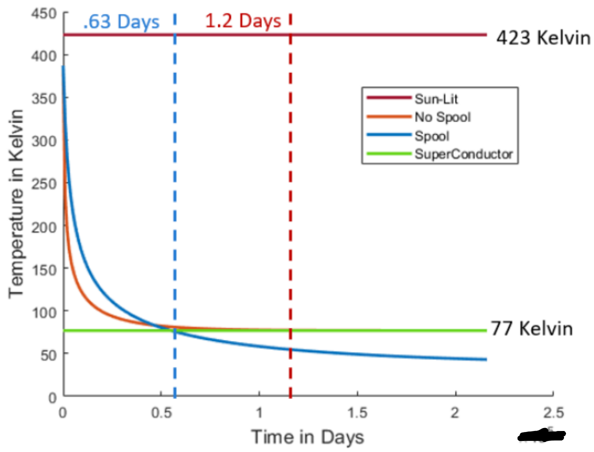
4.5.3 CCT Spool Heat Dissipation

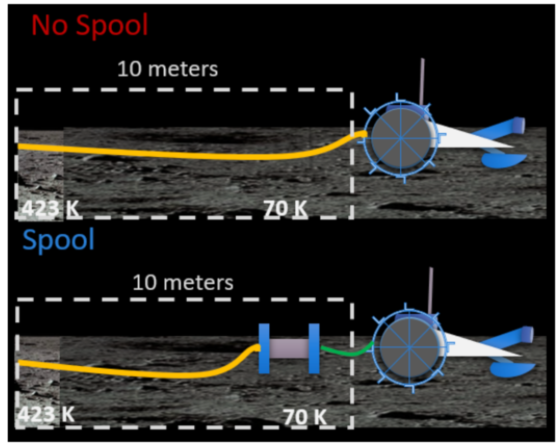
REQ ID	Name	Verification method	Test data folder name
SPA-03	CCT Spool Heat Dissipation	Analysis	STR-Thermal Studies – CCT Spool

Analysis Description: Once in the PSR, T-REX begins its pre-decent cooldown phase where the rover waits until superconducting temperatures are reached. As a part of this, the CCT spool is dropped from the rover to act as a thermal interface between the hot CCT leading outside the region and the SCT mounted on the rover. This barrier allows the rover to move a shorter distance into the crater before superconducting temperatures are possible, allowing for less weight and better efficiency for our overall tether. In order to ensure effective heat conduction between the wire and the spool, a thermally conductive ceramic, such as beryllium oxide, acts as an interface between the innermost wire layer and spool shaft. This system is modeled using NX Space Systems Thermal software to determine the amount of heat dissipated by the spool through radiation into the surrounding environment.

Results: Results show that the CCT Spool is able to dissipate heat from the conventional conductor faster and more effectively than a conductor alone. However, the amount of energy dissipated is highly dependent on the temperature difference between the temperature of the conventional conductor and the temperature of the superconducting spool atop the T-REX.

Path Forward: Analysis results show that the CCT spool is able to create a thermal interface zone between the two tethers when dropped in the PSR. Before this requirement can be green gated however, a physical test of the spool's capability to dispel heat within a vacuum environment will need to be completed. This test will likely take place alongside vacuum chamber testing of the T-REX.





4.5.4 SCT Spool Thermal Isolation

REQ ID	Name	Verification method	Test data folder name
SPA-09	SCT Spool Thermal Isolation	Analysis	STR-Thermal Studies - Mk2_Sim

Analysis Description: Before power and data can be transmitted through the superconducting material, the conductor must reach 77K. To determine the feasibility of achieving this inside the PSR, a simulation of the T-REX was created in NX Space Systems Thermal. The entire rover was modeled in order to gain a more holistic understanding of how components such as the electronic heaters and MLI would impact the rate of cooling of the SCT Spool. Calculation focus was on determining radiative cooling to space as well as conduction throughout the rover.
Results: This analysis evolved over multiple iterations and came down to determining how best to isolate the SCT Spool from the SCT Spool motor while minimizing the amount of heat lost by the electronics into the frame. These design changes to isolate the spool incorporate MLI to keep motors and electronic stacks warm as well as using a composite shaft for the motor controlling the TMS system. Current simulation estimates have the rover taking approximately 48 hours before reaching its lowest temperature, though better understanding of our power budget will yield more accurate results.
Path Forward: Future thermal modeling will continue as the rover design progresses.

4.6 Vision and Mobility

4.6.1 Obstacle Identification

REQ ID	Name	Verification method	Test data folder name
VIM-01	Obstacle Identification	Test	TP-VIM-001

Test Description: The terrain surrounding and inside a lunar PSR will be difficult to navigate. Large rocks, craters, and steep slopes are hazards that will be encountered in these regions on the Moon. Using a camera mounted to the exterior of the rover, T-REX must be able to identify obstacles in its path. Using this video feed an operator can then determine whether or not the obstacle is small enough to traverse or if it is too large and must be avoided. This video feed serves as the primary means of navigation that the operator will use to steer the rover.
Results: Our team was successfully able to operate the MK2 T-REX rover using only the video feed for navigation. This capability was confirmed over multiple test days in which T-REX was subjected to different terrain scenarios where craters, rocks, and uneven terrain features were present.
Path forward: The next step in development of the camera vision system is to harden the system for use inside the DTVAC. To do this, we will need to select a new camera that is rated for high vacuum and low temperatures. Vacuum rated cameras are available, but there are few options for cameras that can withstand cryogenic temperatures. To solve this problem, we will need to fabricate a housing to enclose the camera.

The housing will be insulated and heated using resistive heating elements in order to keep the camera at operating temperatures.

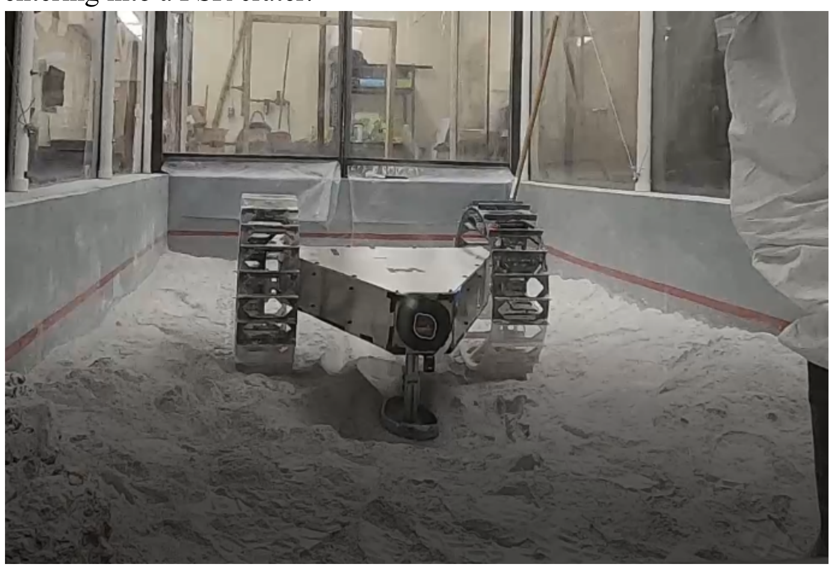
4.6.2 Terrain Mobility

REQ ID	Name	Verification method	Test data folder name
VIM-02	Terrain Mobility	Test	TP-VIM-002

Test Description: In order for T-REX to be successful in its mission the rover must be able to traverse a variety of terrain conditions without becoming immobilized. Obstacles located in the Lunar environment include rocks, craters, and slopes of all sizes. For testing purposes, we have selected four primary terrain scenarios to test the T-REX on. These are, flat terrain without rocks or craters, flat terrain with a mix of rocks and craters, sloped terrain without rocks and craters, and sloped terrain with a mix of rocks and craters.

Results: Initial tests with the MK2 T-REX rover showed that the rovers design was well suited for flat terrain traversal. Our next phase of testing will be on sloped terrain with a maximum angle of 45 degrees. Slope terrain testing is scheduled to take place in early December 2020.

Path forward: At this time, the MK2 rover has been tested on flat terrain with successful results. In December we will begin slope terrain testing with the MK2 rover and also unspooling testing with the SCT. Sloped terrain testing will be done inside the PSTDL sandbox using a large ramp platform layered with lunar simulant to simulate the rover entering into a PSR crater.

4.7 Structures

4.7.1 Launch Survival Analysis

REQ ID	Name	Verification method	Test data folder name
STR-01	Survives Launch Gs	Analysis	N/A
STR-06	Survives Launch Acoustic Pressure	Analysis	N/A

Test Description: In order for T-REX to survive launch, it must be able to withstand the G forces as well as the acoustic pressure imparted by the rocket. Based on data derived from SLS Mission Planner's Guide, all components of T-REX shall withstand -4.1g vehicle axial, and ±3g vehicle radial loads. T-REX shall also withstand 143.2 dB of sound pressure. In order to greenlight these requirements, computer FEA and simulations will be used to determine failure points of the robot that will allow us to design solutions that mitigate any potential failure points.

Results: These tests have not yet been performed.

Path forward: An appropriate FEA software that can perform these tests still needs to be selected so that we can run these tests and greenlight the requirements.

4.7.2 Lunar Conditions Survival Analysis

REQ ID	Name	Verification method	Test data folder name
STR-03	Thermal Tolerance	Test	N/A
STR-04	Wear and Durability	Test	N/A

Test Description: To ensure that the rover can survive the extreme conditions of the PSR a series of tests will be conducted in the dusty thermal vacuum chamber. The chamber will be lowered to 73K and basic functionality will be tested to ensure that the structure and rover as a whole can survive the cryogenic temperature. The second test to confirm that the rover will survive environmental conditions during the mission, is a wear and durability test. This test consists of disassembling the rover and inspecting moving parts and wear surfaces after all other mobility related tests are complete. The time that the rover spends doing tests is much longer than its total mission duration so if the rover survives its testing without needing mechanical maintenance and wear is considered to be acceptable then it is prepared for the moon.
Results: Mobility Testing is still in progress and these tests will be conducted after mobility tests are complete.
Path forward: Once mobility testing is complete and the DTVAC is operational, lunar conditions testing can commence to ensure T-REX can handle the environment of the PSR.

5 PATH TO FLIGHT

The path-to-flight for the T-REX rover will primarily revolve around raising the TRL of the superconducting tether's power and data relay. TRL will be raised via continued environmental testing in the sandbox and vacuum facilities. The priority at this moment is on the spooling assembly because much of the hardware enabling mobility on the T-REX rover is not novel in design or the focus of this project. Currently, the MK2 rover chassis and hardware integration is nearly complete. Mk2 will enable the continued verification of remaining requirements which need a mobile system and can be done outside of a thermal vacuum facility. The subsystems that MK.2 is composed of have been individually verified prior to integration.

System-level testing in the DTVAC facility will commence once commissioning at Michigan Tech has been completed. The first tests to be conducted will be to verify the ability of the spool to dissipate heat for the transition between the superconducting and conventional conducting tethers. Complexity of subsequent tests will increase until the entire MK.3 rover can be placed in the DTVAC facility. During the MK2 to MK3 transition, hardware will be switched from the Raspberry Pi to BeagleBone-controlled architecture. Pi architecture was used because it reduced the time required to get the MK1 rover moving by 3 weeks - a necessity given the 2-month development delay caused by Covid. BeagleBone architecture was originally preferred because CubeSat hardware based on that board exists and is TRL-9. Other changes to the rover include modifying all custom boards and motors for operation in cold vacuum. Additional heaters will be installed to keep hardware at operating temperature whose upcoming addition has been accounted for in earlier PCB designs. The transition to vacuum-rated operation is understood by the current team due to prior experience and will not be a major technical burden. The most difficulty expected is from Covid-induced schedule delays.

The T-REX mission is well-postured for the upcoming Watts on the Moon Challenge. The power delivery requirements for the Watts challenge can be met by the rover with minimal modifications. A physical path to developing and acquiring funding for a flight-rated T-REX mission can be pursued via this competition. In the context of this competition, a high-fidelity engineering model of the T-REX rover should be prepared by the Phase 2 deadline of fall 2022. This final Mk.4 model will possess the same hardware (not rad hardened because unnecessary for Earth testing) and full-length tethers.

6 SAFETY PLAN AND PROTOCOLS FOLLOWED

The T-REX team works in various facilities/labs on the MTU campus. The main location is the Planetary Surface Technology Development Lab (PSTDL) which locations are supervised by Dr. van Susante. All students have received general safety and awareness training as well as lab specific safety training. This includes safety training for working with lunar simulant (dust) and proper PPE use, working with LN2, vacuum chamber, electrical systems, FANUC Robotic arms, ladder use, emergency procedures, proper ordering, handling and storage of supplies and most importantly this time: COVID-19 safety procedures. All these are described in the PSTDL **Safety Procedures & Standard Operating Practices Document**, which gets updated as changing circumstances occur. These safety procedures and training are reviewed and approved by the safety representatives of the departments the labs are in and MTU environmental health and safety representatives. The main points are that students have to do a daily symptom check before coming to campus, they need to sign-up for a lab time slot on google calendar so the maximum number of allowable people is not exceeded, they have to follow mask, physical distancing, hand-washing and disinfection protocols (including sign-in and disinfection/cleaning logs) when in the labs. When anyone comes into contact with a suspected COVID-19 case, they report it, self-isolate and the lab is disinfected and cleaned extra thoroughly before anyone is allowed back in.

7 RESULTS & CONCLUSION

Key results from testing have shown that the unspooling system we developed functions for unspooling the SCT. The SCT has been found to have higher-than-expected resilient mechanical and electrical properties. This lowers the risk of utilizing a narrow vapor-deposited tape superconductor as a tether. Further testing is required on the CCT half of the tether. The rover's skid mount has proven to function during horizontal sandbox testing. Further slope testing will be conducted after the Thanksgiving holidays to verify sloped spool deployment.

The current development of the T-REX rover is still underway despite major setbacks due to the Covid pandemic. Subsystem-level testing in vacuum environments will begin soon. The current Mk.2 prototype rover is more than capable of verifying all requirements which can be tested at atmospheric conditions. The arrival of the DTVAC will enable more complicated environmental testing. Prototype testing is still underway to achieve the proposed science objectives in one complete system. Objectives have been proven in part via low-level testing and system-level requirement gates will begin flipping. Testing has shown that the T-REX rover could be an effective solution for providing power and data into PSRs and can be developed within the timeline required for the ARTEMIS program and CLPS demonstration missions.

8 TIMELINE

	May				June				July				Aug.				Sep.				Oct.				Nov.				Dec.			
T-REX MK1																																
MK1 System Design				✔																												
MK1 Fabrication								✔																								
MK1 Preliminary Testing												✔																				
MK1 Sandbox (Flat terrain)																✔																
SCT Liquid N2 Testing																✔																
T-REX MK2																																
MK2 System Design																✔																
MK2 Fabrication																				✔												
MK2 Preliminary Testing																					✔											
MK2 Sandbox Testing (Flat)																											✔					
MK2 Testing Continued																																
MK2 SCT Deployment Testing																													✔			
MK2 Angled terrain (*Smooth)																													✔			
MK2 SCT Deployment Testing																														✔		
MK2 Angled terrain (*Rocks)																														✔		
MK2 DTVAC Testing																																✔
PSTDL Lab Facilities																																
DTVAC Arrival/Installation									Delayed due to covid →																					✔		
DTVAC (Regolith Bin) Design								✔																								
DTVAC (Regolith Bin) Fab.																													✔			
Sandbox Construction													✔																			
Produced simulant (Sandbox)													✔																			
Produced simulant (DTVAC)																														✔		

9 BUDGET

An overall NASA BIG Idea T-REX project budget of $162,637. - was awarded, $74,589.10 in Phase I (Feb 14 - May 27, 2020), and $88,047.90 in Phase II (May 27, 2020 - Jan 8, 2021). Since originally the Forum was to take place in November 2020 but due to COVID-19 was moved to Jan 2021, a no-cost extension was granted. The 53% overhead from MTU, for a total of $61,568 and MI Space Grant for a total of $5,300 was waived. Partners on this project include MetOX who custom made a two-channel superconducting tape for us, Space Application Services in Belgium who loaned us their first HOTDOCK active docking system (valued at $10k) and Maxon Motors who gave us discounts on the regular and vacuum rated motors. Machining time in the form of water-jetting aluminum was donated by Great Lakes Sound and Vibrations. Other grants were leveraged where overlap existed such as producing the lunar simulant MTU-LHT-1A: this work was directly supported by NASA's Solar System Exploration Research Virtual Institute cooperative agreement notice 80NSSC19M0214 for the Center for Lunar and Asteroid Surface Science (CLASS). Due to COVID, several items and categories have been adjusted (e.g., travel funds were redistributed). At the time of submitting this report, approximately $20k is left for continued testing of the T-REX rover in the DTVAC which will take place during December 2020 and January 2021.

Phase I	**$74,589.10**	**via NIA**
fabricated equipment	$ 8,001.00	
supplies (except bulk LN2)	$ 13,728.10	
services	$ 5,000.00	
50% of grad student stipend	$ 10,000.00	
50% of hourly grad student	$ 4,200.00	
50% of hourly undergraduate students	$ 32,760.00	
50% of grad fringe	$ 900.00	
53% overhead	$ -	waived
	$ 74,589.10	
Phase 2	**$ 88,047.90**	**via Spacegrant**
Faculty summer (20.5%) (2 weeks)	$ 5,158.00	
supplies (remainder plus LN2)	$ 24,992.51	
services	$ 1,500.00	
50% of grad student stipend	$ 10,000.00	
50% of hourly grad student	$ 4,200.00	
50% of hourly undergraduate students	$ 30,240.00	
50% of grad fringe	$ 900.00	
faculty fringe	$ 1,057.39	
travel	$ 10,000.00	
53% overhead	$ -	waived
	$ 88,047.90	

10 APPENDIX

10.1.1 10.1 Spool sizing Math

Equation 1. Calculating Length of Cable on Spool
L = i=1n(ri+W2+((i-1)Dc)*2*WDc
ri=radius of inner shaft =.00635 m
W=Width of spool =.191 m
Dc=diameter of cable = .005 m
n=number of layers = 21 layers