Testing and Development of the Tethered-permanently shadowed Region EXplorer (T-REX): a rover designed to lay superconducting tether into Lunar PSRs.

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1 Abstract

Power and communications are required for successful operations in the Permanently Shaded Regions (PSRs)s located at the lunar poles. However, due to the location of PSRs, direct solar power from the Sun and line of sight communications to Earth is limited. NASA solicited solutions from universities within the United States with the Breakthrough, Innovative, and Game-changing (BIG) Idea Challenge. The Planetary Surface Technology Development Lab (PSTDL) at Michigan Technological University (MTU) developed the Tethered-permanently shadowed Region EXplorer (T-REX) to address this problem. A conventional round tether in series with a superconducting tape tether connects to a lander at a crater rim to provide power and communications to T-REX during its descent into a PSR. This mission is enabled by passive cooling of hardware within the naturally occurring cold environment of a PSR. T-REX was developed using an iterative approach with testing conducted from component to system-level. System validation included testing within a sloped lunar regolith simulant chamber and component-wise testing under cryogenic temperatures.

T-REX has shown to be capable of traversing down 45 deg slopes and obstacles in lunar highland terrain simulant during system mobility testing. The on-board tether deployment system was able to unspool a superconducting tether while maintaining controlled rates of under 5 N of tension. A data transfer rate of 94 Mbps via VDSL-2 and 132.2 W of DC power transfer over the superconducting tether when cooled to 77 K was validated through testing. Thermal analyses on the system analytically validated the performance of T-REX during the transition between

shaded and illuminated regions. The T-REX rover technology was raised to Technology Readiness Level (TRL) 5 over 1.5 years of research. Superconducting tethers are high efficiency, low mass means of providing power and data in extreme lunar environments.

2 Introduction

The Artemis program aims to return humans to the lunar surface and prepare for sustainable missions to Mars. [1] To create a truly sustainable program, using the local resources is critical to reducing the launch mass of a mission. An initial goal is to confirm the presence, properties, and distribution of the water ice detected in the PSRs at the lunar poles. Following this discovery, mining, and processing the water ice can enable lunar manufacturing of propellant. [2] Orbital measurements are limited in their ability to measure the properties of the water ice. Designing proper extraction equipment requires high-resolution distribution maps as well as geotechnical properties. Determining the in-situ distribution and properties will allow the ice deposits to be quantified as a reserve if they are found to be viable for extraction. This process requires surface operations.

Extracting significant quantities of water ice from PSRs requires long-duration industrial-scale operations. Besides extreme environmental conditions, one of the most significant challenges is the limited power generation and line of sight communications. PSRs in polar craters with sufficiently steep rims may have both sunlight and line-of-sight communications to Earth blocked seasonally or permanently. These infrastructure gaps in the Moon's polar regions prevent any substantial excavation effort and limit the capabilities and duration of smaller near-term exploratory missions, necessitating an intermediary step to relay resources to missions within the PSR. Precursor communications and power architecture must be established to maximize the science potential of long-duration PSR missions. During manned operations on the Moon, a resilient communications and power system is paramount to ensure the safety of astronauts.

3 Current Solutions

The NASA BIG Idea Challenge is an annual design competition for university student teams to submit technology proposals to the Space Technology Mission Directorate and the Office of STEM Engagement. In 2020, this challenge called for proposals for sample lunar payloads that demonstrated key technologies within PSRs on the Moon. The three main categories for the challenge were: the exploration of PSRs, technology to support Lunar In-Situ Resource Utilization (ISRU) in a PSR, and capabilities to explore and operate in PSRs. The PSTDL chose to focus on the third category, proposing a solution to provide power in the kilowatt range to systems operating within shaded regions. When designing a solution to address the need for power within PSRs; Radioisotope Thermoelectric Generators (RTGs), solar towers, and solar reflecting towers were considered for local power generation, and power beaming and tethered solutions were considered for power transmission.

Volatiles such as water ice deposits are often located in locations with conditions that are a hindrance to robotic operations. Radioisotope Thermoelectric Generators provide a method of power generation directly within the environment. RTGs are a largely explored technology due to their long lifespan, slow degradation, and their ability to produce constant energy in the range of hundreds of watts. For example: the RTG on-board the Mars Research Laboratory Curiosity rover was designed with a power output of approximately 120 W. [3] While RTGs could remove the need for power transmission into PSRs completely, they are difficult to scale, either requiring multiple units to provide power generation in the kilowatt range or restricting their use to lower power scientific missions rather than future commercial applications.

An alternative to RTGs for power generation within a shaded region is solar towers to elevate solar arrays into altitudes with more consistent sunlight. Because solar towers use solar arrays, mature technology for space applications, they offer an effective solution to power generation. Solar cells currently used in space applications have a power to mass ratio of approximately 350 W/kg.[4] Small scale solutions capable of deploying up to 32 feet in height[5] have been developed. Still, solar tower solutions may need to reach kilometers in height [6] in order to be effective in many PSRs, which requires either a sizeable deployable solution or the construction of a sufficiently tall structure. These towers must be supplemented by an additional power transmission system such as a tether or power beaming.

Sunlight reflecting towers are another power transmission method making use of solar power. These towers use assemblies of mirrors set up outside of the shaded region to direct sunlight to solar arrays inside. Like solar towers, this approach often requires large structures or specific placement. The power transfer capabilities of sunlight reflecting towers depend largely on mirror’s solar irradiance, the diameter of the mirror, and the distance of power transmission. These parameters have been modeled using an example rover with 6 m^2 solar array operating at

16% efficiency 10 km away from the reflecting tower. To transfer the 300W needed for the rover to operate, the mirrors must have a diameter of approximately 40m.[7] Sunlight reflecting arrays are being developed for lunar applications, including TransAstra's Sunflower™ which can deploy itself up to 800m in height within PSRs.[8]

The steep crater descents into PSRs create a unique opportunity for wireless power and data transmission. Beaming power is a transfer method that offers significant mass savings, lacking the need to deploy large stationary infrastructure. Rectennas for microwave power beaming have been demonstrated at total efficiencies of 54% transferring 495W within a laboratory setting.[9] In comparison to microwave power beaming, laser and millimeter power beaming operate at efficiencies in the range of 50-60% and 35%, respectively.[10] These formats offer comparable transmission ranges of up to kilometers of power transmission.

Tethers are capable of power transfers at high voltages well within the kilowatt range and are the default for long-range power and data transfer here on earth. The conductor material, wire AWG, tether input voltage, and temperature are the main factors governing transmission efficiency. Power transmission can be achieved at efficiencies of 75 to 99.7% and demonstrated 10 kW power transfers over 10 km with an ~ 14 kW power source.[11] Tethered systems also provide a considerable advantage by mitigating the potential line-of-sight problems between systems inside and outside PSRs and allowing for power and data transfer over the same medium. Superconductors can further improve the performance of tethers because they have effectively zero resistance. Superconductors need to be cooled in order to reach a superconducting state, making them unsuitable for many applications on earth, but permanently shaded regions can remove this need for cooling altogether with their low environmental temperature.

The PSTDL reviewed and compared each of these options for power transfer to systems within shaded regions. Solar towers and solar reflecting towers require larger structures that are more challenging to deploy. Power beaming is a promising solution, but the total efficiency of power transfer methods is significantly lower than that of tethers. RTGs are another unique solution that provides significant power generation with a long lifespan but are highly regulated and require extensive safety measures. While RTGs are an effective power generation solution, they do not offer power transfer capabilities and need to be supplemented with another power transfer solution to service multiple systems within the PSR. Due to efficiency and logistical issues present in other solutions a tethered approach was chosen to deliver power and data connectivity to systems operating within a PSR.

4 Superconducting Tethers

Power transfer using tethers into and within a PSR will occur over kilometers. T-REX was designed using a superconducting tether to provide as much power as possible to client systems to minimize ohmic losses during transmission. Superconductors are materials that can reach a state of conductivity where the electrical resistance is effectively zero. This state is achieved by cooling this superconductor down to the transition temperature. Materials that exhibit superconductivity are categorized as either a High-Temperature Superconductor (HTS) or a Low-Temperature superconductor (LTS); differentiated by having a transition temperature above or below the boiling point of liquid nitrogen at 77k. In most situations, a HTS is a more practical choice for the conductor. One of these materials is Yttrium barium copper oxide (YBCO). YBCO reaches its transition temperature between 80-93 K.[12] While not the highest temperature superconductor, YBCO can maintain a high critical current density and at a lower cost per unit length of the conductor when compared to other materials.[13] The YBCO tether chosen for T-REX (Figure 1) was produced by Metox[14] and had a rated current capacity of 75 amps. The MetOx tether consists of copper shielding, Hastelloy substrate, and YBCO as the superconducting material. The HTS can transfer the same 120V of power required for the T-REX mission as a 16-gauge copper twisted pair with essentially zero losses, while this same copper twisted pair will lose 54% of the power over just 250 meters at this voltage. Additionally, a two-channel superconducting tether is only 34% of the weight of the twisted pair conventional tether.

The cryogenic environments of PSRs provide an opportunity to use superconductors without the energy-intensive need to cool the material below its transition temperature actively. Within these regions, the superconductor is not heated by ambient air and will cool through radiation to space passively. The copper cladding on the conductor also allows the tether to be used for small amounts of power transfer before reaching the transition temperature. This will enable T-REX to maintain survivability temperatures until the tether can transfer its max power to support other missions.

5 Mission Overview

T-REX is an infrastructure technology demonstration mission employing tethered power and data transfer into a PSR. Using a conventional round tether in series with a superconducting tape tether connected to a lander at a crater rim provides power and communications to T-REX during its descent into a PSR (Figure 2). This mission is enabled by passive cooling of hardware within the naturally occurring cold environment of a PSR. This mission will support the exploration and excavation of lunar resources by providing a power source and data communication point where conventional line-of-sight radio frequency communications and solar power generation are limited.

Phase 1: Upon a successful landing via a Commercial Lunar Payload Service (CLPS) lander, T-REX will egress from the CLPS lander via ramp or other means once all systems report nominal operation. During egress, T-REX will initiate an on-board spooling system and begin deploying a round Conventional Conducting Tether (CCT) for power and data transfer. Movement control, telemetry, and vision with T-REX are done via commands issued through the Deep Space Network and relayed by CLPS lander. This architecture aims to minimize mission mass by removing dedicated wireless communication equipment.

Phase 2: T-REX will traverse towards the boundary of a PSR inside a crater while passively deploying the conventional tether with tension. The lander will be a nominal 100 m from the PSR as outlined in the BIG challenge [15]. T-REX was designed to deploy up to 250 m of CCT to account for a non-direct path towards the PSR. Temperatures in the illuminated south pole of the

Moon are nominally 200 K but can be as high as 350 K.[16] The CCT is used for deployment in the illuminated regions because the SCT cannot operate in a superconducting state at temperatures above 92 K[12]. Ideal candidates for the current implementation of T-REX would be locations where the PSR is close to a crater rim such as in Lovelace crater.[17]

Phase 3: T-REX will descend the crater rim and enter the PSR, following a planned descent path that accounts for temperature change along the deployed conventional tether. The full unspooled CCT length into the PSR will be designed to exceed an estimated distance dependent on a temperature transition zone varying by PSR[18]. Heat dissipation by the deployed tether and unspooling system into the ambient lunar environment can bring the SCT below the superconducting temperature. The entire length of the CCT is unspooled to maximize the radiative surface area and fully utilize landed mass.

Phase 4: Following complete deployment, the CCT spool will be ejected from T-REX onto the lunar surface. The ejected spool maintains a tethered electrical connection between T-REX and the CLPS lander. Active deployment of the SCT begins concurrently with the CCT spool drop. Power and data transfer along the SCT is done at conventional rates until the measured resistance of the entire tether length lowers sufficiently to indicate that the superconductor has reached the transition temperature. The superconducting tape-like tether with a cross-sectional area of 0.2mm x 4mm can conduct up to 75 A of current below 92 K. The SCT is connected to the detached secondary spool via a slip ring at one end. Unspooling of the primary spool is actively controlled to minimize tension. While the SCT is strong enough to suspend the entire rover in Earth gravity, tension is minimized to reduce the chance of damage. Deployment continues for up to 1 km or until the bottom of the PSR is reached.

Phase 5: Upon successful traversal to the selected location within the PSR, T-REX will park and enter the service phase of its mission. Power and communication will then be relayed for other missions within the PSR. A HOTDOCK detachable coupling interface is activated on T-REX. [19] This connector then provides up to 1 kW of power to any rover with compatible coupling mechanisms mated with T-REX. Once a client mission utilizing T-REX has received an adequate charge, the client mission can detach and continue its mission. Communications within the PSR between T-REX and client missions are performed using a full-duplex radio frequency communication system. Commands can be sent from Earth via the deep space network to the CLPS lander, then through the tether into T-REX. Received commands are broadcast to client missions in the PSR. T-REX's video feed and telemetry follow 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 than optical fiber, speeds offered by VDSL are an order of magnitude faster than current high-TRL wired communication protocols like RS-485 at long range. [20] Data rates provided by the deep space network are the current bottleneck of the mission at 10 Mbit/s. VDSL retains signal integrity up to 5 km and can use the existing SCT substrate to transfer power. The VDSL protocol balances simplicity, technology readiness level, durability, and bandwidth.

The T-REX mission is baselined to last 12-14 earth days, as outlined by the BIG Idea Challenge guidelines. [15] This period is from the duration a CLPS lander is continuously illuminated by the

Sun at the lunar poles. The lander will no longer 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 when the CLPS lander is no longer illuminated.

6 System Overview

The T-REX rover was designed using an agile systems engineering approach with a focus on rapid prototyping to quickly expose problems and identify solutions which are proven to perform. Design decisions were guided by a requirements verification matrix that defined the success criteria to accomplish the mission (Table 1). [21]

The T-REX chassis houses all necessary components for operation and is suspended above the lunar surface via two wheels and a skid. Each wheel is 15.24 cm wide and 48.5 cm in diameter with 2 cm tall grousers, designed to allow regolith to pass through. Unobstructed access in the front and rear of T-REX allows for mating of the HOTDOCK, and ample room for the operation of the tension measurement system. The front skid is used instead of a wheel as it offers better controllability while descending steep slopes. The added friction caused by the sled acts as a natural brake which prevents T-REX from rolling if power to the motors is cut (Figure 3).

T-REX has been designed to fulfill all its mission requirements through the operation of its six subsystems. [15] These subsystems include the spooling system comprised of the Conventional Conducting Tether (CCT), Superconducting Tether (SCT), and tension measurement system, the electrical power system, the communications system, and vision and mobility (Figure 4).

The spooling assembly manages the two tethers within the rover and maintains their proper operating conditions as defined by the mission Requirements Verification Matrix (RVM). The relevant RVM goals include the ability to unspool and deploy the CCT spool and accurately measure the tension in the SCT while maintaining tension less than 5 N. The components used to achieve these goals are the CCT spool, the SCT spool, and the tension measurement system.

The electrical power system of T-REX is separated into two parts, the power transmission train, and the internal electrical systems. The power transmission train consists of the CCT, slip ring, and SCT. Its function is to provide power from the CLPS lander to T-REX during portions of its descent. Upon the successful traversal down the rim of a PSR, the power transmission train will provide power to client payloads during servicing of other missions. The internal electrical system regulates, monitors, and provides power to both T-REX and its clients. The internal electronics take the incoming power from the tether, step the voltage down, and distribute it to the various subsystems. The communications subsystem also employs the physical connection provided by the CCT and SCT. It is responsible for routing all messages from T-REX to the ground control. The communication subsystem consists of an on-board ethernet switch, the main on-board computer, and an active ground control instance. Communication between T-REX and its ground control instance are achieved through the CCT and the SCT. The vision and mobility subsystem manages the cameras to provide visual feedback from T-REX and the components required to allow T-REX to traverse the lunar environment for its mission. A theoretical power budget of T-REXs electrical systems was created to estimate the overall power draw for each mission phase (Table 2).

7 Thermal Analysis

The T-REX relies on the passive cooling of the superconducting tether to reach the full power transfer capability of the mission. The cooling of the tether is dependent on the environment of the PSR and requires analysis to determine whether the transition temperature can be achieved. Of particular interest is the time required for the junction point on the CCT spool to reach superconducting temperatures. The model developed simulates how junction points impact the heat-affected zones on the tether and how the superconducting section cools within the PSR.

7.1 Calculation Methodology

The T-REX tether can be represented by a one-dimensional model as the tether is assumed to have little temperature variation along thickness and width. Representative lengths of a single-channel CCT and SCT were chosen to reduce the number of elements as only tether portions near boundary points and the tether junction would show significant results. An idealized PSR (Figure 5) where there is an immediate transition from sunlit-zone to shaded-zone was assumed rather than a gradual transition. An initial tether temperature of 200 K was set to represent average surface temperatures outside PSRs. Temperatures near the poles remain cooler than regions near the equator due to the constant low angle of the sun.[16] The CLPS lander and rover are constant temperature boundaries held at 250 K to represent heating elements that would keep the T-REX and lander above their electronics survival temperature. To isolate the superconducting tether from the rover, an insulating composite motor shaft separates the SCT spool from the rover body.

A total tether length of 100 m was chosen to describe the thermal interface regions and the equilibrium temperatures of either tether. This numerical model was developed in MATLAB and took the form of the Finite-Difference Euler-Forward method:

$$T_i^{j+1} = T_i^j + \Delta T_{\text{cond}}^j + \Delta T_{\text{gen}}^j - \Delta T_{\text{rad}}^j + \Delta T_{\text{irr}}^j \quad \textbf{(Equation 1)}$$

Where T is the temperature of element i at time step j (Equation 1). ΔT values represent the change in temperature resulting from conduction from regolith and adjacent elements, generation due to resistance, radiation to space, and irradiance from solar energy. Summing these values with the current temperature of the element, the temperature at the next time step is computed. This process is repeated for each element of the tether. An explicit equation for this 1D planar conduction problem is presented (Equation 2).

$$T_i^{j+1} = T_i^j + \frac{\Delta t}{\rho_i c_i A_i}\Big[k_{i+1}A_{i-1}\frac{T_{i+1}^j - T_i^j}{(\Delta x)^2} - k_{i-1}A_{i-1}\frac{T_i^j - T_{i-1}^j}{(\Delta x)^2} + h \times k_{\text{lunar}}(T_{surface} - T_i^j) + \varnothing_i^j A_i - p_i[\epsilon_i \sigma (T_i^4 - T_{\text{space}}^4) - E_i]\Big] \quad \textbf{(Equation 2)}$$

Many physical properties of the tether, such as specific heat and electrical resistance, are highly temperature-dependent and require computation at each iteration. Temperature-dependent specific heat and resistivity for copper and aluminum were used for the simulation.[22–24] Other model parameters and constants used in the model are represented (Table 3).

7.2 Results

Results from the simulations show that the main section of SCT can reach the transition temperature of 92 K within the PSR after 7.4 hours of deployment and the tether junction at the spool takes 18.7 hours to cool through radiation ten meters into the shaded region (Figure 6). One of the major factors of the current design that slows cooling is the thermal mass of the CCT spool at the tether junction. The removal of this spool brings the junction to the transition temperature after 9.1 hours and could be reduced further by increasing the heat rejection of the conventional or superconducting tether. Further modeling will also require the inclusion that dust has on the cooling time of the tether. Investigations on the impact of lunar simulants on thermal control surfaces have found that emissivity can be impacted by sub-monolayer coatings of dust - though not as greatly as absorptivity. This study also noted that surface dusting did not greatly affect the steady-state temperature of the surface[26], though the time needed to reach superconducting temperatures will increase with more dust. Additionally, future in-depth modeling of tethers in PSRs should use the transitional temperature profiles seen within these regions, ideally with a target location in mind.

8 Subsystem Testing

The tether is the most critical component to mission success. Thus, the focus of the testing described in the following sections is to ensure that the tether can perform to the mechanical and electrical requirements of the mission. Other subsystems have been tested for T-REX to enable functionality for system-level integration but were not directly relevant to the tether.[15]

8.1 Spooling Assembly

The tethers are a single point of mechanical failure for the rover but are crucial to the mission's success. While the robustness of conventional tethers has been explored, [20] relatively little on mechanical properties is known about superconducting tables. Tether testing for the spooling assembly subsystem was focused on the SCT. The goal of these tests was to understand the tether strength, abrasive wear effects, and the ability of the SCT to be used in active tension measurement.

8.1.1 Tether Abrasive Wear Testing

After several months of development in the lab and sandbox with the repeated testing of the same portions of the SCT, scratches and delamination of layers were noticed. Scratches were determined to be caused by contact against abrasive surfaces. Delamination was discovered after excessive bending and pinching the tether over obstacles such as rocks (Figure 7). Repeated heat cycles from testing in LN2 also contributed to delamination in the tether, but this failure mode would not be present on the lunar surface

Because delamination and scratches are the most likely failure modes for the SCT, passive geometry was designed into the spooling assembly to prevent bending around a tight radius.

While inside the rover, the tether is constrained to not bend around a radius smaller than 20 mm. Thus, the tether is held above its minimum bend radius of 2 mm.

Abrasion tests were conducted to explore the durability of the tether from scratches. By using the tension measurement system to reduce the tension, the wear would be significantly reduced. The high-tension rubbing scenario (Figure 7) is considerable as rocks are 5-10 times more common on the edges of craters when compared with level terrain (Figure 8). [27]

Limits on the allowable tension to avoid scratching the superconducting layer in the tether were determined through testing. This consisted of passing a section of SCT across an abrasive rock under tension fifty times. Fifty passes were found to be adequate to determine the difference in wear. SCT samples were inspected and photographed at the end of the test. Wear was analyzed at 1, 5, 15, and 35 N of tension in the SCT to simulate possible operating conditions and the potential resulting damage when operating at high tensions. As the tension increases to 14.3 N and higher, deep surface scratches become frequent and expose the silver layer of the SCT underneath the copper. Further damage to interior layers of the SCT can cause a reduction in performance or tether failure. Tensions above 5 N are unsafe if the SCT is in contact with an abrasive surface.

8.1.2 Tether Strength Testing

Early in the design process, there were concerns that the tether may be prone to damage from tension caused by a high acceleration event such as descending a large obstacle. A tensile test was conducted to assess the risk of such a failure. Results show that the superconductor has an ultimate strength of about 930 N and a yield strength of approximately 510 N (Figure 9). Because the tether is already held below 5 N to avoid failure due to abrasion, the risk of excessive tension was deemed negligible. In an emergency case, the tether can bear the rover's weight, further considered in section 10.

8.1.2 Tension Measurement System Testing

The tension in the tether is actively limited to less than 5 N during deployment using the tension measurement system to mitigate the risk of scratching and delamination discussed in the previous two sections. Closed-loop control is achieved by routing the SCT through a series of pulleys and allowing a central pulley to translate in one axis, compressing a spring with known properties (Figure 10). The displacement is then measured by a string potentiometer and compared against a setpoint corresponding to 1 N of tension in the tether.

Two tests were conducted to characterize the effectiveness of the tension measurement system during tether unspooling. Static calibration tests were initially used to characterize and calibrate the tension measurement system. These tests consisted of pulling on the tether with a force gauge while the rover was stationary and reading the corresponding value of a string potentiometer. A linear correlation between the tension and string potentiometer positions was developed after measuring values for 1, 2, and 3 N of tension. Tension was then measured with the rover moving at an operating speed of 0.5 m/s on flat terrain to verify the accuracy in a dynamic setting. Obstacles less than 10 cm in height were placed in the test area. Operators avoided these obstacles to simulate a more natural and realistic driving pattern. After the static and flat terrain driving tests, the tension measurement system was proven to remain accurate within ±0.5 N when compared with the force gauge on the free end of the tether (Figure 11).

8.2 Communications

Data passthrough tests were performed on sections of the SCT in laboratory conditions with a 1 m length. Sections of the SCT were fully submerged in LN_2 to cool the tether below the transition temperature (Figure 12).

Two 1 m long sections of single-channel SCT were spliced on both ends with a 30 cm section of CAT5 copper wire. A network bandwidth test was performed [28] displaying an average symmetrical bandwidth of 94.1 Mbits/s over a duration of 10 tests (Figure 13). The performance meets the VDSL2 transceiver manufacturers specifications. [23] The previous two tests were repeated at 20°C to observe potential failure modes in the SCT. However, the tether exhibited a similar bandwidth of 94 Mbits/s.

This behavior of the SCT has the potential to make the overall system much more efficient and lightweight. If further testing shows that the SCT is not damaged by long-duration operations at room temperatures, the hybrid CCT and SCT tether can be replaced by a single SCT. Some modifications might have to be made to the copper plating on the SCT to handle the appropriate amount of current. Insulation on exposed copper paths would also be used to minimize short-circuiting risk. The previously described tests were conducted using a small test segment of the tether. Future versions would have multiple channels, two channels carrying power (positive and return), and two channels for the differential signal used for VDSL communication. Comparatively, the tether performance should scale linearly with the length of the superconducting tether.

8.3 Electrical Power System

The SCT portion of the power transmission train was tested to show that it is capable of handling 100 W both at room and cryogenic temperatures. A 70 cm section of the SCT with a length of copper wire soldered to the copper backing on each end was connected to a power supply and five-ohm power resistor in series. For the test at cryogenic temperature, the SCT was submerged in LN2 (Figure 13). Using the current limiting feature of the power supply, the current was increased from 1 to 5 A over the course of the test. During each trial, the SCT and CCT to SCT solder joints were visually inspected to ensure there were no faults. The results from this test proved that at a small scale, the SCT can handle over 100 watts of power both at cryogenic and room temperatures, which is more than sufficient for the T-REX demonstration mission.

Currently, the CCT and slip rings are the limiting factors for increasing the overall power transmission capabilities. To test in the kilowatts range, changes would need to be made to both the CCT and slip ring size, as well as the connection between the SCT and CCT to handle the additional power transfer (Table 4).

9 System Testing

T-REX will encounter a variety of terrain during its mission. An official polar landing site for Artemis is not picked, but several potential locations have been proposed, including areas near large PSR craters like de Gerlache, Shoemaker, Haworth, and Shackleton. [30] Of these, Shackleton has been identified as a promising crater to explore due to its unique lighting characteristics, the potential for lunar volatiles, and close to a continuously illuminated region on its rim where a base station could be established for astronauts. [30]

9.1 Flat Terrain Testing

Mobility tests were conducted to confirm obstacle avoidance and steep terrain navigation requirements. The first set of tests involved driving T-REX on a consistently compacted bed of lunar simulant. The purpose of these tests was to evaluate the performance of the rover's wheels and front sled (Figure 14). The testbed was prepared by compacting the simulant until it reached a bulk density of 1.67 g/cm^3. The surface was then raked smooth to allow an even plane for conducting mobility tests. During testing, a static pressure-sinkage of 10 mm for each wheel and 23 mm for the sled was observed when resting on compact regolith simulant. During these tests, it was found that a "sled" provides excellent stability to the rover when driving. Due to its shape, the sled sits below the surface slightly when driving, causing a shallow trench to form as the rover moves. The action of cutting the trench behind the sled influences the rover to follow a linear path based on where the sled is pointing.

To evaluate the performance of T-REX under loose regolith simulant conditions, a small area of roughly 1.2m×1.5m×0.2m was manually aerated through the action of shoveling and mixing until reaching a bulk density of 1.19 g/cm^3. Static pressure sinkage of the wheels and the front sled was 44.5 mm and 28 mm respectively. The maximum dynamic pressure sinkage for the wheels was 10 cm below the surface when the rover was driven in loose simulant. The rover was able to free itself out of the sunken area under its own power due to an increase in surface area for traction as the growsers sank into the regolith. This is similar to how sand tires and paddle wheels work on vehicles designed for use in sandy environments. [31]

9.2 Sloped Terrain Testing

Shackelton crater was used as a model for what terrain the T-REX rover would expect to encounter. Shackleton's slopes are a maximum of 5° accent to crest the rim and a 45° on descent into the crater. To simulate crater slopes, an adjustable wooden ramp was used inside the lunar simulant sandbox at the PSTDL. Simulant was shoveled onto the ramp to a depth of approximately 7.5 cm and then manually compacted until it remained firmly in place on the sloped terrain. The first tests conducted were for a 45-degree slope without obstacles. In this test, T-REX was placed at the top of the ramp and then driven down at a controlled speed. The rover was able to maintain stability on the 45-degree slope, and the wheel grousers were able to provide sufficient traction to keep the rover from sliding down uncontrollably (Figure 15). This test was meant to prove that T-REX could operate in a worst-case scenario of a crater side-wall descent of 45-degrees.

After confirming that the rover could traverse a 45° slope without slipping or exceeding safe tensions in the tether, tests were conducted involving a 30° slope both with and without obstacles. 30° was chosen to simulate standard operating conditions, rather than a worst-case scenario of 45°. During these tests, T-REX was driven down the ramp as before, but obstacles were placed in the path of the rover. Results showed that the maximum obstacle height T-REX could traverse in this scenario was roughly 14 cm. At heights taller than 14 cm, a tip-over event occurred where the center of gravity moved outside the wheelbase of the rover. Although the rover was able to traverse an obstacle of up to 14 cm during these tests, a smaller obstacle height of 11 cm was determined to be a maximum safe limit. Mobility testing was performed under earth gravity conditions without the use of a gravity offload system.

Slope testing was also used to characterize the effectiveness of the tension measurement system. Drop-in analogs of both the CCT and SCT were used to simulate and observe the mechanical behavior of the unspooling system. Three orientations of rocks were used to gather tether tension data (Figure 16). The "Clear Terrain" test was used as a control. During testing, the tension measurement system maintained a tension in the tether below the 5 N limit set after the abrasion tests (Figure 17). The "Left Wheel Obstacle" test was also successful at keeping the tension below 5 N. However, increases in tension occurred after descending the obstacle on a slope. The tension measurement system exceeded the 5 N target during the "Bowl Obstacle" test. This was to be expected, given that the test was designed to define the limits of the TMS. The rover was pushed above operating conditions defined in the requirements verification table both in speed (> 0.5 m/s) and the size of the obstacle (> 10 cm) it was trying to traverse. [15]

The electrical performance of the powertrain (CCT, slip ring & SCT) was not tested in unison and will require additional testing in the future. Over the course of the test, the telemetry from the rover's internal electronics was monitored and recorded to help better understand the mobility and unspooling systems. It should be noted that the internal electronics of MKI, MK2, and MK3 were designed for temporary testing and did not necessarily reflect the final flight-ready hardware. Initial testing was completed with current measurements from the EPS system that were recorded over the duration of the first full system tests. The following two graphs show the measured current on a power line against time. Events that occurred during the test are annotated with vertical dotted lines (Figure 17).

The three most relevant data sets that reflect the performance of the rover are the left motor, right motor, and 5V rail (the 5V rail powers the spooling assembly system). Acceptable spikes and dips can be seen during accelerations of the mobility subsystem highlighted by events E1, E2, E5, and E7. Events E3 and E4 define the start and stop of the spool drop sequence, seen by a spike of 0.15 A on the 5 V rail. The 12 V rail stayed relatively constant throughout the duration of the test, as expected. This rail supplies power to the COM transceivers as well as the OBC.

While descending 0.152 meters down the 30-degree slope with a motor speed of 100 rpm, the on-board electronics consumed on average 27.34 W. Compared to the theoretical power budget, the average power when resting is about two watts higher than the predicted value from mode 2. The predicted value of 40.45 watts for mode 1 is about 13 watts higher than the measured average when moving. This increase was expected as the rover descended at a minimal rate and motor rpm, leading to a significantly lower power draw (Figure 18). It should be noted that these values are subject to change for a flight model of T-REX, as the prototype does not include heating elements and other flight-specific hardware. CLPS landers such as the Space Systems XL-1 lander developed by Masten can provide up to 100 watts to their payloads [32], which is sufficient for the current version of T-REX.

9.3 CCT and SCT Deployment Testing

A full system operation test was performed on the 30-degree slope test ramp. A thin strip of steel was used to simulate the SCT, and a 16 AWG electrical cable was used to simulate the CCT. Both simulated tethers were shortened to make testing easier to complete inside the test sandbox. During this test, both the CCT and SCT were deployed as described in concept of operations, and the CCT spool was released when the rover was roughly halfway down the ramp (Figure 19). Data from the TMS was monitored closely during descent. The results for this test showed that the CCT was able to passively unspool as the rover drove down the ramp. At the halfway point, the two separation nuts holding the CCT spool under the rover body activated, dropping the spool assembly onto the slope. From there, the rover was driven forward, and the SCT began deployment. The rover was driven to the base of the ramp and then an additional 1 m to continue deploying the SCT tether. After reaching a point of 1 m past the base of the ramp, the test was stopped. Because successful deployment of the CCT spool, power, and tension requirements were met, the test was considered successful.

10 Discussion

A technical mission risk analysis identified the design limitations encountered during development (Table 5). Each presented risk is then discussed and paired with a mitigation strategy to reduce the occurrence probability or mission impact. The proposed solutions to minimize risk will be implemented as T-REX development continues. The presented risk analysis process only addresses results from the research described in previous sections and is not comprehensive of all risks which T-REX may encounter.

Risk 1: Damage to the tether from abrasive wear between the unspooled superconductor and the environment was assessed as the most substantial risk to the T-REX mission. Tether wear was initially not a significant concern for the two-week mission T-REX was designed for as a contestant in the BIG Idea Challenge but should be considered for larger-scale architectures. Tensile and bending modes were not regarded as sources of substantial risk to the mission; tether would be actively unspooled from the rover before approaching the SCT ultimate tensile strength or the force required to reach the minimum bend radius of 2 mm. Passive geometry built into the tension measurement system also prevents the tether from bending around tight radii and restricts the tether from being caught in the wheels for in-place turns of up to 90°.

A flat protective layer would encapsulate the SCT to minimize the chance of tether damage from wear. Polymers such as Polytetrafluoroethylene (PTFE) were identified as an ideal candidate due to high tensile strength, flexibility, and low outgassing [29, 30]. PTFE, in particular, has been shown to improve the wear resistance of softer metals against lunar regolith. [35] Polished metal surfaces with PTFE coatings have excellent heat rejection qualities due to increased emissivity [25], which would increase the cooling rate of the superconducting tether as an added benefit. The PTFE tape identified for the SCT has a thickness of 0.0508 mm and a density of 2200 kg/m^3. The PTFE coating would increase the spool diameter from 312 mm to 476 mm for a 1km long SCT wrapped around a 15.875 mm wide shaft. Tether mass will increase from 8.06 kg to 10.7 kg, respectively. The proposed changes can be supported by the current T-REX chassis and will reduce the chance of disruption to the mission.

The high tensile strength of the SCT can be leveraged to improve the T-REX mission flexibility. A load-bearing tether enables the transfer of power and data to locations that require descent into steep, vertical terrain.[31] An application would be the exploration of lunar lava tubes for science and habitation missions.[36] [37] To increase mobility, the spooling motor and TMS would be redesigned for higher loads. Cladding would be added to the SCT to prevent increased scratching.

Risk 2: To minimize the SCT cooling time, the optimal tether deployment location for T-REX is where the temperature gradient from the illuminated to the shadowed region is steepest. While preliminary thermal modeling validated passive tether cooling in theory, it represents a best-case scenario. Most polar craters will have a gradual transition zone to the PSR, which varies seasonally due to the axial tilt of the Moon. [17] Besides environmental effects, components such as the deployed CCT spool have been found to act as a thermal capacitor, increasing the overall cooling time. Increasing the radiative ability of the spooling system and tether could mitigate the extended cooling time risk. An immediate solution would be to increase the radiative surface area of the CCT spool. Removing the CCT spool would reduce the SCT cooling time by up to 9.6 hours but add complexity to the unspooling system from additional deployment mechanisms. Near-term missions expected to last a single lunar day would consider extended cooling times greater risk than later long-duration counterparts.

Risk 3: Difficulty in terrain navigation was assessed as the third major risk to the mission. The ability of T-REX to avoid or move through obstacles affects the probability of occurrence for the previously identified risks. To mitigate this risk, T-REX was designed and tested in terrain environments representative of lunar PSRs. Results from the testing discussed in section 9 demonstrated that the rover can meet or exceed minimum requirements for successful terrain traversal. An ability to go down a steeper slope will result in a greater temperature gradient and thus better cooling of the tether. Improved avoidance and traversal of rock obstacles results allows for better tether placement to minimize abrasive wear. While difficulty in terrain navigation can hinder the T-REX mission, the probability of occurrence is minimal due to the proven design of the rover.

The current limiting factor for maneuverability of the rover is the angle at which the chassis can turn without either growser contacting a tensioned tether; approximately 90 deg left or right. Maneuverability for terrain navigation could be improved by creating a new spooling assembly which can deploy tether from any direction. Similar systems use a rigid free-rotating arm which could unspool tether past the rover wheels.[38] Implementing these changes would allow T-REX to deploy tether at any angle without any risk of contact with the rover.

11 Conclusion

The T-REX rover form factor, mass, and power consumption requirements are within the range of capabilities of current CLPS landers. [32] Preliminary thermal analyses determined that the current tether configuration can radiate enough heat to reach superconducting Temperature. Full system sandbox testing confirmed that T-REX could deploy tethers at controlled tensions while navigating obstacles on downward-sloped terrain. The functionality of VDSL-2 data and DC power passthrough over a superconductor was demonstrated via testing in LN2. The T-REX technology has been raised to TRL-5 during this testing regime, and development is ongoing.

Additional testing at vacuum and higher voltages is required to explore the SCT limits fully. Thermal vacuum tests of the SCT will eliminate unrealistic heat transfer via LN2 or air convection. Increasing the scope of these tests to include kilowatt testing for long durations will validate thermal models on the T-REX system. These tests are planned to be conducted on beds of lunar regolith simulant in a thermal vacuum chamber to demonstrate the capability of the payload realistically. [39] The successful completion of these environmental tests would raise the T-REX payload to TRL-6.

T-REX is designed to fulfill a role for supporting near-term pathfinding missions in the 100s of watts range. However, large-scale ISRU operations on the Moon will require equally large amounts of power. A more extensive overall system is needed to support kilowatt-range power distribution. [40,41] For high-power missions entirely in shaded regions, superconductors scale easily while conventional conductors do not. Long-distance kilowatt DC power transfer requires high voltage to minimize ohmic losses in the tether. Increasing the voltage will reduce the required cross-sectional area and, ultimately, the landed mass. This, in turn, requires the development of high-efficiency and high-power space-grade converters. However, even high-efficiency converters will produce hundreds of watts of heat at multiple kilowatt power levels. Future research into the utilization of high-power tethered rovers should maintain a balanced approach between power transfer and thermal management. Overcoming these hurdles will provide the backbone for producing a wired Lunar power grid to support a future space economy.

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