SLOPE: South Lunar Observational Prospecting Expedition

"Come, my friends, 'tis not too late to seek a newer world." - *Ulysses*, Alfred, Lord Tennyson

Theme: Large Scale Lunar Crater Prospector
Category: Undergraduate
University: Columbia University

Team Contacts

Casandra Martinez**
(cm4149@columbia.edu)
Mechanical Engineering '25

Nidhi Shah**
(ns3684@columbia.edu)
Mechanical Engineering '26

Christian Yupanqui**
(cy2635@columbia.edu)
Mechanical Engineering '25

Student Members

Serdar Kaltalioglu, Mechanical Engineering '26
Teresa Alves Sabin, Astrophysics '26
Stella Densley, Astrophysics '27
Joel Montano, Mechanical Engineering '27
Michelle Mai, Mechanical Engineering '27
Maxwell Gaynor, Physics '27
Joeramon Tijerina, Mechanical Engineering '27
Anya Ganeshan, Computer Science '27
Catherine Su, Applied Physics '27
Case Schemmer, Computer Science '27
Srihari Balaji, Mechanical Engineering '24*
Claudio Solano, Mechanical Engineering '25

*Graduate
**Team Lead

Faculty Advisor
Dr. Michael J. Massimino, Department of Mechanical Engineering

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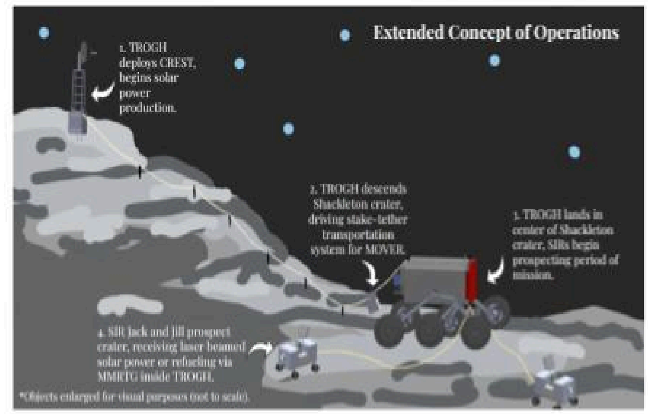
Columbia University
SLOPE: South Lunar Observational Prospecting Expedition

Theme: Large Scale Lunar Crater Prospector

Objectives & Technical Approach:

- Large-scale lunar rover system to prospect the distribution and physical state of lunar polar water and volatiles throughout a 1+ year span
- A power generation system (CREST) connects to a central prospector hub (TROGH) via a zipline system for sample transportation
- Two prospecting samplers (SIRs) tethered to the TROGH and equipped with TRIDENT drill & associated sensors
- Power provided by a two RTGs hosted within TROGH and laser beaming from CREST to SIRs to allow for longer prospecting



Key Design Details & Innovations:

- TROGH and SIR system will be transported into the crater using a tether-stake system, allowing for extraction of system from crater for future missions.
- Model includes altered TRIDENT drill equipped with neutron spectrometer and penetrating radar for hazardous drilling prevention
- Samples of interest will be transported to the main base via tether system and MOVER
- Possibility for astronaut interaction with the CREST system including further sample analysis and system control
- AI models are enforced for efficient prospecting and detailed mapping and navigation of terrain

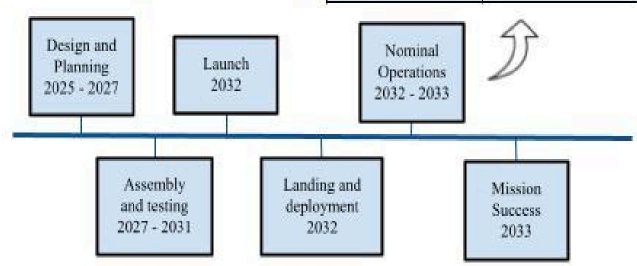
Schedule

Budget Overview

Launch Mass	4.02 T
Power Consumption	3.04 kW
Cost	$1,459,600,504

Operations Time Breakdown

Setup	10 Days
Prospecting Sites	168 Days
Hibernation	30 Days
Transportation	105 Days



I. Introduction

If other worlds than our own are ever to be inhabited, the most critical place to start is our closest neighbor: the Moon. With the recent emergence of the Artemis era, it is more important than ever to study the conditions on the Moon and how its natural resources can be utilized for societal advancement and future space exploration. While the lunar South Pole remains largely a mystery due to its extreme weather conditions, there is a significant probability that subsurface water ice or other volatiles are prevalent there. Investigating these volatile-rich sites can provide essential insights into the Moon's geological history and composition, and more broadly, the history and chemistry of the inner solar system. Data on the extreme temperature variations and illumination conditions can help in planning future human and robotic missions. Understanding the lunar environment, including its radiation levels, temperature variations, and micrometeoroid flux, is crucial for planning future missions and potential human habitation.

The presence of water-ice volatiles was confirmed by NASA's Moon Mineralogy Mapper (M3) on the Indian Space Research Organization's Chandrayaan-1 spacecraft, revealing multiple locations of water-ice volatiles in the permanently shadowed regions of the Moon. Mission South Lunar Observational Prospecting Expedition (Mission SLOPE) intends to conduct large-scale prospecting within Shackleton Crater, a 4.4 km deep and 21 km wide crater located inside the South-Pole Aitken (SPA) basin (Age: 3.9-4.3Ga). Modeling the evolution of the Moon's spin axis (currently approx. 1.5°) and the South Pole location indicates that the floor has been in permanent shadow for ~2 Ga, during which it is hypothesized that the Shackleton Crater was accumulating volatiles. Because of its large size and extreme conditions, Shackleton is an appropriate reference crater to ensure that SLOPE will operate successfully within a wide range of multiple south lunar craters. The SLOPE mission is led by Columbia University in collaboration with the Indian Institute of Space Science and Technology (IIST).

I. Mission Overview and CAD

Mission SLOPE is projected for a 2032 launch aboard SpaceX's largest rocket currently in development–the SpaceX Starship–which is the primary spacecraft of the Artemis Era. The total weight of the undeployed system is approximately 4016 kg, a mere fraction of Starship's 150 metric tons of payload capacity. SLOPE will softly land near the rim of Shackleton Crater, after which it will navigate to a predetermined peak along the crater rim. The mission architecture consists of four main systems: the Crater Rim Energy System Transporter (CREST), the Tethered Radial vOlatiles Garage Hub (TROGH), the MObile Volatile ExporteR (MOVER), and two prospecting Sampling Ice Rovers (SIRs) named SIR-Jack and SIR-Jill. During launch, the CREST, MOVER, and both SIRs will be stored safely within the TROGH, awaiting deployment via connecting tethers.

Fig 1. CAD model of CREST

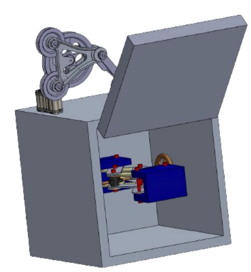


Fig 2. CAD model of MOVER.

In order to plant the CREST and descend the SIRs, the TROGH acts as the primary transport system. After landing, the TROGH will position the CREST on the Shackleton rim utilizing a forklift mechanism and stabilizers for secure detachment. CREST will then drill itself securely into the lunar regolith using its four aluminum Kevlar anchors, perform communications testing, and begin solar power production. At this point, AI troubleshooting will ensure a smooth transition into nominal operations. Once the power base has been secured and deemed fully functional, the TROGH system will begin to unravel the tether connecting to the CREST and its fully autonomous descent into the crater. Navigation systems will initially follow a mapped path of minimum slopes, utilizing its sensors along the way to detect soil composition and navigation challenges to inform its AI algorithm.

Mobility technology is essential for descent into the crater, long-term operation, and sample collection. Rovers would face challenges traversing steep slopes with limitations in power, so the TROGH transports SIRs and sets tether infrastructure over terrain that would not be suitable for rovers. As the TROGH descends, it will utilize its housed drilling mechanism to periodically drive stakes into the ground, which are continuously connected via a tether. The stakes provide sufficient height for the tether above ground as well as support its weight. The tether is pulled by a winch on TROGH, allowing it to rappel the rocky descent and increase stabilization. In addition, the rocker-bogie suspension system maintains stability and consistent wheel traction force, protecting internal components from excessive vibration.

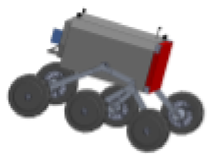


Fig 3. CAD model of TROGH vehicle.

Once fully unraveled, utilizing Shackleton's dimensions, the tether is expected to sit at a hypotenuse of about 11 km, and requires an estimated 230 stakes to support the tether over this distance. The entire setup process will take about 10 days.

At this point, SIR-Jack and SIR-Jill can deploy from the TROGH while attached to their respective 11 km tether, allowing SIRs the mobility to prospect the entire surface of the crater. The twin SIRs are fully autonomous, utilizing initial mapped paths and AI software to guide their exact trajectory and movements.

Fig 4. SIR, equipped with modified TRIDENT drill.

The SIRs will work together to prospect 20 target sites each (about 10 km^2 in area) on opposite sides of the crater. Equipped with volatile-detecting sensors, they will efficiently scan the lunar surface of water and ice. When valuable volatiles are detected, the operating SIR will drill one meter deep into the regolith, using its specialized sensors to read volatile presence. Samples of interest will be stored in the hull of the SIR.

Once a site has been fully prospected and sampled, the SIRs will transport relevant samples to the TROGH, where they will be brought out of Shackleton by the MOVER transportation module, which is attached to the tether between the CREST and TROGH. The MOVER and SIRs are internally equipped with a motorized pusher mechanism to translate samples from SIR to MOVER to CREST. At the CREST, samples will be stored in a secure thermally protected storage drawer until pickup by astronaut crews to run further experiments or to transport back to Earth.

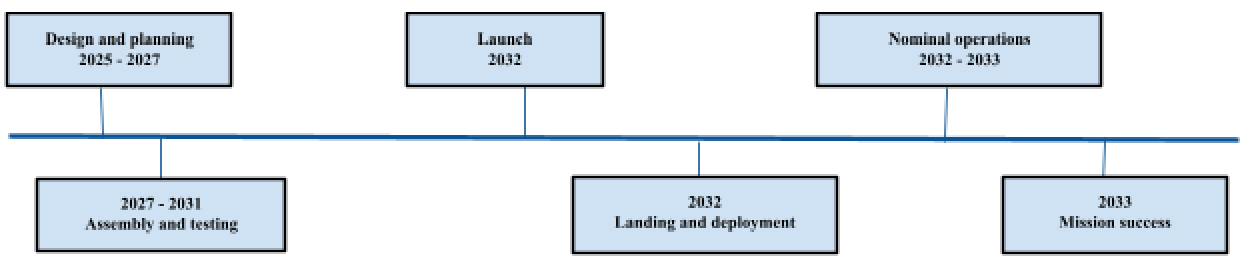


Fig 5. Timeline

II. Subsystems and Budgets

Design Assumptions

The following assumptions were made in the design of subsystems. The lander will be strategically guided by SpaceX's highly precise Starship within 0.5 km of the Shackleton Crater rim. As detected by NASA's Lunar Renaissance Orbiter Camera, several points along Shackleton's rim will experience continuous sun exposure for over 90% of the year. CREST solar panels will generate at least 500 W per square meter of panel in continuous sunlight exposure. Astronauts will provide limited support on the lunar surface for CREST and TROGH communication. Before the locations of the stakes are determined, the TROGH will determine if the surrounding 1 km area around the stake is drillable, to ensure that the next stake is able to be anchored.

Power

Within the complete darkness of the crater floor, it is crucial to have an efficient and reliable power supply. In order to ensure reliability throughout the length of the mission, we will use a combination of solar power, radioisotope thermoelectric generators (RTGs), and lithium-ion batteries.

RTGs will be the primary power source within the crater as the technology does not rely on sunlight or heat to generate electricity; instead, they utilize radioactive decay and thermoelectric couplers to turn heat into electrical energy. RTGs are commonly used in spacecraft and rovers, such as the Mars Perseverance, and can meet our needs to generate electricity within the crater between a period of a few months to over a year. Two multi-mission RTGs will be housed in the TROGH to meet power needs inside the crater.

Solar power will be implemented at the CREST, actively harnessing the continual sunlight of regions of Shacketon's rim. The PV cells in the panels would have no atmospheric disruption and therefore generate more power than the 500W per panel amount on Earth. Solar energy will be used as a secondary power source and a way to passively collect and store consistent solar energy. Solar panels will be mounted on three sides of the CREST, as one side will be reserved for the tether and sample deposits. To accommodate for the Sun's low angles to the horizon, solar panels will be oriented toward the horizon and hinge at changing angles to maximize solar energy collection.

	Power Consumption (kW)	Power Generation (kW)	Mass (kg)
CREST	0.81	2.5	477.6
Power	-	2.5	421.96
Thermal	0.15	-	20
Communication	0.23	-	5
Structure	-	-	25
Sensor	0.43	-	10.64
MOVER	0.07	0	129.8
Locomotion	0.07	-	102.3
Power	-	-	8.5
Structure	-	-	18.5
TROGH	2.35	0.24	1782
Locomotion	0.14	-	32
Power	-	0.24	93
Thermal	0.8	-	27
Communication	0.16	-	5
Structure	-	-	1600
Sensor	1.25	-	25.3
SIR	2.55	0	957.2
Locomotion	0.2	-	426
Power	-	-	17
Thermal	0.5	-	22
Structure	-	-	400
Sensor	1.84	-	52.2
Payload	0.017	-	40
TOTAL (20% margin)	5.78	2.74	4015.9

Table 1. Mass and power budgets

Because both MMRTG and solar panel energy production are continuous, our system will be consistently generating more energy than is needed by the daily operations of our mission. Lithium-ion batteries housed in the CREST, TROGH, MOVER, and both SIRs will serve as energy storage. This energy surplus is necessary to meet peak energy demands as well as function as a backup in case of unexpected disruptions.

Our power budget stays positive throughout the lifetime of the mission, as it cycles through transportation, experiment, and charging modes, as well as safe mode in the case of anomalies. Both safe and charging modes are power-positive. The ability to flexibly enter charging mode throughout the SIRs operations as a result of the power-beaming technology keeps power above 25% at all times. This accounts for power generation losses over time as well as losses due to transportation over the tether and power-beaming technology.

The MOVER and SIRs will not have any power generation capabilities of their own but can be charged by the CREST and TROGH respectively. The SIRs can be charged by the CREST through power beaming. Since the SIRs are required to travel far for longer periods during transportation mode, they must always have enough power to operate. In order to send power to the SIRs at any given time, we will implement power beaming.

Power from solar panels on the CREST will be transmitted down into the crater through a high-efficiency laser. This laser will transmit near-infrared light for maximal efficiency over longer distances. The TROGH and SIRs will all be equipped with laser PV converters to convert the power from the lasers back into electricity to power their operations and batteries. These converters are made up of many small x-band antennas, each connected to a rectifier diode, that will convert the laser to DC power. This will allow the SIRs to recharge without returning to the TROGH, extending their operating time. This system will also provide supplemental and emergency power to the TROGH to run its operations. The CREST's laser beaming system can transmit more than 10 kW, allowing it to both charge batteries and actively power the operations of individual SIRs or the TROGH.

Power beaming is still under development and, in its current form, would not meet the needs of this mission. However, this technology is receiving attention and investment from multiple avenues. In 2023, the US Naval Research Laboratory's power-beaming experiment surpassed 100 days of operations. In addition, the Naval Research Laboratory's SCOPE-M project has successfully sent 1.6kW over a distance of 1km on Earth, through a microwave power beam. A satellite built by Caltech has also beamed power to targets in space, and has even beamed down a small amount to Earth, thus proving that energy can be sent over far longer distances than would be necessary for SLOPE. With the resources being invested in this technology from NASA and the Pentagon, and the more favorable conditions on the Moon, we are confident that this technology will be viable within the timeline of this mission.

Navigation

A compact laser range scanner in conjunction with HazCams and NavCams, modified designs of those onboard NASA's Mars Science Laboratory, will be utilized for terrain mapping and navigation. On each SIR, a mounted laser range scanner scans the environment and generates a map, supporting obstacle detection, localization functions, and terrain assessment. Two NavCams on each SIR scan and collect data on the geology of the surrounding terrain while providing geological context for samples. They will also collect images to further aid navigation, improve terrain mobility to allow the wheels to adapt accordingly, and gather information to properly point sensors and other onboard tools. We will have four HazCams on each SIR– two in the front and two in the back. The HazCams support the functions of the NavCam while focusing on collecting information about the surrounding terrain to alert the SIRs of potential hazards and allow for smooth movement over the crater surface.

Safe	Charging	Transportation	Experiment
Total duration: 30 days Systems on: • Power production • Communication • Thermal	Total duration: 5 days Systems on: • Power production • Thermal	Total duration: 105 days Systems on: • Navigation • Power production • Locomotion • Thermal • Communication	Total duration: 168 days Systems on: • Power production • Thermal • Prospecting • Communication

Table 2. CONOPS Modes

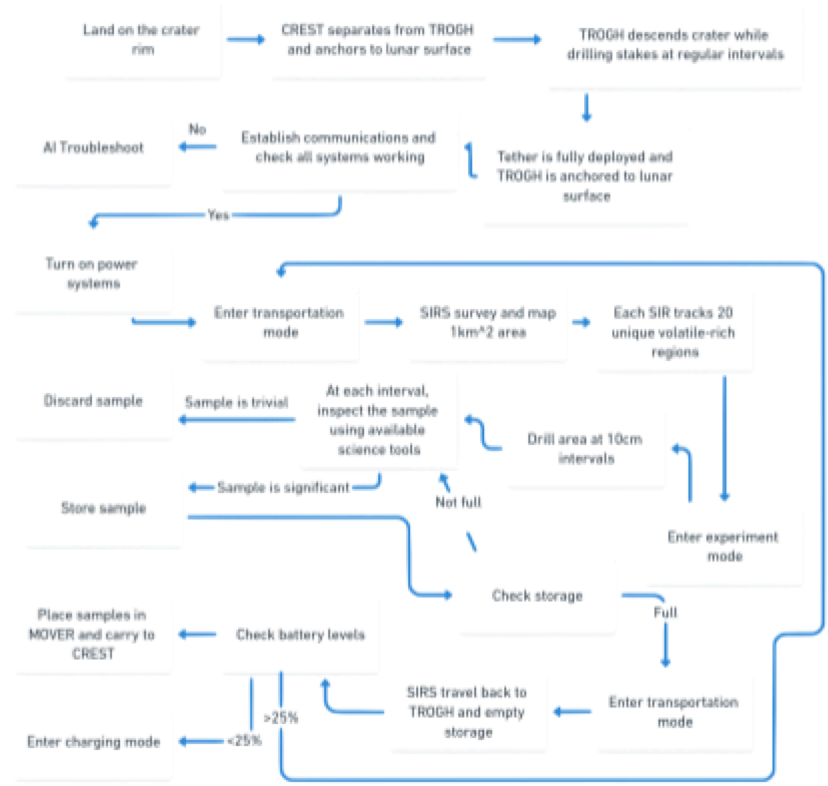


Fig 6. CONOPS

The laser scans at a range of up to 120 m, with fast scanning at 2 Hz and a high resolution of 2-5 cm. Both cameras are able to image over a range of about 5 m and can orient to be able to image the entire surroundings of the SIR. The two cameras use a CCD detector for imaging; however, the darkness within the crater means this will be ineffective on the SIRs. As a solution, the cameras will have an integrated photoelectric sensor specialized to detect lunar regolith.

The data collected by the cameras and scanner will be fed into the SLOPE AI model and will be crucial in effective path planning, drilling site and regolith mapping, and dynamic collision avoidance.

As the Shackleton crater is largely unexplored, an AI detection system will be the critical analyzer to accurately predict the best drilling sites. Under the VIPER mission, NASA has already begun the use of AI to improve missions on the lunar surface, using the SHERPA (System Health Enabled Real-time Planning Advisor) AI software to help mission controllers make informed decisions. As SHERPA will gain data from the VIPER mission about the general soil composition and environment of the lunar South Pole, our system can build upon the anticipated data to create optimal paths. Our AI model will take in sampling data to better understand the lunar terrain and patterns in the presence of certain elements and the uniqueness or volatile composition of a certain sample.

Specifically, as the two SIRs prospect the crater surface, they will form a map based on collected data, which the AI will use to make a predictive map of the crater surface and inform consequent drilling sites. Areas previously determined to be rich in volatiles or containing unique compositions will be prioritized over those with redundant or unimportant samples, mitigating inefficient sampling, and thus shortening the mission timeline in a single crater.

Locomotion & Articulation

When descending the crater, the TROGH will be able to utilize previous data on the crater to efficiently travel through the flattest portions of the crater side. Cameras on all sides will inform the TROGH of any dangerous terrain. Similarly, the SIRs will be able to efficiently navigate the crater surface through the use of onboard sensors. Artificial intelligence will aid the systems by using collected data to inform efficient paths and avoid steep hills.

In order to support a 1-meter-deep drilling core and withstand steep descents, the SIRs are stabilized with four wheels and a dynamic chassis meant to stabilize drilling operations and maneuver steep slopes of unconsolidated soil. Additional features include a compact body for improved thermal regulation, laser scanners for navigation in the crater darkness, and a power system designed for a persistent, low-capacity source.

For locomotion, the SIRs roll on wheels and lift each wheel (like walking) to get across loose sand. The wheels will specifically be able to perform 360° rotation so the SIRs can face one direction while moving in another. A key feature of the locomotion of the SIRs will be specific speed designations for targeted purposes. When traversing the lunar surface, the SIRs will travel 0.85 kph, while slowing to 0.4 kph when navigating prospecting terrain.

SIR-Jack and SIR-Jill will each prospect and sample 20 volatile-rich sites within transportation mode. When SIR-Jack and SIR-Jill are first deployed to a site, they will begin prospecting, looking for areas that seem to have high concentrations of water and other volatiles. They will take note of these areas and continue prospecting for roughly eight days. The SIRs will then return to the most promising locations and enter experiment mode to collect samples, taking about six days to collect samples before returning to the TROGH.

Prospecting & Drilling Methods

The volatile collection and scanning technologies on the SIRs will reflect those being implemented within NASA's VIPER mission. The drilling system utilized on board the SIRs will be a modified version of NASA's TRIDENT drill. TRIDENT is a rotary percussive drill that executes a rotating and hammering motion to drill out approximately 1 m worth of lunar regolith in 10 cm pecks to promote stability and preserve power. The samples are then transported through flutes within the drill to the SIR's surface where they are analyzed for value and collected accordingly. Samples not considered unique or valuable are simply pushed from the SIR onto the lunar surface. TRIDENT also consists of a stand-alone temperature sensor for regulatory measurements. Information collected by these sensors as well as those from regolith composition and hardness sensors on board the drill will inform the drilling rate and force.

The Neutron Spectrometer System (NSS) will routinely scan the 10-cm deposits of regolith. The NSS is specifically a two-channel neutron spectrometer that assesses hydrogen, and bulk composition, allowing it to identify areas with a high potential for buried water and ice. This system will also run when not drilling to collect information about the regolith on the SIRs' paths.

In addition, the prospecting system will be equipped with a Near-Infrared Volatiles Spectrometer System (NIRVSS). The key measurements of NIRVSS will consist of detecting H_2O, OH, CO_2, mineralogy, surface morphology, and temperatures. It also has the capability to determine whether any detected hydrogen came from a water source, shedding light on the origin of any water discovered. This system will be installed on the bottom of the SIRs and will operate continuously. This will allow the SIRs to identify the most promising drilling sites prior to disturbing the regolith.

Finally, a mass spectrometer, specifically the Mass Spectrometer Observing Lunar Operations (MSolo), will scan all drilled samples. MSolo primarily targets and measures isotopes, including water. Data collected in conjunction with TRIDENT informs an important relation between water concentration and depth. This system can complete a rapid scan in less than 100 ms and will operate continuously on the bottom of the SIRs while operating. When drilling, it detects volatiles sublimating from the cuttings as the samples come to the surface.

Altogether, the different spectroscopy systems can be combined to create a model of the lunar regolith encountered by the SIRs. This information can be used by the SLOPE AI system to identify areas with the highest potential for water and focus the SIRs' drilling efforts in those locations. This information can also further scientists' understanding of the composition of lunar regolith by effectively identifying areas of potential scientific data. Increased success in encountering volatiles at key locations allows the SIRs to collect and store more valuable samples to transport back to the CREST.

Furthermore, by monitoring torque and speed, AI neural networks optimize drilling techniques. TRIDENT is already equipped with the ability to change drilling speeds according to the surface properties; however, it is restricted to two levels of speed. Our AI model will increase this efficiency and allow for more targeted sample collection. If, based on the quality of collected samples, it is determined that a particular drilling site is not valuable, the drill may not drill to the entire 1 m depth. Understanding this relationship between the quality of samples and drilling depth, an AI model can eventually make such a decision with confidence. This function would cut down time spent in experiment mode and allow for more valuable prospecting.

Currently, a multitude of factors make prospecting the lunar surface particularly difficult such as debris along the surface and the climate and microgravity environment of the Moon. Employing origami bellows will assist with the protection of the more fragile parts of the drill against debris and will additionally permit increased compressibility. As opposed to typical metal bellows, the structure of the origami bellows improves stowability and decreases the weight of the apparatus. The BYU Compliant Mechanisms Research Group reports a maximum compressibility ratio for metal was 1:8, whereas it was as high as 1:30 for the origami pattern. A higher compressibility ratio permits a reduction in the length of the drill shaft, which corresponds to a decreased total weight. This increased ratio additionally licenses deeper penetration into the surface, allowing the collection of more unique samples. Moreover, utilizing a collapsible structure instead of the traditional metal bellows permits rotation around the axis of compression, increasing the mobility of the drill.

Tether

Given that the large-length samples must be transported, it is optimal for certain systems to be physically connected through tethers. The first component of the tether system will connect the CREST to the TROGH. This tether will be able to support the MOVER as it carries samples out of the crater and any supplies back into the crater. The MOVER will autonomously scale up and down the tether using an onboard motor. The cable itself will be made from polyester braided rope to minimize weight. It maintains its strength in the extreme temperature cycle of the Moon's South Pole while handling the weight of the MOVER and the payload. Specifically, the braided rope maintains its ductility at low temperatures better than other materials such as steel.

This system requires support towers, as the cable would not be able to span all the way to the top of the crater without breaking. These supporting stakes will be between 500 m and 1 km apart, and will be installed by the TROGH as it descends the crater. The TROGH will take the path down the crater with the least difficult terrain, avoiding uneven ground and cliffs. AI navigation software will detect areas of steep elevation change and existing data of the lunar surface to structure this optimal path. At designated intervals, the TROGH will stop to install supporting stakes via its housed driving motor. Using a magazine loaded onto a driving mechanism, 230 stakes will be placed for 11 km of cable as it goes.

Mission Component	Key Technology	TRL
Power	Laser beaming power over a 10 km from CREST to charge SIRs during charging mode, allowing for longer prospecting time.	6
Data collection	AI models allow the SIRs to locate the most valuable drilling sites and samples; The system will also operate largely autonomously using AI troubleshooting models.	6
Sensors	The cameras on board the TROGH and SIRs will have an integrated photoelectric sensor specialized to detect lunar regolith. Sensors including MSolo and NIRVSS will scan samples during drilling to evaluate importance. These technologies are being developed by NASA	8
Tether system	10-11 km long tether systems allow SLOPE to span large distances while remaining connected and allowing the TROGH to deploy smoothly and ascend the crater to prospect additional sites. Tether systems also allow for more efficient risk management and allow for sample transportation to the crater rim via the MOVER.	6

Table 3. Technology Readiness Levels

The second component of the tether system connects the SIRs back to the TROGH. The main function of these tethers is to pull the SIRs back to the TROGH in the event of a critical malfunction or loss of power, where they can recharge or be repaired. These SEDS tethers are comprised of eight braided Spectra 1000 fibers, which are high-strength polyethylene fibers weighing 0.30 g/m (1.06 Ib/mi). Although the tether has a high strength-to-weight ratio, the material has a very low melting point of 147 °C (297 °F).

Communication

In an effort to take full advantage of existing NASA commercial technologies on the Moon by 2033, the primary communications system utilized will be Lockheed Martin's Parsec, a communications and navigation network composed of small lunar satellites. This will serve to communicate with the CREST and TROGH and relay information back to Earth. Communication signals are expected to take 6-10 seconds to reach Earth, making communication quick and operations seamless. Due to the proximity of these orbiting satellites, our CREST and TROGH will require Ultra High Frequency transceivers. These transceivers will also facilitate communication between the CREST and TROGH in the case of an anomaly. Signals may be manually sent from the CREST to the TROGH by astronauts on the lunar surface.

SIR-Jack and SIR-Jill are equipped and programmed to be fully autonomous, from path selection to risk avoidance. Information about collected samples, prospecting sites, and sensor data analysis will be manually uploaded by SIRs via the loading dock upon their return to TROGH. In the event of a malfunction with a SIR, the TROGH will use the attachment tether to reel the SIR back for troubleshooting and possible repair.

Budget

SLOPE will cost a total of 1.46 billion dollars over fiscal years 2024-2034, 1.87 billion dollars when accounting for 2.5% inflation per year. This amount was derived from the anticipated material and manufacturing costs of SLOPE's subsystems, and extrapolated to include research and development, assembly and integration, safety and

	Cost
CREST	$220,668,122
MOVER	$466,410
TROGH	$673,437,321
SIR	$321,761,900
TOTAL (20% margin)	$1.46 Billion

Table 4. Cost Budget

testing, operations, and unanticipated costs based on historical NASA exploration-class missions. Costs are expected to be spread between budget sectors based on anticipated timeframes of development: for example, research and development costs are the highest at the beginning of SLOPE's lifetime, and taper off once in final production. SLOPE's funding plan is reasonable as it takes into account the anticipated decommissioning of the ISS and increased funding for the Artemis missions, as SLOPE's funding increases steadily until 2034.

III. Long-Term Endurance and Risk Mitigation

To ensure that the SLOPE mission is able to operate for over a year, several key fail-safes and design considerations have been made.

Meteor Showers

During meteor showers, the surface of the moon is pelted with small meteors that pose a risk to the SLOPE mission. Made out of 7075 aluminum alloy (tensile strength of 470-525 MPa), the walls of the TROGH are able to protect against regular ping-pong-sized meteorites and larger, less frequent collisions. In the event of a meteor shower, the SIRs return to their home base at the center of the crater where the TROGH will close, enter safe mode, and withstand impacts.

Via the SLOPE AI software, predictive models can foresee possible meteor showers effectively. This software would utilize NASA's extensive past data on lunar meteors along with SIRs' collected data on meteorites and the craters in the basin of Shackleton. This AI routing software can specifically plot the SIRs' trajectory to ensure they have enough time to return to the TROGH.

Radiation

The area outside Shackleton has many areas of high solar radiation, which could pose a problem for the CREST. While the interior is naturally protected from high levels of solar radiation, the exterior is more difficult. Radiation hot spots have been mapped and a landing site will be chosen to minimize exposure to radiation. In addition, natural rock can be used to insulate structures to protect both hardware and samples from radiation. The SLOPE system can be utilized to drill and transport lunar regolith up to the CREST, where astronaut crews can then add a shell of lunar regolith to the CREST to prevent it from getting highly radioactive. This measure is key as astronauts will regularly be in contact with the CREST to collect transported samples.

System ID	Risk	Causal Factors		Post Mitigation Risk	Pre Mitigation Risk	Risk Reduction	
		Likely Causes	Knowledge Gaps			Preemptive Mitigation	Corrective Actions
CREST	Electrical System Failure	Prolonged radiation exposure	Lunar radiation environment	1,2	2,4	Redundant shield wiring for all internal systems	Implement backup power sources; Repair or replace malfunctioning components
SIR	Unprotected equipment during meteor shower	Collision with meteorites and larger objects	Modeling accuracy of meteorites and reliability of AI routing systems	3,2	3,4	Predictive models for meteor showers, AI routing for SIRs	Structural reinforcement of equipment
TROGH	Stake and Cable Failure	Terrain irregularities, extreme environmental conditions	Uncertainty in lunar surface properties and obstacles, complexity of infrastructure establishment	4,3	2,5	Development of redundancy systems for stake and cable failure, thorough design and testing before flight readiness	Stable factor of safety(1.5 >) for wedge failure, including testing of driver mechanism on simulated conditions

Figure 7. Risk Register

Critical Malfunctions and Power Losses

For power generation, the combination of solar energy transmitted through the laser and the RTGs allows for operations to continue if one system fails. While the primary purpose of the RTGs is to warm the TROGH, it also has limited power generation that can power one SIR enough to complete limited tasks.

The tethers connecting the SIRs to the TROGH act as a failsafe as well. In the event of a sudden power loss to a critical mission component, the power-beaming laser will work to recharge the system. If that fails, or in the case of another critical malfunction, the tethers can pull the SIRs back to the TROGH to undergo diagnostics and repairs. This mission also calls for two identical, independent SIRs which ensures that even if one falls into disrepair, the other can still continue to carry out its objectives.

The CREST and MOVER are both easily accessible to astronaut crews expected to be on the Moon by 2033, and are thus able to be troubleshooted and repaired manually. Additionally, the MOVER can be utilized to transport essential materials if needed, such as extra sample tubes, or automated repair modules. In the case of extreme environmental hazards or malfunctions, the TROGH has the capability of holding the SIRs and driving back up to the CREST. The entire system may then relocate as needed. This functionality is also implemented for the prospecting of multiple craters.

IV. International Outreach

In accordance with the efforts made by the Artemis Accords encouraging international collaboration and policies on space exploration, the SLOPE mission has been aided in a design and informational capacity by the Indian Institute of Space and Technology (IIST). Specifically, the team primarily contributed to the overall design of the MOVER and tether system. Collaboration with IIST consisted of consultation on materials and overall design intent, along with projected budgetary restrictions. This, in turn, allowed the SLOPE mission to make numerous improvements to the cost-effectiveness, simplicity, and feasibility of the MOVER.

Collaboration is an integral part of any mission; one perspective alone does not create innovative designs or result in novel approaches. Through communication and inspiration from one another, the mission has gained a level of preparation and complexity that would have otherwise gone undone.

V. Conclusion

In order to ensure a successful SLOPE mission, significant testing and data collection, particularly from ongoing and future lunar endeavors, must be completed. The limited access to energy within the crater as well as innovative power systems requires extensive research into the power budget over the mission timeline. While we have developed a working power budget, there are various considerations left to be made regarding power losses over time and their effects on the duration and efficiency of prospecting. The mass budget is similarly crucial as much of our mission architecture relies on the ability of tethers to pull the weight of a system or the efficiency of locomotion systems to traverse steep slopes. We also plan to clearly outline mission success criteria in terms of defined quantities of successful samples and area prospected. While the mission timeline is set to around one year, our power budget and system capability to travel to other craters predict a much longer timeline. Further developing our budgets and mechanical systems to sustain a longer timeline, as well as developing AI systems to adapt to different crater environments, will ensure the long-term success of mission SLOPE.

Appendix

Appendix A: References

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Appendix C: Budgets

	Quantity of items	Cost
CREST	**34**	**$220,668,122**
Power	11	$3,875,000
Thermal	1	$200,000
Communication	5	$406,000
Structure	3	$186,862.
Sensor	14	$216,000,260
MOVER	**7**	**$466,410**
Locomotion	5	$12,810
Power	1	$350,000
Structure	1	$103,600
TROGH	**284**	**$673,437,321**
Locomotion	9	$17,200
Power	5	$219,050,000
Structure	238	$629,321
Sensor	32	$453,740,800
SIR	**30**	**$321,761,900**
Locomotion	4	$106,000
Power	2	$700,000
Structure	2	$4000
Sensor	20	4226,951,900
Science	2	$94,000,000
TOTAL (with 20% margin)	**355**	**$1,459,600,504**

System	Component	Quantity	Power Unit Power (kW)	Total Power (kW)	Mass Unit Mass (kg)	Total Mass (kg)
		CREST		**-1.69**		**477.6**
Power	Solar Panel	5	-0.5	-2.5	336.96	336.96
Power	Battery	10	-1.5	-	8.5	85
Thermal	Radiator	1	0.15	0.15	0	20
Communication	OBC	2	0.01	0.02	1	2
Communication	Antenna	3	0.07	0.21	1	3
Structure	Sample storage	1	0	0	10	10
Structure	Sample discard	1	0	0	10	10
Structure	Casing (Aluminum, Kevlar)		0	0	1658	
Sensor	Hazard Camera	8	0.0022	0.0176	0.245	1.96
Sensor	Navigation Camera	4	0.0022	0.0088	0.22	0.88
Sensor	Flood lights	2	0.2	0.4	3.9	7.8
		MOVER		**0.07**		**129.8**
Locomotion	Tether	1		1	100	100
Locomotion	Motor	4	0.283	1.132	0.57	2.28
Power	Battery	1	1.5	-	8.5	8.5
Structure	Shuttle	1	0	0	18.5	18.5
		TROGH		**2.11**		**1782**
Locomotion	Engine (0.72km/hr)	1	0.1405	0.1405	10	10
Locomotion	Tires	6	-	-	1.5	9
Locomotion	Stake driver	1	0.003	0.003	3	3
Locomotion	Drivetrain	1	-	-	10	10
Communication	OBC	2	0.01	0.02	1	2
Communication	Antenna	3	0.07	0.21	1	3
Power	RTG	2	-0.12	-0.24	45	90
Power	Battery	3	-1.5	-	8.5	25.5
Structure	7075 Aluminum Bars		-	-		4974
Structure	Operating door	2	0.4	0.8	58.967	117.934
Structure	Winch Cable	4	1.02	4.08	16.7	66.8
Structure	Stakes	230	0.005	1.15	2.5	575
Sensor	Cameras	4	0.1	0.4	1	4
Sensor	Flood lights	4	0.2	0.8	3.9	15.6
Sensor	Hazard Camera	16	0.0022	0.0352	0.245	3.92

Sensor	Navigation Camera	8	0.0022	0.0176	0.22	1.76
Thermal	Radiator	2	0.4	0.8	13.5	27
		SIR		**2.55**		**957.2**
Locomotion	Drivetrain	2	0.1	0.2		420
Locomotion	Tether to TROGH	2	-	-	3	6
Power	Lithium ion batteries (power storage)	2	-0.3/hr	-	8.5	17
Structure	Sampling pods	2	-	-	200	400
Sensor	Neutron spectrometer	2	0.0015	0.003	1.6	3.2
Sensor	Cachecam	2	0.1	0.2		2
Sensor	Flood lights	4	0.4	1.6	11	44
Sensor	Laser Range Scanner	2	0.0018	0.0072	0.15	0.15
Sensor	Hazard Camera	8	0.0022	0.0176	0.245	1.96
Sensor	Navigation Camera	4	0.0022	0.0088	0.22	0.88
Payload	Drilling mechanism (avg)	2	0.0087	0.0174	20	40
Thermal	Radiators	2	0.25	0.5	11	22
TOTALS:				**3.04**		**4015.9**