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Design of a Lunar Architecture for Tree Traversal in Service of Cabled Exploration (LATTICE)

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Traditional wheeled locomotion systems struggle to climb slopes greater than 20° and are unable to independently return samples from lunar regions of interest such as ISRU-enabling permanently shadowed polar craters. To reliably enable a diverse range of future robotic activities within lunar craters, this paper presents LATTICE, a lightweight, rapidly deploying, long-lived robotic infrastructure. Utilizing a novel, terrain agnostic, cabled locomotion modality, it is well equipped to repeatedly transport existing robotic systems and scientific hardware into and out of lunar craters and provide power for sustained activities within. LATTICE may be scaled indefinitely, providing a framework for unprecedented bulk transportation of volatile-containing regolith collected in permanently shadowed craters across the lunar surface and beyond.

I. Nomenclature

R	=	pulley radius, m
g	=	gravitational acceleration, m/s^2
n	=	normal force, N
m	=	mass, kg
θ	=	angle of inclination of crater, °
τ	=	torque, N·m
v	=	velocity, km/hr
μ	=	coefficient of static friction

II. Introduction

Permanently shadowed southern polar craters promise the richest volatile deposits on the lunar surface and therefore demand thorough scientific exploration in the coming decade [1–3]. The rims of these craters offer an attractive landing site with line-of-sight to Earth, temperatures of 250 K - 270 K, and 95% sunlight [4, 5]. The kilometers of between these locations requires crossing ejecta boulder fields, rugged slopes up to 40°, and fluffy, slumped regolith while battling 30 K surface temperatures without external power.

Since 1969, lunar and planetary exploration has primarily been conducted by wheeled rovers [6–8]. These rovers face limitations in power, thermal management, and payload capacity, and struggle to climb slopes greater than 20°. As a result, wheeled rovers are incapable of independently returning samples from the floor of all but the smallest craters. Many proposed alternatives (e.g., limbed robots, hopping landers) [9] are inefficient and short-lived due to the rapid draining of their propellant or power. NASA's Technology Roadmap for Robotic and Autonomous systems emphasizes this need for improved mobility technologies in extreme terrain, such as highly-sloped crater walls and soft, friable ground [10]. The Roadmap also notes that improving excursion time, traversal distance as a function of payload, and system reliability are desirable goals for a mobility system, specifically citing tethered technology and anchor-placement as areas for development.

To reliably enable a diverse range of future robotic activities within lunar craters, we present LATTICE, the Lunar Architecture for Tree Traversal In service of Cabled Exploration. LATTICE is a lightweight, rapidly deploying, long-lived robotic infrastructure. Utilizing a novel, terrain agnostic, cabled locomotion modality, it will repeatedly transport payloads into and out of lunar craters and provide power for sustained activities within. LATTICE may be scaled indefinitely, providing a framework for unprecedented bulk transportation of volatile-containing regolith, robots and scientific hardware in permanently shadowed craters across the lunar surface and beyond.

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We detail our full-scale vision for LATTICE in the following concept of operations plan: After deploying from a medium-large payload Commercial Lunar Payload Services (CLPS) lander near a volatile-rich, permanently shadowed crater, a “set-up rover” will use its mounted “staking module” to extend a stake-supported cableway (the LATTICE) from the CLPS lander onto the lunar surface. The staking module processes compact magazines of lightweight, deployable, helical-pile stakes and cables. As depicted in the Extended ConOps, multiple robotic shuttles are pre-packaged on this cable inside the CLPS lander. The shuttles may then traverse the LATTICE network, fully agnostic to the intervening terrain using a novel adaptive tensioning pulley mechanism. The stakes act as both a pylon and a ground anchor, and the cables act as a transit rail and a tether. Together, the stake-cable system enables the set-up rover to simultaneously establish infrastructure and rappel down the the crater wall. Once established, LATTICE may shuttle payloads of up to 80 kg, which includes small- to medium-weight rovers and scientific hardware, to and from the crater floor, while its cables transmit power for activities within. Robotic payloads transported via LATTICE will then be able to repeatedly recharge at the terminus of the cableway, vastly increasing their mission duration and utility in permanently shadowed craters. In comparison to traditional railways, aerial cable systems improve terrain agnosticity and minimize dust disturbance at significantly less mass. With future modifications to accommodate branching cable junctions at each stake, LATTICE may accommodate enhanced exploratory activity, redundancy and transport volume, using roundabouts to prevent congestion and probing new areas of expansion at the crater floor.

If implemented on the Moon, LATTICE will be the most scalable and expansive infrastructural system on an astronomical body outside of Earth, thus advancing the state-of-the-art for space exploration.

Table 1 Comparing LATTICE to existing mobility solutions

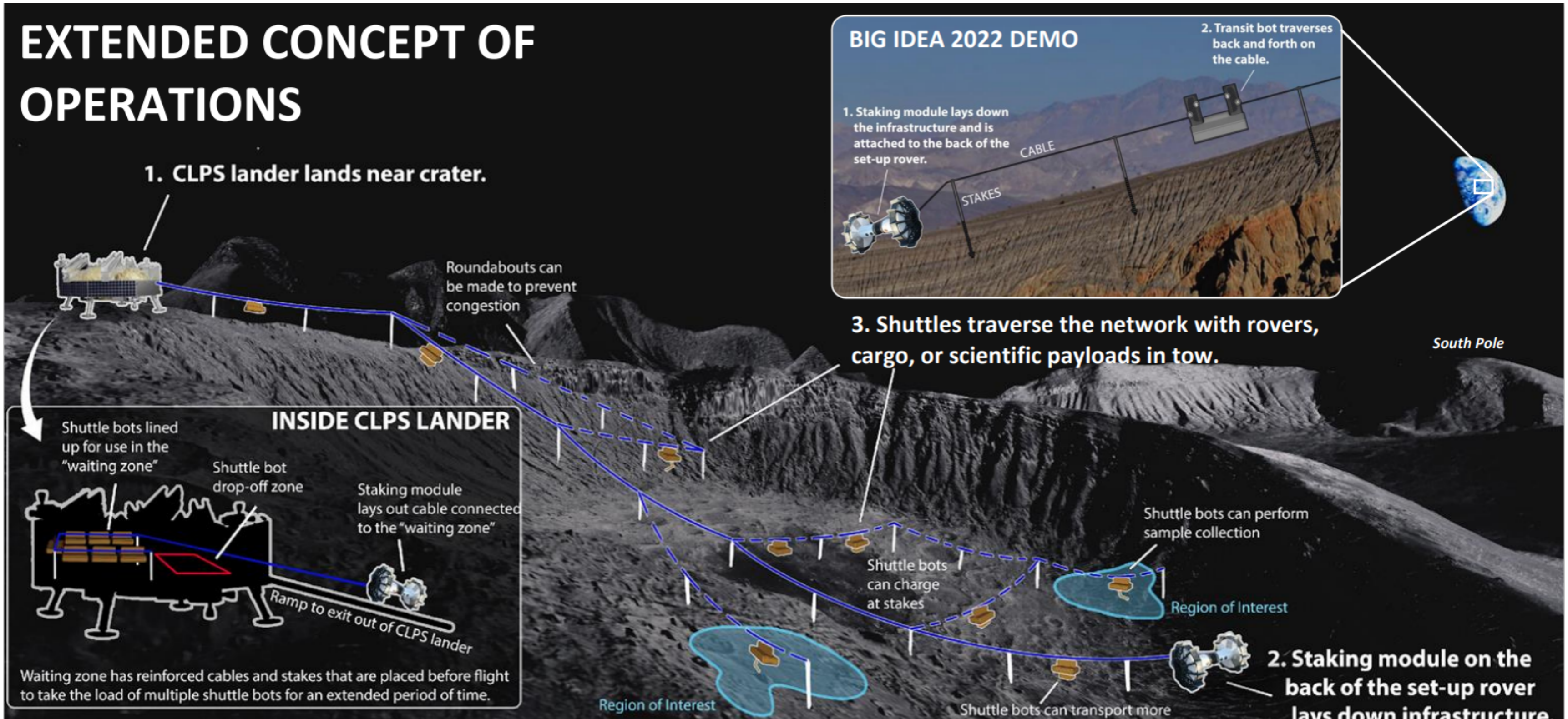
Mobility Technique	Focus	Payload/Mass	Dust Disturbance	Range [km]
Rover	Exploration	10^{-1}	High	20
Hopping Lander	Exploration	10^{-1}	High	30
LATTICE	Hybrid	>1	Low	15
Compacted Regolith Road	Infrastructure	10^{-1}	Mid	8
Railroads	Infrastructure	>1	Low	8

Mobility Technique	Travel Speed [km/hr]	Technology Duration	Navigating >20° Slopes
Rover	0.8	100 earth days	No
Hopping Lander	10	3 hours	Yes
LATTICE	5+	Many months	Yes
Compacted Regolith Road	10+	Many months	No
Railroads	10+	Many months	No

A. Mission Summary

LATTICE is an infrastructure technology demonstration mission that will serve as a platform for scientific payload and regolith transportation, provide terrain-agnostic navigation, and generate power for missions to PSRs in support of the Artemis Base Camp. This distributed robotic system will leverage highlands with reliable power to enable extending into nearby regions: overcoming slopes up to 40°, operating in temperatures from 30 K - 270 K, and navigating fluffy regolith and boulders up to 0.5 m.

The low gravity lunar environment crucially enables LATTICE’s premise of self-propelled suspended vehicles. We expect that as the concept matures, commercial and government aerospace organizations can adapt the basic framework of LATTICE to various extended lunar applications, including lava tubes, mountain traversal, ferrying large quantities of regolith for in-situ resource utilization (ISRU), establishing long-term resource highways, and assisting other rovers or humans in navigating, carrying heavy payloads, and resupplying in similar extreme environments.



* This is a graphic representation and objects are enlarged for visual purposes (not to actual scale).

ID	Design Assumptions [Part 1]	Design Assumptions [Part 2]	ID
DA 1	Deployment on lunar surface before 2026	Lander produces 280 W from solar power under direct illumination	DA 4
DA 2	Land within 1 km of permanently shadowed crater rim in a location with > 80% illumination	Limited direct support (astronauts); operable from and in communication with Earth	DA 5
DA 3	Commercial lander with payload capacity between 500-1000 kg (e.g., Astrobotics Griffin)	Existing rovers are designed such that they are pre-attached to the shuttles	DA 6

B. Requirements & Mass Distribution

Table 2 System Requirements

ID	System Requirements
1.1	System shall be capable of transporting a minimum 80 kg payload up and down the length of cables
1.2	System shall meet an active lifetime of two lunar days and nights (52 earth days)
1.3	System shall meet a passive lifetime (cable, stake system) of 2 years
1.4	System shall be able to establish stakes on crater slopes less than 40°
1.5	System components shall be able to operate in dust and radiation rich environments
1.6	System shall remain operational in 30 to 400 K environments with +75-10 K margin in $> 10^{-9}$ Torr
1.7	System shall span 5 km from crater rim to crater floor
1.8	System shall be operable from and in communication with Earth

Table 3 Staking Module Requirements

ID	Staking Module Requirements
2.1	Stakes shall be deployable to a depth of 1 m in <40° lunar regolith
2.2	Stakes shall remain anchored to the ground following 100 cycles of up to 1000 N load
2.3	Staking module can successfully deploy >50 stakes
2.4	Stake-cable system materials shall survive two years of exposure to lunar environment extremes
2.5	Stake-cable system driver shall be <50kg
2.6	Stake-cable system driver shall interface with slope descending set-up rover's power system

Table 4 Shuttle Requirements

ID	Shuttle Requirements
3.1	Securely traverse LATTICE cable network at 5 km/hr
3.2	Carry payloads of less than 80 kg on the LATTICE cable network at 2 km/hr
3.3	Operate continuously for 10 hours (to elucidate power consumption in models)
3.4	Less than 20 kg unloaded
3.5	Shall have an active thermal management system to survive PSR

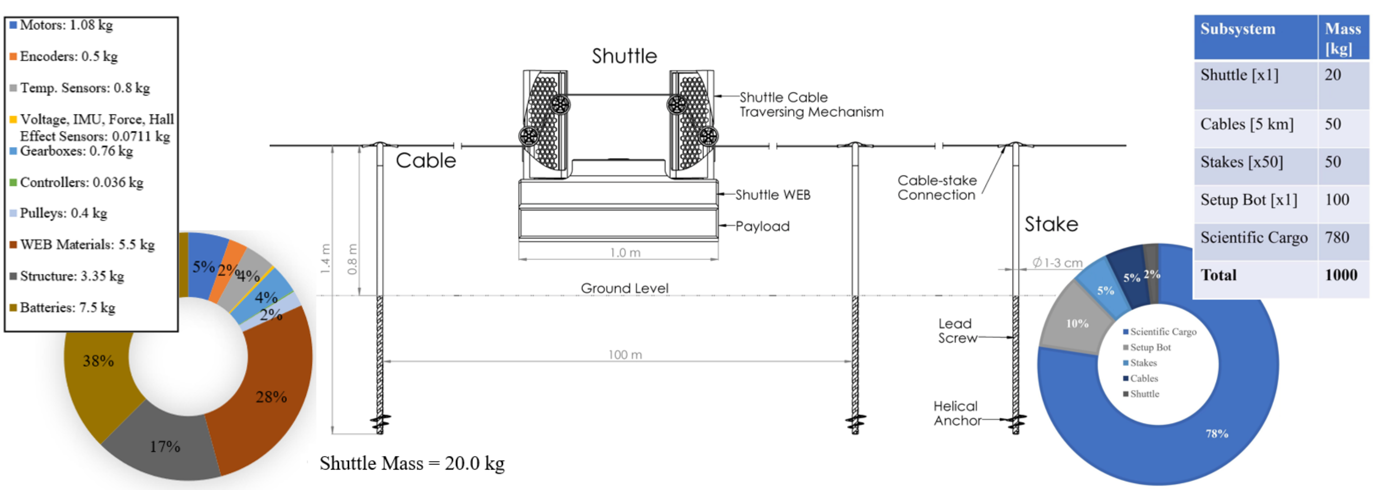


Fig. 1 Foreshortened full scale system schematic and mass budgets

C. Staking Module

1. Cable-Stake Parameters & Feasibility Study

True terrain-agnostic cabled locomotion requires that suspended 100kg fully loaded shuttles reliably clear the lunar surface. To achieve this at minimal system mass, we trade long spans–which reduce stake frequency but increase droop–against the large diameter cables at greater tension, and tall stakes are required to compensate. The yield stress of modern high-tensile fibers and maximum holding moment of lunar ground anchors under uncompensated tension will ultimately dictate the design and feasibility of LATTICE. Modeling the maximum droop of a representative elastic cable under self-weight and worst-case shuttle load conditions over linear slopes <40°, we map the driving Cable-Stake design-parameter space in Figure 2 [11]. It is worth noting that crater walls have positive curvature, significantly increasing ground clearance in the proposed mission scenario, and potentially affording longer unsupported spans.

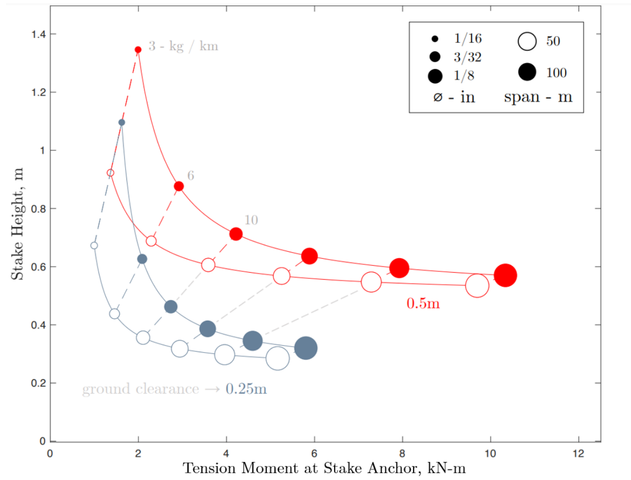


Fig. 2 Minimum stake height and peak moment as determined by minimum ground clearance, mechanical cable diameter, and cable span for a 750 MPa peak load

2. Anchoring Design

We selected a helical auger stake for our anchor as they have been demonstrated to meet the necessary loading conditions in lunar regolith simulant, and allow the stakes to be unscrewed and repositioned in the event of unexpected objects encountered within the regolith. Relevant studies of helical anchors with sand, cement, and simulated lunar regolith show small diameter anchors hold better at the same depth compared to larger diameter anchors. Preliminary studies of helical anchors on lunar simulant show that a single helix anchor with a 3.8 cm outer diameter anchored only 30.5 cm deep results in a vertical pullout force of approximately 2,200 N [12]. We will prototype a small diameter, hollow, single helix anchor with a dull wedge tip made of 310 steel which should offer strong stability in lunar regolith at low-cost, but we will also explore more expensive materials such as titanium for the flight product. [12].

3. Anchoring Analysis

To ensure that the stakes are capable of bearing the required loads, preliminary analysis was performed using existing Earth-tested models which use the volume of soil, distance displaced, and accounts for friction using the shear stress of the soil of helical piles. These models were adapted to the documented properties of lunar regolith and caution was built into the analysis procedure by modeling for worst-case anchoring environments. Dimensions used in the model are based on those outlined in Section II.C.2.

Lateral loading capacity was evaluated using a flexible, free anchor model for a depth of 0.5 meters, accounting for disturbance of regolith below during installation. Using this model, we find that with 1 kN of tension applied at the stake, a lateral deflection of up to 3.6 mm at the top is expected.

Uplift force required for the anchors versus installation torque was calculated for our target uplift force capacity of 1 kN. At an effective anchoring depth of 0.5 m an installation torque of 800 Nm is necessary. By comparison to the previously mentioned work on helical regolith anchors (~2 kN at ~0.25 m, ~0.2 kg), this model is highly conservative due to failing to capture the high cohesion of sharp interlocking regolith particles [13][12].

4. Stake Driving Mechanism

When designing the stake driving mechanism, we researched existing helical pile drivers used in foundation construction and repair as well as existing formulas that dictate the behavior of the helical piles. We identified two key design features of the driving mechanism for our current stake design: it must apply a consistent downforce on the order of ~100 N and it needs to exert a rotational moment on the order of ~800 N·m. While we intend to prototype different stakes and drivers to develop robust experimental evidence, our current design features a ~1kg motor, driving the lead screw down at 5 RPM and a short-stroke electric linear actuator (force ~750 N, mass ~0.5 kg) to clasp around the stake. These specifications may be matched to the set-up rover's rappelling winch. As stake driving is a static operation, a clutch and crown gear or u-joint mechanism would let this motor drive both tethered slope descent and stake driving functionalities. We have also identified passive designs that utilize an open, geared lead screw sleeve to eliminate the vertical actuator. The weight of a 100 kg stake-driving robot generates sufficient downforce in both designs.

5. Stake-Cable Interface

There will be two types of stake-cable connections: pre-attached, enabling continuous stake-cable chains, and free segments, where cables are attached to the adjacent stakes as they are planted. This hybrid approach minimizes risks while maximizing the flexibility of LATTICE's deployment. Reloadable 'magazines' of continuous stake-cable chains minimize both the set-up rover's requisite payload and cable-stake points of interface failure while leveraging the shuttle robot's high payload capacity.

We have identified several viable solutions for establishing either cable-cable or cable-stake connections when switching between magazines. First, we require the transfer of a new cable-stake module, then it must attach a cable end to a stake with sufficient tensioning capabilities. The most promising solution to this is a push-to-lock connector, which can withstand high tension with minimal risk of the cable disconnecting. With this connection, the set-up rover will use a stake to provide the necessary tension to achieve cable clearance, and once the cable is connected to a stake, the next module of stakes can be deployed.

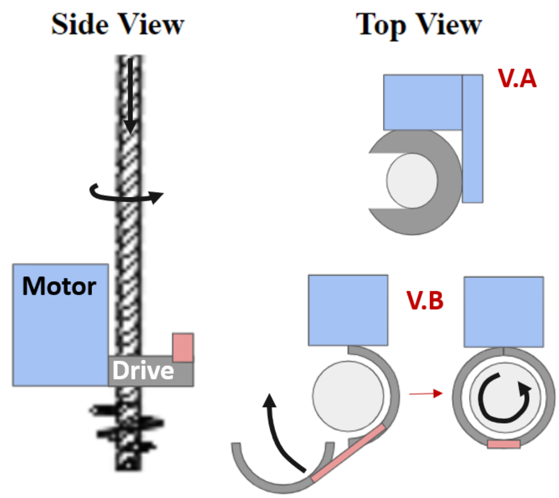


Fig. 3 Stake driving mechanism

6. Cable Design

LATTICE's cables will have to endure the harsh lunar environment. Some of the factors that might affect the integrity of these cables include massive temperature changes from highlands to PSRs, abrasion caused by repeated shuttle traversal and lunar dust, and UV radiation. Thus the cables are designed to address these concerns and ensure the cables' robustness whilst maintaining minimum mass and diameter.

The structural components of LATTICE's cables will be made of a fiber with a high strength-to-weight ratio and resilient thermal properties. These fibers will be woven into a braided form, which contributes to robustness, minimizing elongation, and increasing redundancy [14]. 3-D braiding of fibers can reduce the effective coefficient of thermal expansion depending on braiding angle and density, as well as reduce bending fatigue [15]. This strong braided interior will carry the bulk of the tensile load on the cable and determine (and reduce) the thermal expansion of the cable. This feature extends the working lifetime of the cable.

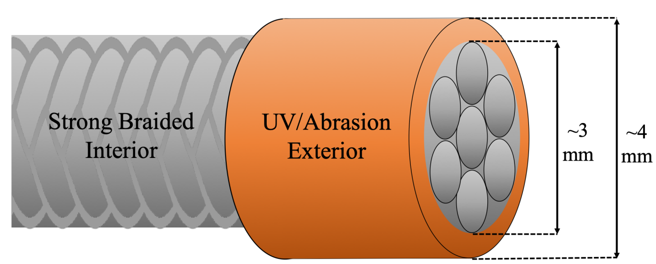


Fig. 4 Cable design and cross-section

Some material options and properties for this section of cable are listed in Table 5. Their high tensile modulus, low coefficient of thermal expansion, low density, high tensile strength, and low creep make them excellent material choices for the core of LATTICE cables.

Although these fibers have excellent thermal and mechanical properties, they usually have poor resistance to UV radiation, which is a significant risk on the moon. For example, Kevlar loses about 50-80% of its strength after 900 hours of exposure to UV radiation on Earth [16].

To prevent UV radiation from weakening the cable, the strong interior will be surrounded by a sleeve made of a material with high UV and abrasion resistance. A Nomex, or similar material, braided exterior sleeve provides benefits similar to the extra resilience introduced by interior braiding. Using a braided sleeve does not significantly alter the flexibility of the cable like an extruded sleeve might. It is also a lightweight option, making the cable easier to transport. The trades for selecting specific cable materials are highlighted in Table 5.

Table 5 Possible cable materials and their properties

	Kevlar	Vectran	Technora	Zylon (PBO)
Tensile Modulus [GPa]	112.4	103	80	270
Coefficient of Thermal Expansion [1/K]	-4.9 $\times 10^{-6}$	-4.89 $\times 10^{-6}$	-5 $\times 10^{-6}$	-6 $\times 10^{-6}$
Density [kg/m^3]	1440	1440	1390	1560
Tensile Strength [GPa]	3.6	3.2	3.0	5.8
Creep	Lowe	Very Low	Low	Very Low

7. Staking Module Design

The staking system is designed for inter-operable attachment to various existing and proposed wheeled lunar rovers exceeding 100 kg. It will process magazines of prepackaged stakes and cables, drive the stakes into the lunar surface, deploy cables as a supporting tether, and attach interconnects. As illustrated in Fig. 5, both stakes and cable connectors are fed along constrained rails in the magazine. A protrusion from the winding drum catches the leading connector and takes-up the length of packaged cable 'flake' corresponding to the nearest 'uphill' stake. After unwinding and traversing the length of this cable (step A), the stake module drives the next ready stake. Depending on cable-stake interface schema, the same winding drum may establish a connection in (step B), before taking up the next length of LATTICE's cable in (step C).

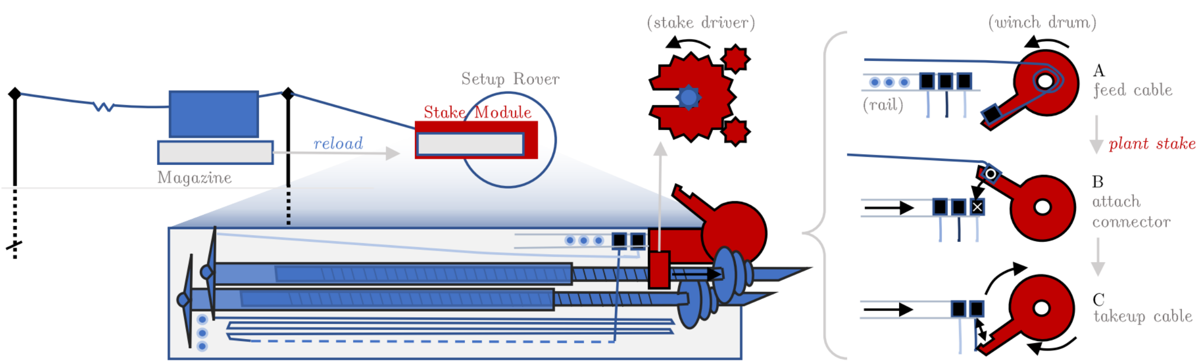


Fig. 5 High-level illustration of the staking module's integrated multi-functionality

D. Shuttle Robot

1. Shuttle Design

Central to the utility of LATTICE, robotic shuttles have been designed to transport scientific, robotic and ISRU payloads across steep cables, traverse cable-stake connections and operate in the PSRs. These three design objectives have been answered with a novel adaptive pulley mobility and tensioning solution mounted on a 5.5 kg Warm Electronics Box (WEB) with a modular rail mount for payloads up to 80 kg. A notional design this robot is shown in Figure 6.

2. Shuttle Mobility Mechanism

To reduce the mass and points of failure of LATTICE as the system spans larger distances, the stakes have been designed to perform few functions. In turn, the shuttle mobility mechanism must solve the issues of thermally induced strains in the cables, slack resulting from set-up robot positional variability, and cables mating at sharp angles with stakes. The cable traversing mechanism consists of two mirrored modules with two vertically orientated pulleys each situated at the front and back of the shuttle. Each module has three degrees of freedom (DOF): each pulley is driven to ensure the equal distribution of friction applied to the cable, the innermost pulley is actuated vertically with respect to the shuttle to take up slack and thermal strains in the cable, each module is able to pivot freely around the vertical axis directly through the outermost pulley allowing for the navigation of sharp bends at stake junctions. The stroke length of the vertical actuation is 0.375 m on each module, summing to 0.75 m of cable take-up ability, accounting for the predicted 10 cm cable length change from thermal strains and 0.65 m of stake position variability. Each module is able

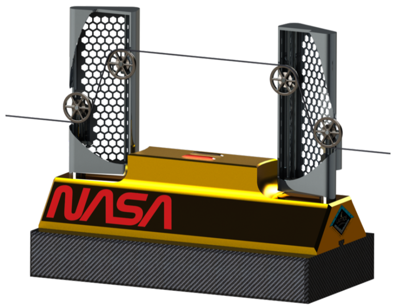


Fig. 6 Shuttle render

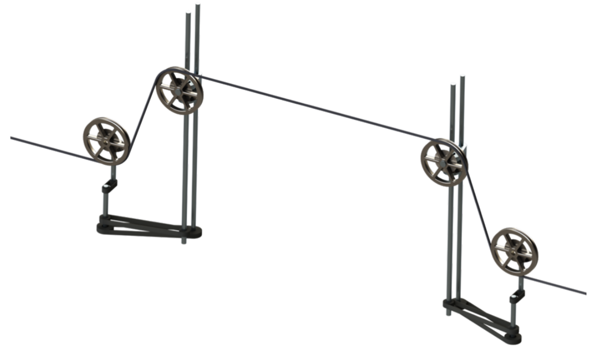


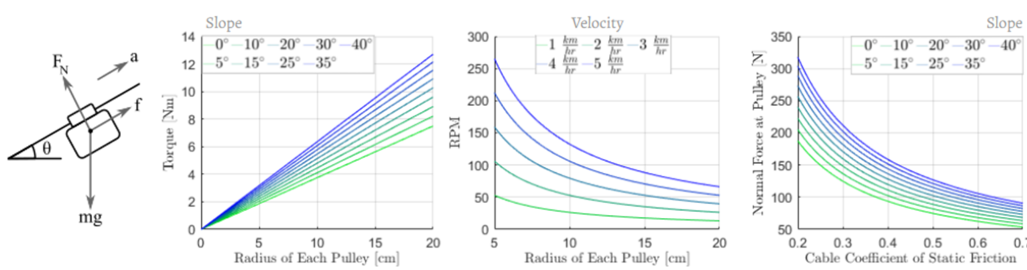
Fig. 7 Shuttle adaptive pulley tensioning mechanism

to rotate more than the necessary 120° to traverse the maximum allowed angle between cables at a stake junction. To ensure the protection of the actuating motors and electrical cabling, each module utilizes a set of three concentric shafts allowing the motors to be contained within the WEB. In the notional design presented in Figure 7, the pulley motion is rotated using belts and miter gears, and the vertical tensioning motion is translated using a lead screw. When mounting a stake junction the pulley module nearest the stake will lower the innermost pulley and align the module to allow for the junction to pass through the robot. As the second module reaches the junction the same operation is performed. When exiting the junction, the same operation is executed in reverse. In the event a shuttle robot becomes disabled on the cable, a one DOF arm could extend from an adjacent follower forcing the pulley module to pivot. This would cause the nonfunctional shuttle to be removed from LATTICE, mitigating blockages.

3. Locomotion Analysis

Traversal of the shuttle along the cable requires the motors to generate a sufficient torque without stalling. We propose a maximum velocity $v = 5\frac{km}{hr}$ at an unloaded capacity, incline $\theta = 40°$, and acceleration $a = 1.5\frac{m}{s^2}$ for a four pulley system each with some radius R.

For each pulley, we solve the equations that govern the torque τ and required normal force n at a loaded capacity for maximum acceleration, and the RPM at an unloaded capacity for maximum velocity. This yields the equations in Figure 8. Using these relationships, we optimize pulley size and motor choice for different inclines and velocities. By distributing the frictional force to multiple pulleys, we reduce the necessary torque and ease the stress on the shuttles' motors.



$$\tau \approx \frac{mR}{4}(a + g\sin(\theta))$$

$$\text{RPM} = \frac{v}{R}\left(\frac{1\text{rev}}{2\pi}\right)\left(\frac{60\text{s}}{\text{min}}\right)$$

$$n \approx \frac{m}{4\mu_s}(a + g\sin(\theta))$$

Fig. 8 Torque, RPM, and normal force per pulley

4. Shuttle Components

Each shuttle will contain five 24 V (10 Ah) cells, six 24 V motors, a radio, and an array of sensors. Existing cells weigh around 1.5 kg each and are recommended to be charged at 3 A. By referencing consumer motors, gearboxes, and motor controllers and constraining the pulleys' radii to 0.05 to 0.2 m, the shuttle's velocity was calculated to approximately 2 km/hr when loaded. In particular, these motors, gearboxes, and motor controllers each weighed around 0.270 kg, 0.190 kg, and 0.009 kg respectively. Two rotary encoders redundantly track the shuttle's position and velocity along the cable. Force sensors synchronize the pulley pressures applied to the cable. A temperature sensor, voltage sensor, and existing Ka band phased array antenna will also be mounted in each shuttle robot to gather telemetry data

Table 6 Power modes table

Subsystem	Peak Power Consumption [W]	Cruising Power Consumption [W]	Housekeeping [W]
Mobility	164	50	4
Comms	1	1	1
Sensing & Computing	3	3	3
Total	168	54	8

Peak assumption: 80 kg payload, 40deg slope, 2 km/hr
Cruising assumption: 0 kg payload, 0deg slope, 5 km/hr
Housekeeping assumption: stationary

and communicate it back to the lander. Commands can be received from the CLPS lander using the full duplex protocols through the power cable and sensed with a contactless current probe [14]. The robot will also contain a Hall effect sensor to detect stakes and correct positional errors, and an inertial measurement unit (IMU) to monitor its angular motion.

5. Autonomy for the Shuttle

The shuttle will use a cable encoder to measure the distance of cable traversed. Once a shuttle reaches a stake (which will be detected using contact sensors), its position will be calibrated as the stakes' positions are known with high accuracy. The shuttle's need to autonomously interact with their payload by sensing the weight of the payload has as well as latching and unlatching a mechanism to deploy the payload.

6. Thermal Management

To survive a -40°C to 60°C temperature range, each shuttle will house its electronics inside a Warm Electronics Box (WEB) located at the bottom of the robot. Existing WEB's utilize five distinct layers: a Barium Sulfate with Polyvinyl Alcohol coating, multiple MLI sheets, an aluminum honeycomb, silica aerogel, and paraffin wax [17]. Barium Sulfate with Polyvinyl Alcohol coating has a very low absorbance (.06) and high emissivity (.88) [18] and will coat the exterior followed by five layers of MLI. 1 mm of aluminum honeycomb panels will follow to provide structure (3.4 kg). 2 mm of Aerogel will line the aluminum honeycomb and provide the majority of the thermal resistance. Due to the melting point between -10°C to 10°C, 2 kg of paraffin wax ($C_{14}H_{30}$) will be inside the WEB in order to provide thermal energy storage [19].

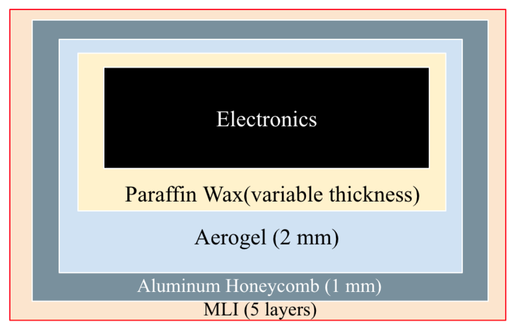


Fig. 9 Material layer for the warm electronics box

E. Future Development

1. Power Line Capability

LATTICE would be incomplete without the addition of a power transmission line along the length of the network. In-depth analyses indicate that a High Voltage Direct Current (HVDC) transmission scheme offers significant advantages over the use of High Voltage Alternating Current (HVAC) scheme. Crucially, most available power sources and power applications on the Moon generate and utilize DC, so transmission through HVAC would increase system complexity and power losses significantly.

We found that for an assumed power draw of 30 W 8 km away from the power source, only two wires of aluminum conductor of 1/3 mm diameter each are necessary, at a DC transmission voltage of 1000 V and temperature of 90 K, to guarantee less than a 1% voltage drop over the network. This represents a total mass of conductor of only 1.78 kg.

Including all power losses, it was found that a HVDC power transmission set-up would allow for a continuous 50 W power supply at the Hub to provide 30 W of DC power at the bottom of a lunar PSR. This power transmission solution could realistically be integrated into the LATTICE architecture with two power lines in the main system's cable, such as in the Moon Diver mission [14], or by deploying a thin dedicated power transmission cable along with the main system architecture, out of the way of following shuttle robot operations. Regardless of the means of integration into LATTICE, such a power transmission cable could provide a constant power supply to the set-up rover during the deployment of the primary infrastructure. But perhaps more importantly, LATTICE could also serve as a reliable, durable power source for resource gathering and science installations in the permanently shadowed regions [20].

2. Potential Set-Up Rover Designs

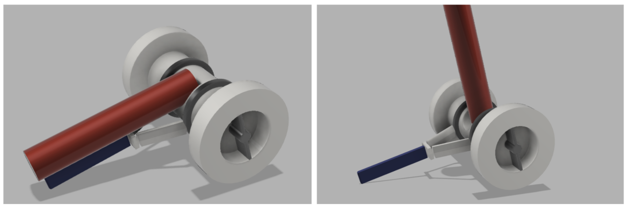


Fig. 10 Axel-type set-up rover

A staking module will be implemented onto a set-up robot, which will be a pre-existing rover. After a cost-benefit analysis and morphology versus set-up robot type consideration, one efficient solution for our application is the Axel rover. The preliminary design for the Axel robot is pictured in Fig. 10. The main body of the Axel robot consists of an axle and the wheels (white). The staking module (red) on the Axel robot will contain the stakes and is parallel to the tail of the robot. When the set-up rover stops, it pivots to a vertical position and drives the stake into the ground, as shown in the second picture in Fig. 10. The tethering system consists of a tether attached to the tail (blue), which extends back to the CLPS lander. This enables the lander to bring back the set-up rover after successful staking and to tension the cable while staking.

Furthermore, to stabilize the rover while staking, an outrigger-type system can be constructed. It can be attached to the body of the rover so that when it rotates to plant the stake, the outrigger-type system would also rotate and make contact with the ground for stability.

3. Autonomy for Set-Up Rover

The set-up rover will autonomously decide where it is optimal to place stakes based on a multi-objective optimization that considers the slope and structure of the terrain, the distance to the base, and other considerations. The rover will then traverse the terrain to the location where the stakes will be planted. For this, the set-up rover will use advanced trajectory planning algorithms such as Probabilistic Roadmap (PRM), Rapidly-exploring Random Tree (RRT*), Sequential Convex Optimization (SCP), or Monte Carlo Tree Search (NTE).

III. Conclusion

If implemented on the Moon, LATTICE will be the most scalable, expansive, and long-lived infrastructural system ever implemented on an astronomical body outside of Earth, thus advancing the state-of-the-art for cableways and extraterrestrial surface payload transportation infrastructure as necessitated by the NASA Artemis program. LATTICE capitalizes on the lower-than-earth gravity of the moon and the positive curvature of crater making it a natural solution for transporting and providing power to payloads across a variety of challenging terrain. The modular and terrain-agnostic payload transport capability of LATTICE allow this technology to scale to different mission scenarios. The key working principles for the novel stake-driving module, stakes, cables and shuttle robot have been validated and merit further design and prototyping. Early surface robotic missions will both assist with scientific exploration and set the foundation for lunar infrastructure for long-term robotic exploration of the moon, with several concepts proposed both as pure infrastructure and as short-term exploration technology [21]. The utility of LATTICE is not just limited to the Moon but also can provide similar benefits if implemented on Mars or small celestial bodies. We propose cabled exploration as an optimal hybrid, Artemis-enabling new locomotion modality–bridging tethered and anchored exploration methods to enable efficient, terrain-agnostic transport.

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