LATTICE

Lunar Architecture for Tree-Traversal In-service-of Cabled Exploration

Caltech

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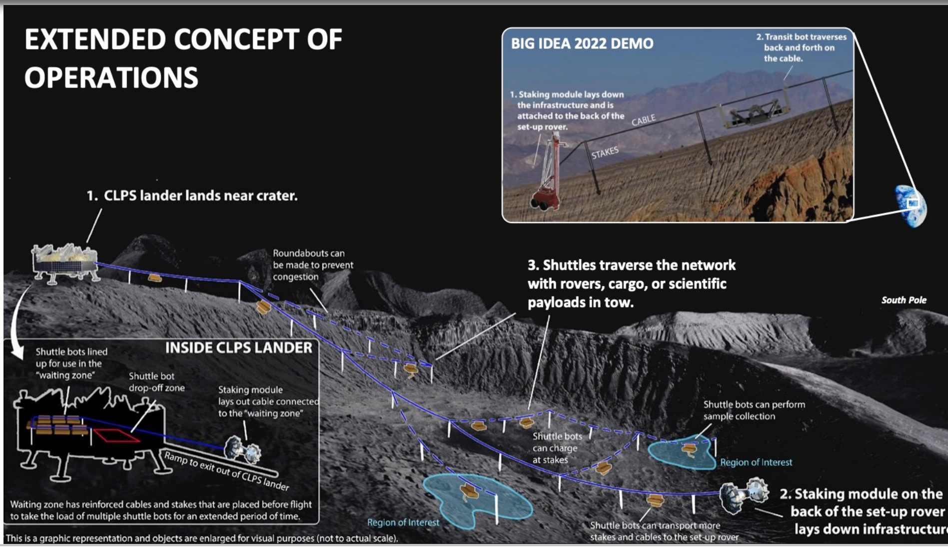
Lunar Architecture for Tree-Traversal In-service-of Cabled Exploration (LATTICE)

Concept Synopsis

LATTICE is a cable-based infrastructure that will enable robotic transport into and out of craters on the Moon. LATTICE targets implementation as the Moon's first scalable robotic infrastructure.

The driving module supports a wheeled rover's descent into a lunar crater, inserting cable-connected stakes into the ground along the way. Robotic shuttles ride this cable with a novel self-tensioning mechanism and can carry payloads 4x their own mass up and down steep slopes.

LATTICE leverages the Moon's reduced gravity and highly cohesive regolith to produce an energy-efficient, rapidly deployable, terrain-agnostic mode of transport. It is particularly applicable to early exploration of permanently shadowed craters and long-term bulk transport of ice, enabling a sustained human presence on the Moon.



Innovations

LATTICE advances the state of the art for accessing extreme lunar terrain, transporting mass, energy, and information in one cohesive system.

- **Light-Weight Infrastructure:** Tensile elements enable light-weight infrastructure and payload-to-mass ratios exceeding existing solutions.
- **Terrain-Agnostic:** Shuttles can traverse steep crater slopes without contacting the ground, limiting dust exposure.
- **Energy Efficient:** LATTICE functions as a crater power line, outperforming laser power beaming. Cable transport is highly efficient.
- **Rapid Deployability:** The stake-cable network can be rapidly and autonomously deployed.
- **Scalability:** LATTICE can be expanded into an arbitrarily large branching network.
- **Modularity:** Each shuttle can be tailored to different functions.

Verification Testing Results & Conclusions

LATTICE has been rigorously tested in both a controlled lab environment and an uncontrolled environment (i.e., Lucerne Valley) .

Stakes: Stakes are back-drivable and withstand cyclic 2.5 kN side load with little ground deflection.

Driver: Driver can drill a stake up to 75 cm in depth while drawing an average of 5 watts of power.

Shuttle: Shuttle can tension and lift itself off the ground to traverse slopes >20˚ and 25m spans.

Easy Use: Driving stakes is semi-autonomous and the shuttle consists of only tensioning arms and motion pulley mechanisms to control the tension, vertical position on cable, and speed of travel.

Testing Specs: Two stakes allowed the shuttle to cover a span of 60-65 m and a height of 18.5 m.

1 Executive Summary

1.1 Operational Synopsis

Traditional wheeled locomotion systems struggle to climb slopes greater than 20°, a key bridge to in-situ resource utilization (ISRU)-based Artemis mission architectures in the Moon's ice-rich permanently shadowed craters [1]. We propose that existing Artemis rover platforms can gain access to currently inaccessible terrains in partnership with the Lunar Architecture for Tree-Traversal In-service-of Cabled Exploration (LATTICE), enabling transport of robotic systems, resources, and scientific hardware into and out of lunar craters.

1.2 Proposed Solution

LATTICE is a lightweight, rapidly deploying, and long-lived robotic infrastructure and exploration system. We propose to augment existing wheeled rovers with a driving module to deliver magazines of deployable ground anchors - stakes and cables. This driving module will simultaneously rappel and plant a stake-supported cableway as the rover descends down the crater wall. Robotic shuttles that are pre-packaged on this cable inside the lander will then traverse the steep cableway system using a novel tensioning mechanism. Once established, each LATTICE shuttle will be able to transport payloads of up to 80 kg repeatedly to and from the crater floor, while its cables transmit power and data for activities within.

To demonstrate the essential elements of LATTICE, the team proved the following:

- Demonstrated that an Earth-gravity scaled Commercial Lunar Payload Services (CLPS) representative set-up rover can drive the proposed stakes into Earth soil with deliverable lunar rover downforces, accommodating for variable distributions of large-grain subsurface obstacles (rocks, boulders).
- Verified the mass-scaled shuttle's ability to repeatedly transition between cable and stake rails, taking up a maximum of 0.6 meter lengths of cable slack, and tensioning the system while traversing up cables at angles greater than 20°.

LATTICE takes its complete form and enables locomotion over extreme terrain only as a fully integrated system. We are working towards a final system demonstration of a scaled and simplified version of a minimal lunar crater operational scenario shown below, establishing the combined self-deploying functionality of its key systems and operational modes–stakes, cables, driver, shuttle, stake driving, stake traversal, and uphill driving–at minimum complexity.

1.3 Verification Testing

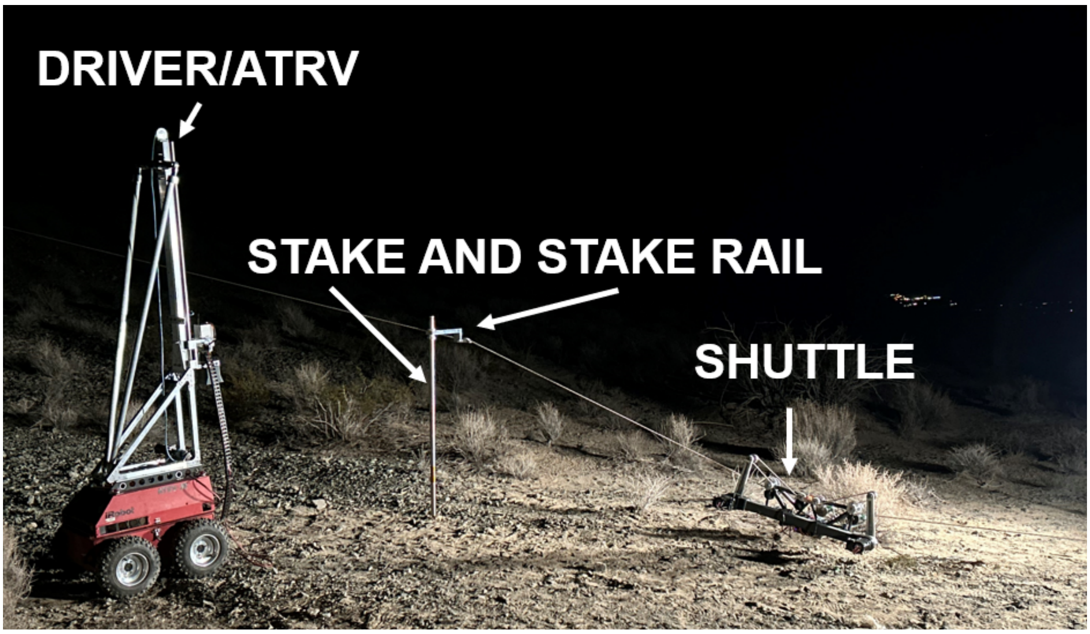


Fig. 1: Major system components at Lucerne Valley

Each LATTICE subsystem has been tested in Lucerne Valley, CA. The driving module has successfully driven a stake to a depth of 70 cm using less than 50 N of downforce at $\sim$5 W power draw over 45 minutes. At a worst-case minimum planting depth of 50 cm, the titanium stake successfully withstood tension loads of 2.54 kN, exceeding the 'fully encumbered' shuttle design load of 2 kN. The shuttle has performed tensioning procedures, transitioned over stake rails, and traveled 20 m cable spans on slopes of 0–20° in an indoor test stand and over 60m spans on a 20.1° slope in a small system demonstration in Lucerne Valley. Proposed future testing includes reliability testing of each subsystem under repeated loading conditions, stake driving and stake loading in a lunar simulant test stand (under construction), cable testing, environmental testing, and a full 'mission scenario' demonstration.

1.4 Impact

LATTICE can be scaled indefinitely, providing a network for unprecedented terrain-agnostic bulk transportation of volatile-containing regolith collected in permanently shadowed craters across the lunar surface and beyond. We expect that as the concept matures, LATTICE can tackle lava tubes, incorporate branching cable paths to explore broad swathes of terrain, and, with growing payload capacities, ultimately scale to something between railroad and broadband power-line: the integrated solution for transport of mass, energy, and information on the Moon.

2 Problem Statement and Background

2.1 Challenge Addressed

The Artemis missions are interested in exploring the lunar south pole in preparation for a future lunar base. The region is attractive due to access to volatile-rich resources, near areas of 95% sunlight, temperatures of 250-270 K, and line-of-sight to Earth [2, 3]. Most notably, the South Pole features deep craters with illuminated rims that sharply transition to permanently shadowed regions (PSRs) cold enough (25-80 K) to trap and accumulate volatiles and water ice over billions of years [4, 5, 6].

Lunar and planetary exploration has historically relied on the use of wheeled rovers. However, these rovers face limitations in power, thermal management, slope traversing ability, and payload capacity. In extreme terrains, even proposed alternatives to wheels (e.g. limbed robots, hopping landers, soft robotics) are inefficient and lifetime limited by propellant or power. Technology capable of enabling mobility in extreme terrain [7], such as steep crater walls, is integral to the longevity and efficiency of long term missions such as the Artemis program.

2.2 Overall Approach



Timeline	Now (Earth demo)	2026 - 2028 (CLPS)	2028 and beyond (HLS)
Location	Lucerne Valley	Crater Rim, partially shadowed regions	Crater Rim, permanently shadowed regions
System Scale	Three 2.5 kg each stakes, 100 m span	100-1000 kg total, 1 km span	1-10 tons, 1-10 km span
Shuttle Payload Mass	80 kg - Earth Equivalent	80 kg	Up to 400 kg
Stake Design	2.5 kg, 1 m tall, 25m flat span	2-5 kg, 2 m tall, 25m flat span	10-100 kg, 3-5 m tall, 25-100m span, guy wire
Architecture	Straight path, continuous cable	Straight path, segmented or continuous cable, power/comm	Branching or looping, segmented cable, power/comm, many implementations

Table 1: Path to Full-Scale LATTICE

LATTICE is an infrastructure technology that will facilitate lunar exploration and serve as a platform for scientific, robotic, and bulk regolith transportation. We propose a distributed robotic system—based on cable and tether technologies—that leverages highlands with reliable power to enable exploration in shaded depressions, with goals of overcoming slopes up to 40°, operating in temperatures from 30–270 K, and navigating fluffy regolith and boulders up to 0.5 m. The following table outlines three mission scenarios: Earth demonstration, which we have shown at Lucerne Valley; a Lunar Pathfinder demonstration scenario, projected to take place between 2026 to 2028; and a long-term large-scale vision of LATTICE at a lunar settlement scale (deployed by a HLS-class lander).

2.3 Earth Inspiration

Initial research reviewed existing Earth-based cabled systems transporting passengers, power, and other payloads above ground, especially sloped terrains [8]. Inspiration was taken from spider webs, mycelium, electrical transmission lines, roller coasters, ski lifts, cranes, and cable cars [9, 10]. Figure 2 depicts some existing innovative cabled systems used in heavy industry that individually demonstrate key functionalities of LATTICE. Rappelling diggers are already used to plant anchors on - and stabilize - steep hillsides. Self-propelled power line inspection robots are able to switch between both cables and rails at junctions. Cabled crane systems are frequently used to carry heavy cargo up slopes exceeding 40° in extreme and undeveloped environments. Doppelmayr Transport Technology has built a cabled transport system that could carry 24,000 metric tons per day over a distance of 1.3 km [11]. All of these technologies are even more effective in the Moon's reduced gravity.

Fig. 2: Inspiration from existing Earth systems

2.4 Mission Scenarios

A scaled-up version of LATTICE will have a large payload capacity suitable for establishing a long-term pathway to reliable resources and assisting exploration by rovers and humans over rough terrain. While there are many different lunar base concepts, we will assess a long-term LATTICE implementation with an extreme of mass transit in the context of Robotic Lunar Surface Operations 2 (RLSO2) study, which was proposed by a group from NASA JPL, NASA Ames, Blue Origin and Honeybee Robotics in 2020 [12].

RLSO2 aims to establish a permanent lunar South Pole base at Shackleton Crater that "produces enough oxygen and hydrogen from lunar polar ice ISRU for four flights per year of a reusable lander shuttling between the Lunar Gateway and the base" [12]. RLSO2 has identified three viable lunar base archetypes for this scenario with estimated system mass:

- Obtain power from the crater rim and set up the base in the crater - 405 t
- Obtain power and construct the base outside the crater and harvest inside - 222 t
- Set up the base outside the crater and harvest from less-enriched ice fields - 287 t

We find that LATTICE can be well-integrated into the most promising mission architectures 2 and 3, enabling as-yet-unresolved regolith transport over nearly 10 km out of steep craters while eliminating the need for lossy power beaming. System scaling of the LATTICE implementation developed here indicates that this can be achieved at less than 20 t—competitive with the FLOAT NIAC, while cutting comparable masses associated with system power draw and less direct access to high concentration water ice [13]. We find that this can be achieved with either 5-10 concurrent linked cableways at the system scale developed here (prioritizing ease of deployment and fault tolerance) or a scaled larger scale implementation of LATTICE with 400 kg payloads—also enabling astronaut transport. Additional mass savings can be had by adapting a portion of LATTICE into a cable conveying system from crater floor to rim if prioritizing mass fluxes in excess of 100 t/day.

In addition to enabling government-run missions such as RLSO2, LATTICE can also fill a key niche in enabling international and commercial operations. While the Artemis Base Camp will be located at the South Pole, other international bases will be located on the order of tens of kilometers away: recent announcements ([14]) have pointed to the joint China-Russia base being located at the Marius Hills in the northwest of the lunar nearside or Amundsen crater near the South Pole. LATTICE could serve as a reliable intermediary infrastructure between international Moon bases. In the case of large scale commercial operations, LATTICE enables modular resource-gathering networks as well as transportation of less capable rovers, such as RASSOR, into lunar craters.

2.5 Modifications to LATTICE

A key advantage of LATTICE is its ability to tailor to specific terrain requirements. LATTICE scales according to a few key system parameters: maximum tension scales with cable span, shuttle mass, the inverse of the cosine of slope, and the inverse of droop (how much the shuttle droops from the top of the stake). Therefore, the system scales by maximizing the span between stakes and minimizing stake height. Furthermore, several parameters tend to scale in our favor. Although wider stakes are heavier, their increased strength allows larger supported tensions and consequently larger spans. This decreases the amount of stakes needed and therefore decreases overall system mass. The maximum tension also decreases with slope. The steeper the slope, the less tension is applied to the shuttle—though the shuttle is less effective at gripping the cable.

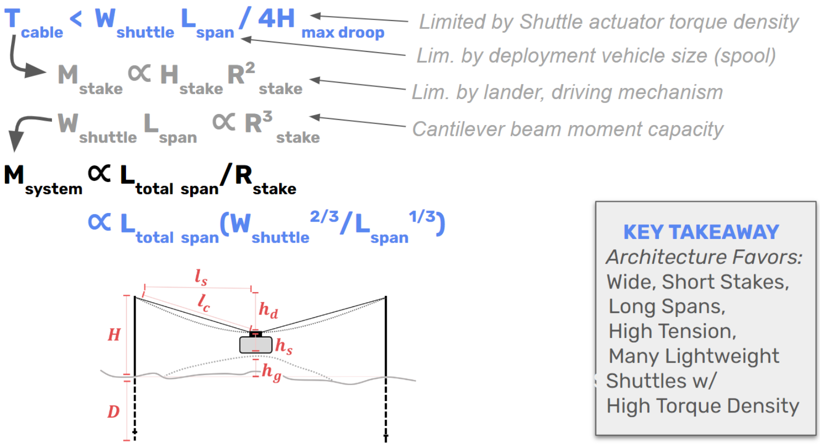


Fig. 3: Scaling laws that key system parameters follow

Minimal modification allows LATTICE to take advantage of the stake's ability to handle high side loads. For example, by attaching a winch line as shown in Fig 4 to a shuttle that can sequentially re-anchor to stakes along the crater wall, bulk cargo ∼10x the mass of the fully

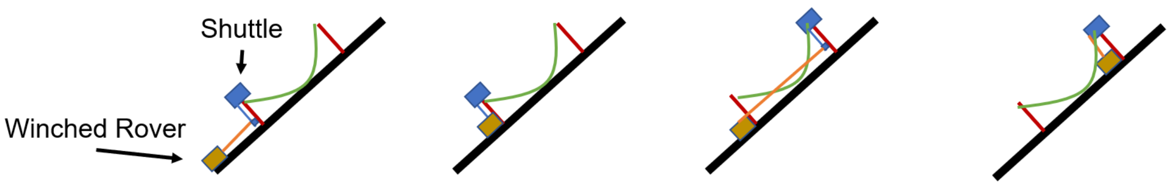


Fig. 4: Using the shuttle as a winch for a rover to progressively move up an incline

encumbered shuttle (∼1T) may tow itself into or out of craters in a slower secondary 'inchworm' transport mode.

Additionally, side-load capacity can be increased with the addition of Manta Ray anchors to individual stakes. On Earth, Manta Ray anchors are used by electric utilities to hold guy wires for transmission poles in tough soil like decomposed rock and permafrost [15]. Adding anchors reduces stake mass with the trade-off of greater deployment complexity and dependency on one or more additional components per stake.

We have found it possible to run stakes at extremely large spans down a crater wall as shown in 5. Although possibly limited by the tensions from shuttle and cable weight that current cable technology can handle, considering the limiting case of maximizing spans would allow for an extreme mass efficiency. These long stake spans can also be used in conjunction with shorter stake spans to create a "spider web" (see right graph in Fig 5) of cables to make the system multipath: introducing resistance to stake failure and eliminating the need for tall stakes in a crater environment.

In anticipation of a lunar surface with multiple bases, future iterations of LATTICE include branching and looping capabilities, which enable two-way transportation along large resource networks.

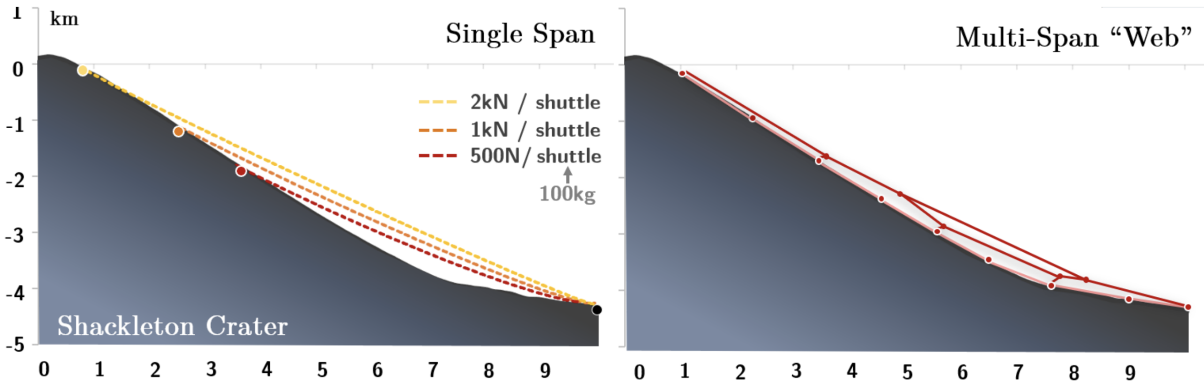


Fig. 5: Possible future implementations and inspirations for a scaled up version of LATTICE

2.6 Comparisons To Other Systems

Mobility Techniques	Rover	Hopping Lander	Compacted Regolith Road	Railroads	FLOAT	LATTICE
Focus	Exploration	Exploration	Infrastructure	Infrastructure	Hybrid	Hybrid
Payload/Mass	~10^{-1}	~10^{-1}	~10^{-1}	>1	>1	>1
Dust Disturbance	High	High	Mid	Low	Low	Low
Range [km]	20	30	8	8	>10	15
Mass / Length [kg/m]	N	N	N	> 40	1-2	1-2
Travel Speed [km/hr]	0.8	10	10+	10+	1.98	1-5
Technology Duration	100 Earth days	3 hours	Many months	Many months	Many months	Many months
Navigation of >20° slopes	No	Yes	No	No	Yes	Yes

Table 2: Comparing LATTICE to other proposed methods of lunar traversal

3 Project Description

3.1 Design Assumptions

ID	Design Assumption
[DA.1]	Land within 1 km of permanently shadowed crater rim in a location with greater than 80% illumination
[DA.2]	Commercial lander with payload capacity between 500-1000 kg (e.g. Astrobotics Griffin)
[DA.3]	Lander produces 280 W from solar power under direct illumination
[DA.4]	Limited direct support (astronauts); operable from and in communication with Earth
[DA.5]	The shuttles are pre-attached to the cable line before deployment

Table 3: Design Assumptions for LATTICE

3.2 Concept of Operations

We have scoped our engineering work for the NASA BIG Idea Challenge in terms of an early Artemis demonstration reference mission. The pathfinder mission scenario begins with a CLPS lander at the scale of Astrobotics Griffin touching down near a lunar crater rim. To set up this system, the ”stake-driver” mechanism, attached to a preexisting rover platform like Astrolab FLEX, sequentially plants stakes outside the lander and then down into the crater wall. Each stake is pre-connected to its associated span of cable. The rover is tethered to the most recently planted stake by a winch that feeds out the cable, allowing controlled rappelling into the crater. When these consumables are exhausted, a shuttle can traverse the cableway to deliver additional stakes and cables, enabling deployment at arbitrary scale. Depending on mission scenario, stakes can be designed with a varying number of junctions, producing branching and loop architectures which the shuttles may freely traverse. Each shuttle carries a payload, transporting materials and scientific instrumentation over terrain that is inaccessible to typical wheeled rovers.

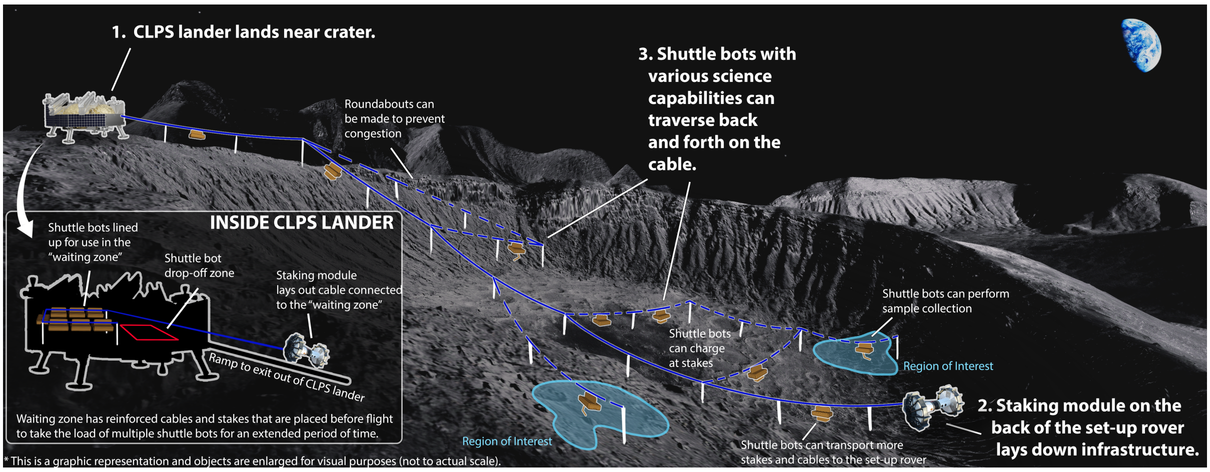


Fig. 6: Full pathfinder mission concept of operations

3.3 Concept Lifecycle

The LATTICE team adopted an Agile method of project management along with NASA project management techniques to maximize the engineering potential of our multiple undergraduate subteams and accelerate the project’s path to NASA TRL 4[16].

We split LATTICE into two phases after proposal submission. Phase 1 consisted of long-term feasibility analyses, design brainstorming and low-fidelity subsystem prototyping in preparation for the mid-project report (MPR), and identifying design requirements and engineering demonstration goals. Following the MPR, Phase 2 focused on developing the demonstration system and validating key low TRL goalposts. Weekly full team progress meetings and design review meetings with mentors and JPL/industry engineers ensured project deadlines were met while integrating external technical feedback. As undergraduate students with busy schedules, the team accelerated the pace of work on hardware between July and August 2022.

3.4 Design Evolution

We have performed verification testing in a laboratory environment and in a relevant environment (i.e., rocky hill side in Lucerne Valley), establishing TRL 4 with progress towards TRL 5. In the MPR, we proposed 100 m spans with 7.5 kN peak tension and stakes driven by a 400 kg commercially-available rover on the Moon. On Earth, a rover representative of this downforce has a 6x smaller wheelbase. Our rover—an ATRV-Jr, RWII/iRobot Mobile Robot (ATRV)—was generously provided to us by Dr. Issa Nesnas. Unfortunately, the MPR design would require shaft diameters and masses in excess of what the ATRV could stably support. For this reason, the cable flat span was reduced to 25 m, corresponding to 2 kN peak tension.

In outdoor demonstrations, LATTICE has proven to handle slopes in excess of 20°. This is constrained by available terrain and access for stake planting. Based on traction testing, we expect that the shuttle can climb vertically, and intend to demonstrate this expanded capability before the close of the competition.

While there has been some characterization of lunar regolith [17] at low latitudes during the Apollo missions, the subsurface mechanical properties of ice-embedded polar regolith are relatively unknown. We previously proposed to follow up existing work on helical piles in lunar simulant with our own stake simulant test stand [18]. However, due to regolith shipping delays and prioritizing full system integration for Earth demonstration, this work remains underway. Research indicates that anchoring is easier on the lunar surface than on Earth due to the cohesiveness of its regolith, at the cost of increased drilling effort [18]. For this reason, we have migrated towards a stake design similar to existing lunar drill technology like Trident [19]. We developed a low power, low downforce drilling system that works without percussive action in the Lucerne Valley, but expect additional percussion may improve its performance in ice-cemented regolith.

3.5 Driver Module

3.5.1 Driver Functional Requirements

Driver System Team-Derived Requirements			
ID	**Description**	**Verification Method**	**Status**
[D.1]	Elevator apply up to 300 N downforce from 1.75 m height over 0.75 m with less than 100 N friction	Testing	Completed
[D.2]	Structure reach out 300 N and 150 Nm along elevator rail length	Testing	Completed
[D.3]	Structure still allow for ATRV lid to be opened, support handoff and capstan structures	Inspection	Completed
[D.4]	Drive actuator apply more than 150 Nm torque, interface with HYTORC spline and mount to elevator carriage	Testing	Completed
[D.5]	Support 3 stakes moving with 50 N bounce, let stake slip at greater than 100 N	Testing	Completed
[D.6]	Release stake under 250 N side load	Testing	Completed
[D.7]	ATRV-Jr moves 25 m out from stake while feeding out cable	Demonstration	In Progress
[D.8]	Mate reliably with stake top, prevent stake arm rotation during driving	Inspection, Demonstration	Completed

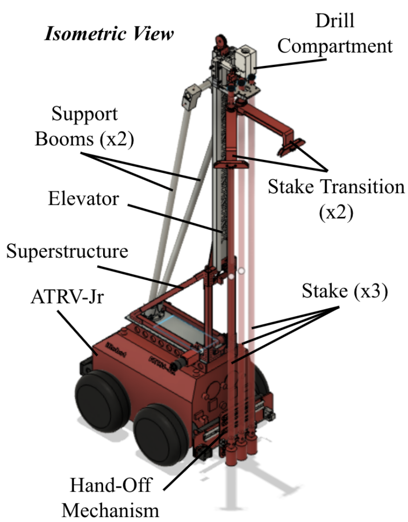


Table 4: Driver Functional Requirements

3.5.2 Superstructure Design

The structure of the elevator drill system used for LATTICE was designed to integrate with the ATRV, which is described in 3.5.6, as well as to ease the integration of the elevator structure with the rail. This structure had to withstand the weight of the elevator and driving system as well as counteract front loads and moments during stake driving. In Fig. 4, the red triangular support at the base of the elevator is the super structure.

3.5.3 Elevator Structure Design

The elevator is designed to support a linear rail with a meter of travel as well as the driver system itself, which produces up to 150 N·m moments and downforces up to 300 N in order to drive helical stakes into the ground. To withstand this moment and reaction force without creating center of mass issues, a balance between the strength and weight of the elevator's structure is required. The structure was designed with a triangular geometry as seen in Fig. 7. The linear rail supported by the elevator structure is designed to withstand up to a 550 N moment. To power the capstan mechanism, a VexPro 775 motor is hooked up to a VexPro Versa Planetary gearbox for a 400:1 reduction, allowing the capstan elevator to easily apply enough downforce through the stake driving end effector.

3.5.4 Driver Interface Design

The driver-interface is the most critical and complicated part of the driver system. It must be able to withstand the downforce and moment required to drive the stakes while being in a small form factor and interfacing with the stake hand-off mechanism and elevator structure. A COTS torque tool, a HYTORC 0.7 Lion Gun, applies up to 900 N·m of torque to the driver system. This device was stripped down to its critical components and then mounted via a reaction arm in an aluminum block with a pocket matching the shape of the reaction arm. The pocket is sealed by a 3D-printed top plate, fully enclosing the reaction arm.

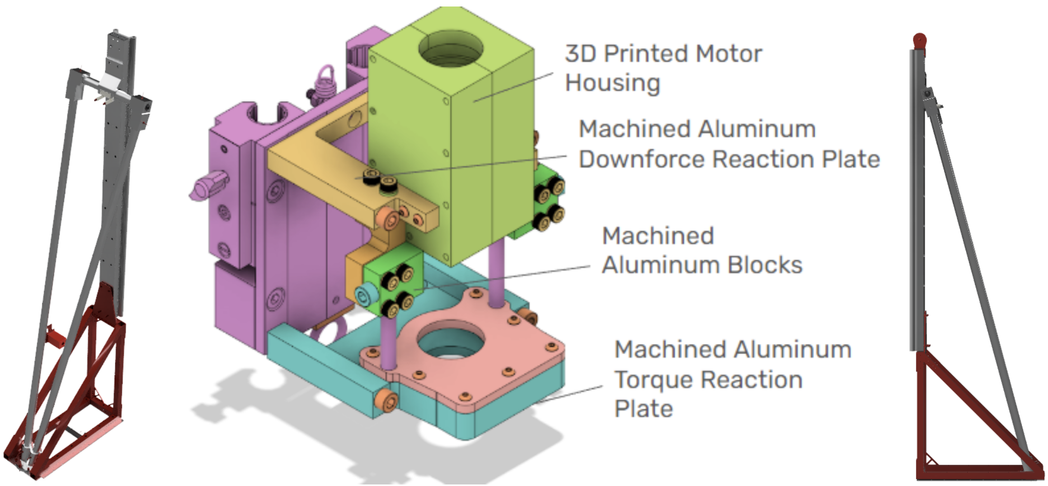


Fig. 7: Render of the entire elevator structure and the driver elevator interface

The reaction arm is mated to the HYTORC tool with a custom spline pattern and a set screw, which transfers both the downforce and moment into the driver-elevator interface. Aluminum blocks compose the structure of the system and are mounted to an IGUS linear rail carriage. In addition, 3D printed stake aligners are mounted on the aluminum plates to ensure the alignment of the stakes with the 6-point socket attached to the HYTORC tool.

3.5.5 Hand-Off Mechanism

In order for LATTICE to drive multiple stakes into the lunar surface, the development of a provisional "stake hand-off mechanism" (see Fig. 8) that aligns each stake with the driving tool is necessary. This system, in the form of a linear rail, holds three 1.75 m stakes, each weighing 2.5 kg. The stakes are held loosely enough to slip under an applied drilling load, but firm enough so the stakes do not fall under their own weight and vibration. They also must be released as the drive system moves away. After extensive custom engineering, we identified passive COTS "broom clips" that meet the design requirements.

3.5.6 Driver Development

ATRV was utilized for multiple NASA/JPL demonstrations and is able to withstand rigorous driving on steep terrain. In addition, testing has shown that ATRV can withstand the forces of the HYTORC drilling mechanism. The internal mechanisms and hardware of ATRV are

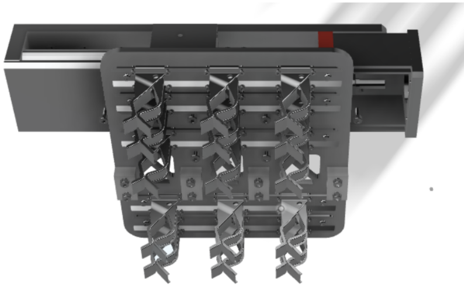


Fig. 8: Stake hand-off mechanism render

physically accessible, which has allowed the reconfiguration of many of its outdated internal electronics. The elevator mechanism has been geared low, and vents have been added for improved cooling of the HYTORC motor in the desert environment. Testing has shown that downforce from the driver elevator system may not be necessary as the 3 kg self-weight of the drill system sufficed in testing. The current design features a NEMA 23 motor with higher output torque capabilities and a double-plated clamp support module. This system—constructed in less than two months—has successfully drilled stakes in the rocky Lucerne Valley.

3.6 Cable Selection

LATTICE's cables are designed to minimize mass while handling the loads imposed by the shuttles and enduring the harsh lunar environment, including extreme temperature cycles, abrasion from lunar dust, and UV radiation [20, 21].

Krypton-D™ Polyester/Dyneema® Double Braid Rope from Pelican Rope was the best option within the engineering, budget, and time constraints of the competition. The smallest version of this rope (the ¼" diameter version) has a mass of only 30 grams per meter and is rated for a tensile strength of over 22 kN, which is an order of magnitude greater than the loads that the cables need to handle within the LATTICE system. This rope also has a braided polyester outer layer, which is highly resistant to abrasion and UV radiation.

3.7 Shuttle

3.7.1 Shuttle Functional Requirements

Shuttle System Team-Derived Requirements			
ID	**Description**	**Verification Method**	**Status**
[S.1]	200 N Drive Motor Push	Testing	Completed
[S.2]	15 cm/s Drive Motor	Testing	Completed
[S.3]	0.6 m Tension Arm Takeup (per arm)	Testing	Completed
[S.4]	Less than 1 kN "up" load on drive pulleys, less than 4 kN out load on leader pulley and arms	Analysis	Completed
[S.5]	Supply drive motors and tension arms at maximum draw for 30 minutes	Demonstration	Completed
[S.6]	Transition onto stake rail at up to 40 degree angle of approach below the horizontal	Demonstration	In Progress
[S.7]	Less than 10 degree swing on cable	Demonstration	Completed
[S.8]	Withstand 2 kN tension on cable	Testing	In Progress
[S.9]	18 kg mass (with 10% mass margin)	Inspection	Completed
[S.10]	Less than 25 cm height dimensions	Inspection	Completed
[S.11]	Less than 0.5 m droop on cable	Demonstration	Completed

Table 5: Shuttle Functional Requirements

3.7.2 Shuttle Design

Central to the utility of LATTICE, the robotic shuttle has been designed to fulfill the critical needs of long-term lunar presence: the transport of scientific, robotic, and ISRU payloads across steep cables in and out of PSRs. To meet these needs, the critical technology element of the shuttle is its ability to move along cables and traverse stakes. These mission and design objectives are answered with a novel, adaptive pulley mobility and tensioning solution mounted on a lightweight truss structure with a modular rail mount for payloads up to 80 kg. A notional design of this robot is shown in Fig 9.

The prototype shuttle's supporting structure is designed to allow easy access to supportive hardware and withstand several loads, including a 900 N·m moment at the tension arms, up to 4 kN on the leader pulleys and arms, and up to 1 kN on the drive pulleys. The internal and external interference refers to possible interference of the tension arm and stake drive interface, respectively, against the shuttle. To handle these constraints, a truss structure composed of carbon fiber tubes is utilized as seen in Fig. 9.

Fig. 9: Shuttle Renders (front and back isometric views)

The motion of the shuttle has three parts: cable take-up and tensioning, cable traversal, and stake-cable transition. Cable take-up and tensioning is achieved by two high torque (900 N·m each) rotating arms that wrap free cable around the leader pulleys. The central drive pulleys work alongside the leader pulleys to propel the shuttle, maintaining fault-tolerant control authority at all stages of cable tension and stake transitioning.

The tension arm is under significant load—structurally similar to an Olympic-standard bike pedal, but experiencing forces five times as large. To minimize mass under torsion and biased moment loading, a hollow beam structure was created with a 7075 aluminum core and stiffening hardened steel flanges. The stiffer steel displayed excellent resistance to loads and deformation. As seen in Fig. 10, peak deformation was observed near the pulleys, which would be reinforced with hardened steel.

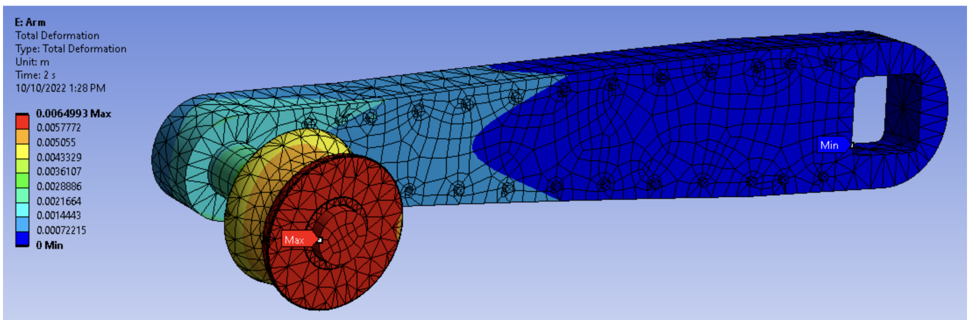


Fig. 10: Deformation chart of tensioning arm with ideal 4 kN loaded tension from the cable

Any reasonably sized aluminum interface would be unable to transmit these high torques to the tension arm without failure. Instead, a hardened steel interface insert was used to distribute contact loads. The final design successfully reduced stresses to only 110 kPa, equivalent to a 5x safety factor in a 500 g housing.

In order to traverse a system that holds up the cable at multiple points in its path, the shuttle must lose contact with the cable at each stake. A schematic of the shuttle transitioning over the stake can be found in Fig. 11.

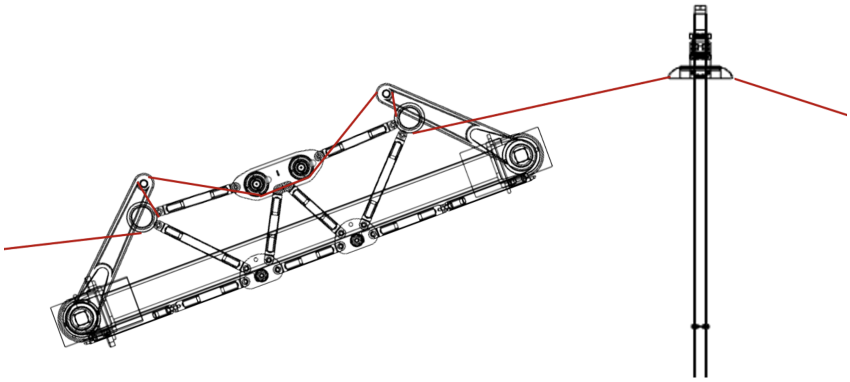


Fig. 11: Schematic of the shuttle approaching the cable for a stake transition

To tackle this issue, we designed a stake rail (Fig. 27 in Appendix) to act as a guiding rack on the stake top. Gears on the drive pulleys engage with the rack as the shuttle pulleys lose contact with the cable, allowing the shuttle to climb onto the stake top. This is designed to function under a range of operational angles of approach, described in the shuttle functional requirements.

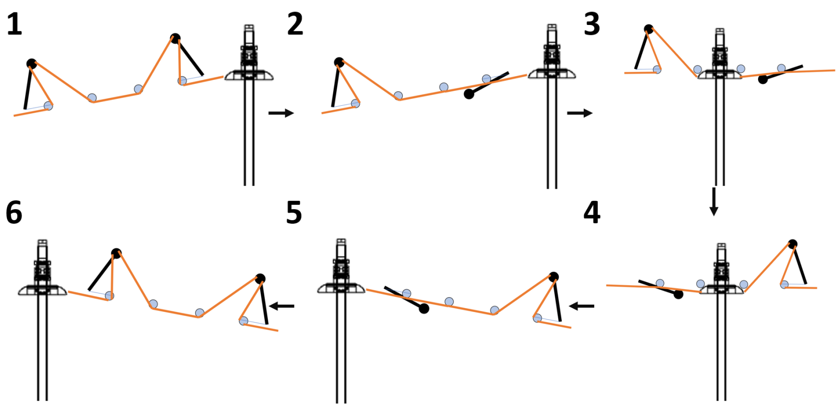
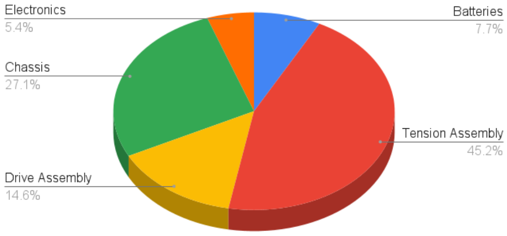


Fig. 12: Diagram breaking down the steps of a stake transition

Operationally speaking, for the shuttle to cross the stake rail, the front arm must be lowered while maintaining constant tension. To do this, the trailing arm takes up the added slack from the disengaging front arm. Once the front arm has cleared the rack, it re-extends, allowing the back arm to lower and clear the rack while the front arm now picks up the slack and the shuttle rolls off the rack. The specific logic and sensors utilized for this stake traversal are described in Section 3.7.4.

The shuttle mass is 18.5 kg without payload, producing an effective weight in excess of a 20 kg shuttle with 80 kg of payload on the Moon, factoring ground clearance. The shuttle is designed to carry a fully laden RASSOR rover (80 kg) [22], or any other bulk regolith, robotic payloads or instruments. The current power system for the shuttle has been designed and tested to last 40 minutes on a single charge, to traverse 200 m of cable in the technology demonstration. The mass and power breakdowns are below in Table. 6.



Item	Quantity	Power of each	Duty Cycle over an Hour	Resulting Power	Description
Arm Motors	2	290 W	0.033	19 W	For providing 900 Nm of torque
Arm Brakes	2	5 W	0.28	2.8 W	To stop arms from moving
Motion Motors	4	24 W	0.31	30 W	To move the shuttle on cable
Total Power				52 W	

Table 6: Mass and power breakdowns of the entire shuttle

Actuators were a significant driver of shuttle mass, since the arms needed to produce up to 900 N·m of torque to clear the ground, and increased torques required heavier actuators. This motivated the use of deconstructed HYTORC nut drivers as actuators, as their torque mass density is 4x that of any other known COTS option. Future iterations of the shuttle are expected to reduce tensioning system mass by a factor of 4 by tensioning cables while supported by the stake and locking the tensioning arms during stake transition.

3.7.3 Shuttle Development

Shuttle material was chosen by prioritizing implementability and weight reduction without compromising on rigidity, mechanical, or thermal performance. Hence, the skeleton of the shuttle is composed of carbon fiber tubes joined together by aluminum brackets. Mounted to the stiff skeleton are aluminum tensioning arms, which have steel inserts at high-stress areas to handle the 4 kN tension with minimal deformation and a 2x safety factor. Oppositely, low-stress areas like electronics enclosures were FDM 3D printed from high-temperature plastics to further reduce weight without deforming under >110 °F worst case testing conditions at Lucerne Valley.

Several design improvements have been made to the shuttle over its three prototype stages (20 N Lego, 200 N MDF, 2 kN final). After extensive design morphology mapping, a rotary cable tensioning method was selected. Two sets of leader pulleys were added to decouple the cable taken up by each side of the shuttle, meaning that the amount of cable taken up by a single side of the shuttle is not affected by the cable on the other side which was present in the previous design. This allows the shuttle to be stable when transitioning between taking up cable with both arms to a single arm when moving over a stake for the stake transition. The placement of the motors and payload has also been changed to improve the shuttle's stability. The number of Maxon Motors was increased from two to four for operational flexibility during tensing and to increase redundancy while driving the leader pulleys. This increases cable traction available to the shuttle as it approaches the stake.

3.7.4 Electronics & State Machines

All of the Earth demo systems are controlled using the Arduino Due. The Due was chosen for its versatility and ability to interface with various components, facilitating the addition of other sensors and components as needed in the future.

Aftermarket ESC's capable of sensorless operation were used to drive the original brushless motors of the HYTORC drill, allowing the built-in Hall effect sensors to be used as encoders. These drills are used in the driver system for the purpose of stake driving and in the shuttle system for the tensioning arms. In addition, the proprietary electronics in the ATRV were replaced with more modern components suitable for Arduino. The stake hand-off mechanism, driven by a single stepper motor, is facilitated through the implementation of a state machine, as seen in Fig. 23 in the Appendix.

Once a stake is in place and the ATRV has driven away, the stake hand-off procedure is triggered which brings the next stake in position for subsequent drilling.

Originally, the elevator was designed to apply 250N of downforce. It was found, however, through testing at Lucerne that the stake auger is capable of pulling itself into the ground while drilling. This means that no external means of downforce application is necessary as the combination of gravitational force and the auger's self-generated downforce is capable of completely driving the stake into the ground. Thus, to fully mitigate the risk of burning out the elevator from running it at stall, the elevator now only serves to raise the drill to load another stake.

For the shuttle, individual motor controllers were used to drive both the tensioning and driving motors. Additionally, relays were implemented to engage brakes retrofitted onto the HYTORC gearboxes to lock tension arm positions, allowing a specific position for the arms to be set and maintained. The sensor setup on the shuttle includes limit switches to determine arm positions and a Hall effect sensor to detect a magnet on the center of the stake rail. A full wiring diagram of the shuttle is shown in Fig. 13. In the Appendix, a state machine is included showing the method in which constant take up drive, arm transition, and stake transition is achieved.

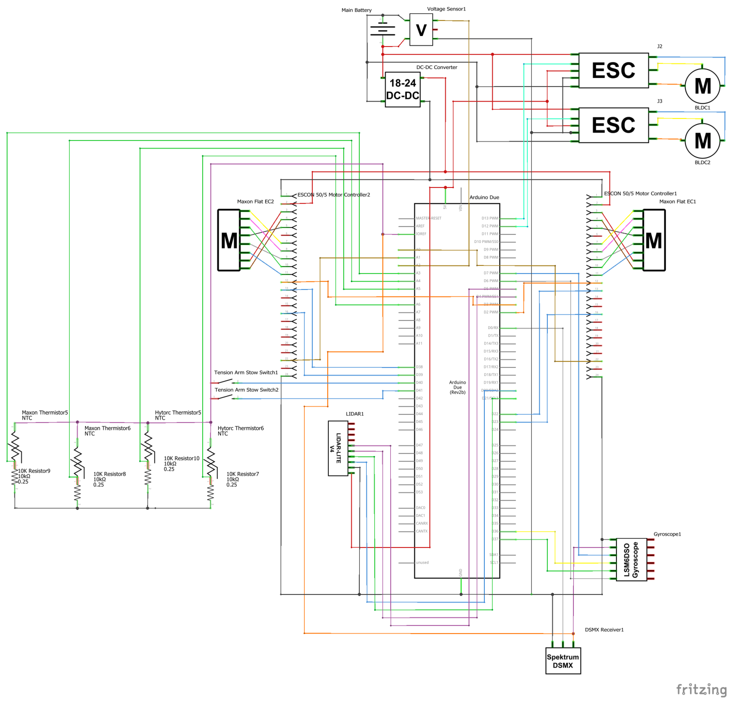


Fig. 13: Complete wiring diagram of the shuttle

3.8 Stake

3.8.1 Stake Functional Requirements

Stake System Team-Derived Requirements			
ID	**Description**	**Verification Method**	**Status**
[K.1]	Less than 3 kg mass (with 10% mass margin)	Inspection	Completed
[K.2]	Driver interface, transmit 300 Nm torque with ¾" hex	Testing	Completed
[K.3]	Driver interface, detach with <250N "upforce"	Testing	Completed
[K.4]	Stake rail, mount to stake body with free rotation before manual rotation lock (100 Nm); <27.5 cm length	Testing	Completed
[K.5]	Stake body withstand 2500 N side load at 1.25 m from anchor surface (Lucerne Valley dirt)	Testing	Completed
[K.6]	Stake body maximum 3.175 cm diameter, 1.75 m length	Inspection	Completed
[K.7]	Auger diameter less than 6 cm	Inspection	Completed
[K.8]	Auger reach depth of 0.75 cm with less than 300 N downforce and less than 100 Nm torque	Testing	Completed

Table 7: Stake Functional Requirements

3.9 Stake Development

The LATTICE prototype uses stakes made of titanium, with a minimum height above ground of 1 m, and a maximum plant depth of 0.75 m (1.75 m length), weighing around 2.5 kg (Fig. 26 in Appendix. The stake design began in reference to helical augers used on Earth, but we identified that large helical blades significantly increase driving down force and torque requirements without adding resistance to lateral loads. A key functionality of the stake design in an uncertain environment is backdrivability. After extensive testing of over 15 COTS augers and drills in the Lucerne valley, we settled on a 3 cm diameter custom helical auger tip that is backdrivable and tailored to our low-power rotary driving scheme.

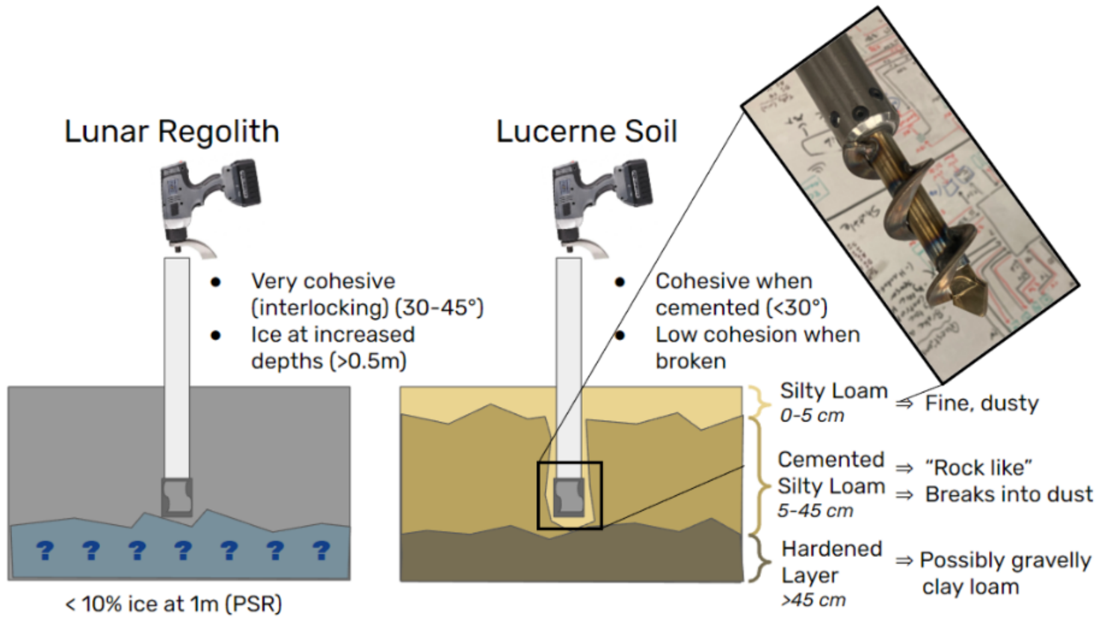


Fig. 14: Left: Stake in Lunar regolith. Right: Stake in Lucerne test site dirt

The highest tension experienced by the stake—2 kN—occurs when the shuttle is directly between two stakes. To minimize mass and maximize lifetime under these loads, we selected titanium shafts with an outer diameter of 31.75 mm and a wall thickness of 3.175 mm. These exceed the strength requirements by a factor of 5, while each stake shaft is only 1.5 kg.

To design the stakes and assess deflection under load in demonstration and lunar implementations, we used LPile, a soil simulation software. LPile [23] uses a p-y simulation, treating soil as a non-linear spring at each point along its length. LPile simulations showed that for regolith and similar soils, the soil is more than strong enough for the 2 kN force we are applying at depths exceeding 50 cm. For an infinitely strong rod at 50 cm depth, the modelled soil deforms 2 cm at the surface under our target load. For an elastic stake under load, the stake primarily bends in the upper 0-20 cm of soil—deep below the ground the soil is strong enough to support the stake under cyclic load. Above the ground, the stake is at a nearly constant angle. In the tens of tests ran with 0.5–5 in diameter stakes near the Caltech campus and the Lucerne Valley, we consistently found that real stakes outperform the LPile predictions for our measured soil parameters. Simulations of bearing capacity of even conservative polar lunar regolith (30° angles of internal friction) predict better stake stability at depth on the Moon than in Lucerne Valley. Future work is needed to assess limitations in stake stability on slopes whose surface is near angle of repose.

4 Verification Testing on Earth

4.1 Verification Testing at Lucerne Valley

The primary testing of the driver system was conducted in Lucerne Valley. Initial testing of manual stake drilling (Figure 25 in Appendix) revealed several system challenges: high drill torque requirements and driver downforce, which impact stake driving depth, and thus the stability of the stake under load. Environmental challenges included clumped, rocky soil and electronic shutdown of the ATRV under significant sun exposure and high temperatures above 38℃. These challenges informed the scope and design decisions of our final system, including drill motor selection, elevator design, and stake material selection. From LPile simulations and further manual testing [23], we concluded that the 100 cm depth in our MPR was not necessary as the soil strength was higher than our loading conditions.

A driver subsystem test conducted on October 19th, 2022 successfully verified stake driving to a depth of 70 cm into compact, sandy soil with no additional downforce applied by the driver. At this depth, the stake withstood transverse loading of over 2.54 kN at the base, which is greater than our highest expected load of 2.0 kN, with little deflection and no plastic deformation.

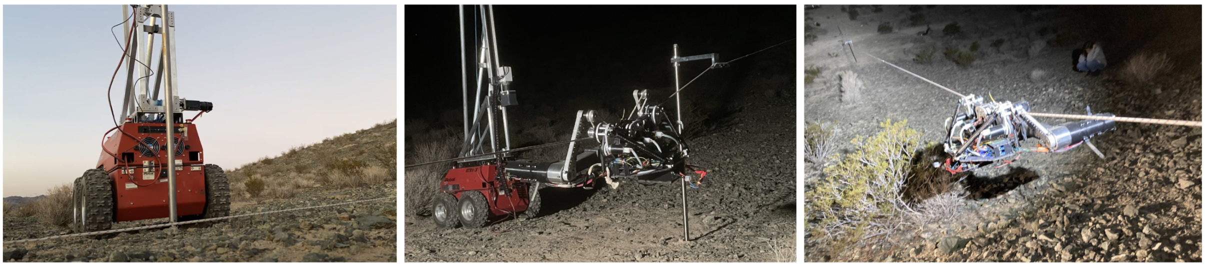


Fig. 15: Verification testing at Lucerne Valley

4.2 Shuttle Verification Testing

A shuttle test stand was built to test shuttle tensioning capabilities and stake transition. A span of cable over 20 m long is secured to support structures of a former hydrodynamic flume. Within the flume (Fig. 16), we can safely perform high-tension shuttle tests. Testing has allowed for progressively loading higher tensions and identifying causes of failures. The shuttle has also demonstrated a successful stake transition in the flume, thus traversing a major challenge we envisioned in making LATTICE.

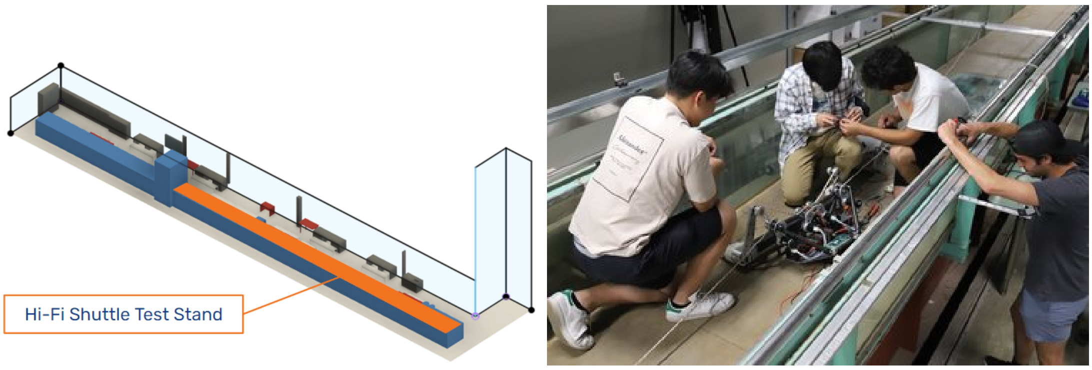


Fig. 16: Left: CAD of shuttle test stand in the lab. Right: Shuttle testing in the flume

On October 18th, 2022, a combined subsystem test of the shuttle on a cable span between stakes was conducted in Lucerne Valley. The driver successfully planted two stakes at the base of a smaller hill bordering Peterman Hill (permission and fresh plums granted by the landowner, Donna Betz) with depths ranging from 65-75 cm. One end of the cable was tied to the first stake and fastened to the second stake with a crane scale to measure cable tension. To control initial slack and release tension under shuttle failure, the other end of the cable was secured by a cable winch—mounted on a simulated lander at the top of the hill. The cable path spanned 60–65 m and covered about 18.5 m of elevation. This section of Peterman Hill had a slope of 20.1°. The shuttle demonstrated tensioning up to 750 N, cable traversal on the incline with external tension, and the ability to ride off of the stake rail. Despite an arm mount deforming at 750 N that prevented an outdoor stake transition (since fixed), this test demonstrated the majority of LATTICE's key functionalities: driving stakes, tensioning on the cable, maintaining traction while riding on the cable, and interfacing with the stake rail.

4.3 Future Testing Plans

Since the breadboard prototype models of the shuttle, stakes, and driver systems have demonstrated their key functionalities in the shuttle test stand—a laboratory environment—and at Lucerne Valley—a relevant environment—LATTICE has demonstrated successful completion of TRL 4 and significant progress towards TRL 5.

To get LATTICE to TRL 5, near term testing goals include full one-shot verification of the system in Lucerne Valley and verification of the driver and stake systems in ice-enriched lunar simulant. Performance in these simulants are critical for a proper implementation on the Moon.

Full system verification at Lucerne Valley consists of a continuous setup and deployment of LATTICE and is set to take place before the competition forum. The driver will place three stakes, utilizing the hand off subsystem to load the stakes. The shuttle will then be set up on the cable and autonomously traverse down and back up the hill, performing a stake transition between the first two stakes. This demonstration would show the brassboard model of LATTICE completing all of its major functions in a relevant environment.

Long-term effectiveness testing and cyclical loading of stakes was unable to be completed due to time constraints. A stake test stand (Fig 17), to examine cyclical loading and soil strength, was built with a pneumatic cylinder to precisely apply high transverse loads. Lunar Highland Simulant 1 (LHS-1) was determined to be most like the expected soil conditions in and around lunar craters in terms of abrasion and cohesiveness. We have received 500kg of LHS-1, but delivery was delayed two months due to large orders by Blue Origin. We therefore prioritized stake system integration for the demonstration over simulant testing. Successful verification of drilling and load bearing in our newly received lunar simulant would help demonstrate the feasibility of LATTICE in a lunar environment.

Fig. 17: CAD model of Stake Test Stand

Due to long lead times for cable materials, it was not feasible to conduct the cable material selection testing mentioned in the proposal. To improve the cable's outer layer, several different outer layer materials should be tested for their friction properties and abrasion resistance. Bending fatigue tests should also be done to select an ideal cable core material. Cyclic bend over sheave (CBOS) tests are commonly used to determine the number of bending cycles a cable will last before failure. However, most companies that run these tests do not publish their results, so it is not possible to find CBOS data for cables under loads similar to those applied by LATTICE shuttles. Running CBOS tests to simulate many cycles of shuttles traversing the cables should be performed to verify the lifespan of the cables.

Other future testing would include testing subsystems and system integration in a simulated lunar environment to verify system consistency and durability. This would examine cable longevity, performance under temperature extremes, vibration testing, and vacuum testing, among other environmental variables to verify successful implementation on the Moon.

5 Safety Plan

At various points during the project, our team evaluated potential hazards and their severity, mitigation, and response. These are outlined in the table below.

Hazard	Description	Mitigation	Response	Concern
Tensioned Cable Failure	At high tension, cable failure can cause injury.	A cable with 10x that of the stress conditions expected was picked out to ensure the cable never exceeds its maximum rated load. Additionally team members are instructed to stand clear of the cable and wear eye protection. In the lab, there is plastic shielding around the test stand.	Conduct first aid care on injured individual and call for medical assistance as necessary.	D, IV
Tool Injury	Injury from use of power tools or other machinery in the laboratory or machine shop.	Safety training and proper personal protective equipment (PPE) is required to operate equipment.	Conduct first aid care on injured individuals and call for medical assistance as necessary.	D, IV
Heat Fatigue	Possible hazard for personnel during testing and demonstration in Lucerne Valley, CA, where temperatures often reach over 100 °F.	Tents, canopies, water, snacks, and first aid supplies are brought for all trips.	Those testing in Lucerne Valley all went through proper heat training and each is given a guide on early identification and care of heat related illness.	D, III
Manufacture Debris Contamination	Debris during the manufacturing process (metal shards, carbon fiber dust, etc.) can contaminate the workplace and pose a hazard to personnel.	Appropriate PPE, including face and eye coverings and respirators, are required while working in hazardous environments, especially when using epoxy and cutting carbon fiber.	Evacuate contaminated areas and remove contamination from the area.	C, II
Contracting COVID-19	Contracting COVID-19 or other illnesses pose a threat to the individual's health and the health of other personnel.	Ensure that local and institute guidelines regarding masking policies are followed while working and engage in biweekly surveillance testing.	Quarantine infected individuals and ensure all team members conduct biweekly testing.	E, II

Continued on next page

Table 8 – continued from previous page

Hazard	Description	Mitigation	Response	Concern
Electronics Causing Fire	There is the possibility of overheating and/or shorting the circuit and causing fire.	Ensure that all circuits are wired correctly and that only the proper/rated voltage and current is applied to them. Ensure a fire extinguisher rated for electronic fires is always within reach.	Immediately remove or shut down the power source and put out fire as necessary.	D, II
Serious Systems Malfunctions	A serious malfunction resulting in unexpected behavior, poses danger to personnel handling them.	All personnel are required to clear the testing area when system is being tested. Ensure that power is off before handling systems and wear proper PPE.	Immediately remove the source of power from the system, conduct first aid care on injured individuals, and call for medical assistance as necessary.	D, III
Failure of Test Stand Supports	Structural support failure in the testing flume may pose danger to personnel working there at the time.	Ensure all load-bearing structures are properly rated and evaluated by the laboratory safety officer and can perform under worst case scenario loading conditions.	Conduct first aid care on injured individuals and call for medical assistance as necessary.	E, IV
Electrocution by Electronics	High currents and voltages in our subsystems can pose a hazard to personnel.	Ensure that all circuits are wired correctly and that only the proper/rated voltage and current is applied to them. Those responsible for electronics must make sure no exposed wires are present before system power-up.	Conduct first aid care on injured individuals and call for medical assistance as necessary.	E, III

Table 8: Personnel Hazard Analysis

	Hazard Level				
Probability	**Severity**				
	Negligible/No Injury (I)	Minor Injury (II)	Moderate Injury (III)	Significant Injury(IV)	Severe/Life Threatening (V)
Expected (A)					
Likely (B)					
Possible (C)					
Unlikely (D)					
Very Unlikely (E)					

Table 9: Hazard Risk Index

6 Path-to-Flight

Despite the scale and complexity of operations inherent in the full-scale LATTICE mission concept described above, key subsystems are able to leverage both future flight analogs and heritage technology to improve flight readiness of the final product. With design development, proof-of-concept, and verification testing in the past few months, the LATTICE team brought several individual subsystems and the small-scale concept demonstration to TRL 4. The operational requirements for autonomously establishing stake and cabling infrastructure to transport a 400 kg payload out of a lunar crater are detailed below. The key subsystems operating in LATTICE are the driver, the shuttle, and the stake-and-cable infrastructure. All individual components in these subsystems are subject to launch vibroacoustic loads, temperature extremes, radiation, and lunar dust [24, 25, 26, 27, 28].

6.1 Driver

When introducing LATTICE to the lunar surface, two primary functionalities are the driver robot's off-road capabilities and the reliability of the stake-planting mechanism. While the rover itself will be based on existing designs with proven capabilities and space-ready hardware, the novel driving mechanism subsystem needs to be fully tested. We descoped implementation of a winch rappelling system for the LATTICE system demonstration to prioritize key technology drivers, but this is required to deliver LATTICE on a truly steep slope. Similar future work is neccessary to hand reload the driver system with stake and cable magazines, and the internal mechanisms to carry and deploy tens of stakes on the driver. To ensure that stakes can be reliably placed on the lunar surface, reliability testing remains a primary concern. Current test conditions include repeated stake-placement procedures in the Lucerne Valley environment and cable tensioning to stakes in a controlled lab environment. However, with further funding and budget, testing in icy lunar simulant will better represent real-time conditions that the driver mechanism will be expected to face on the lunar surface over the course of its lifetime. These tests will additionally include better representations of how deep the stakes may be able to be planted into the lunar surface, providing a better viewpoint into the limitations and capabilities of the system. Upon completion of these tests, additional modifications and designs will be implemented which may include improved sensors to detect placement status, assistance mechanisms to increase downforce, and drill changes to augment stake-driving capabilities. Another area of future study is micrometoroid bombardment, mitigating which may require cable designs like the Hoytether.

6.2 Shuttle

The shuttles traversing the LATTICE network have successfully demonstrated a novel cable tensioning and transfer mechanism and have undergone extensive integration verification in simulated tests. Full mobility capabilities including consistent power transfer between the motor and cable, braking, and a feasible transition between the cable-stake interface have been tested in controlled environments. The shuttle is currently undergoing additional testing to ensure the consistency of these mechanisms on slopes and the shuttles long-term reliability after being exposed to the lunar environment and abrasive lunar regolith.

While we prioritised carbon fibre due to limited access to machining and implementation challenges in Earth gravity, a lunar shuttle would likely be better off built out of aluminum, high performance plastics, or titanium. We are confident that this can be done in a similar mass budget with the design takeaways we have made in the V1 developed here.

Due to time and budget constraints, a Warm Electronics Box was not prioritized for the shuttle. Excepting engineering work for a PSR, thermal management in the lunar environment is a high TRL technology, and the electronics on the shuttle do not have any unique thermal needs.

6.3 Stakes and Cables

With the wide variety of surface conditions and textures on the surface of the moon, the LATTICE system has been primarily designed for operations in and around craters that will likely be locations for near-future lunar missions. As a result, the stake augers presented thus far are those that have been optimized for readily-accessible Earth-based environments that best emulate certain aspects of the lunar regolith during the stake deployment process. To guarantee reliability of the current stake design during a lunar mission, additional testing of stake augers and materials will be conducted in lunar simulant. This will also provide the opportunities to perform additional environmental stress tests that will certify the stakes will be capable of withstanding the regular wear-and-tear of a lunar environment for extended periods of time.

To reduce complexity, the stakes will be deployed with the cable interfaces already engaged. Additional stress testing will be performed to verify integrity of the connections and possible failure points with consistent use and strain. These will additionally be subject to lunar regolith and its abrasive qualities to demonstrate cable resiliency and develop a maintenance regimen if excessive cable wear is observed during the life of the system.

Before sending LATTICE to the Moon, a custom outer layer would be designed for the cable. Most commercially available cables with braided outer layers allow the outer layer to freely slip against the inner layer, which decreases the traction available to shuttle robots. Designing a custom outer layer that tightly attaches to the inner core of the cable would solve this problem. Companies specializing in custom engineering cables, such as Falmat Custom Cable Technologies and Cortland, have created similar designs in the past for extreme environment applications, so designing such an outer layer is not out of scope for a full deployment of LATTICE.

6.4 Autonomy

In the lunar environment, LATTICE will ideally be almost fully autonomous from the placement of stakes to the operation of the shuttle. Currently, the shuttle is primarily manually controlled with ongoing testing and work on implementing a semi-autonomous control scheme for traversing the stakes and cable. Future work would include integrating more sensors to carry out fully autonomous shuttle operation: active terrain avoidance to avoid possible obstacles, failure mitigation to reduce risk of issues like over tensioning or falling off of the cable, and coordinating a swarm of shuttles in a network to optimize the rate and amount of payload moved in a given time frame.

Additional work has been done to simulate and optimize the placement and parameters of stakes, verified key questions of deployment feasibility in a lunar crater. The optimization generates millions of potential paths for various sets of system parameters. With these system constraints alongside a unified stake and cable mass cost function, our method helps determine the optimal system parameters for any given mission's topography map, whether minimum mass or maximum operational flexibility.

We have used these methods to assess the feasibility of a LATTICE mission scenario at Shackleton Crater using high-resolution topographic data provided by LOLA, using Djikstra's algorithm / A* to find the shortest path on a pre-constructed graph of valid stake placements. The site was chosen as a 'worst case' due to its high slopes and long descent. Preliminary results demonstrate the feasibility of our initial system parameters and revealed the feasibility of fewer, shorter, stakes than anticipated such as 500 m spans with 0.05 m ground clearance, shown below. The analysis is pending additional constraints based on set-up rover traversability, shuttles, stake angles, and other parameters.

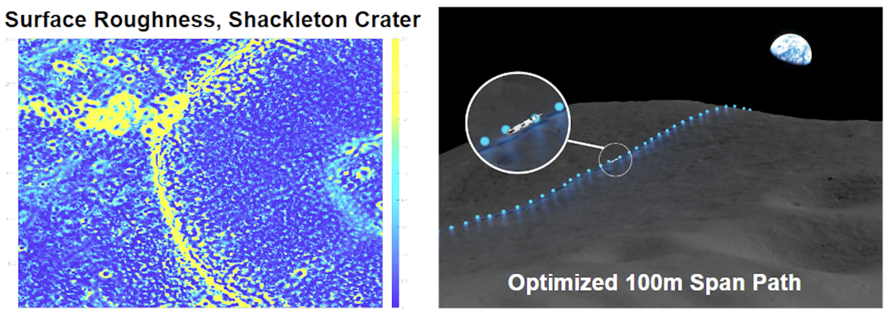


Fig. 18: Optimal path into Shackleton Crater with a 0.5 m ground clearance path and 100 m spans into Shackleton crater visualized (Saturn V for scale).

We have used these reference mission paths to simulate shuttle traversal and spec operational power draw requirements on the Moon. Continuing to explore and develop these algorithms will allow set up rovers to autonomously and effectively plant LATTICE so that it is optimized to best handle extreme lunar terrain.

6.5 Risk Management

Due to the complexity of infrastructure establishment and uncertainty in lunar surface properties and obstacles, system-level LATTICE operational risks will be high. Technology involving rover navigation, deployment and terrain evaluation has substantial heritage with Mars vehicles, but semi-autonomous and autonomous navigation in the Shackleton crater, as well as the success of the cable-staking system in a variety of lunar terrains, will be key to the success of the mission. There are many advantages to developing and maintaining a more permanent lunar infrastructure system. Although there is a theoretical limit of 80 kg on the Moon with the current system, with the addition of guy wires, hollow stakes, or manta anchors, LATTICE scales economically to payloads of 400 kg.

Risk Factor	Risk Rating and Mitigation Technique	
Failure of shuttle in the middle of a cable	Shuttle can be removed from cable by another shuttle	2, 2
Shuttle falls off cable	Shuttle winch	2, 1
Stake falls over or breaks	Increase depth of staking, Safety factors	4, 2
Cable breaks	Parallel cable placement	5, 1
Resistive losses through the cable	Only radiative cooling and some conduction, Sheath improvement	1, 5
Thermal fluctuation with sunlight	Addition of sunlight shielding along stakes or in lander to improve thermal dissipation	2, 5
Radiation	Radiation hardware chips for reboot/communication, Redundancy on shuttle electronics.	3, 5
Cable/stakes posing obstacle to other rovers	Ensure visibility of guy wires	1, 2
Soil is too hard/soft	Improve autonomous navigation, Upgrade manta anchor	4, 3
Large boulders in the way	Landing site & path selection, Taller stakes	4, 3
Cable stretch over time	Shuttle tensioning	2, 3

Table 10: Risk Assessment Chart

Furthermore, cabling infrastructure will be more resilient to communication or electronics failure than a typical rover, as it provides a low-complexity mechanical method of navigation and hauling. A risk mitigation table below details areas in need of further design before flight readiness. The greatest challenge will be redundancy for stake and cable failure.

6.6 Future Work

The team is set to further develop the LATTICE concept after the BIG Idea Challenge and is actively pursuing avenues for future research. Further research and development would target the questions addressed in this section, in addition to architectural level optimization and engineering of LATTICE at large scale. The team is also pursuing industry partnerships, graduate student and faculty involvement, and CLPS mission calls.

7 Conclusion

LATTICE has demonstrated a successful mode of terrain-agnostic locomotion utilizing a self-tensioning shuttle traversing a stake-supported cableway. This demonstration offers a window into the future of extreme terrain exploration and the infrastructure necessary for a reliable and efficient means of ISRU on the lunar surface. Laboratory verification and on-site testing at Lucerne Valley have shown the feasibility of the essential elements of LATTICE: the setup of stakes in variable terrain using a set-up rover and the shuttle's ability to repeatedly transition between cable and stake rails, take up cable slack, as well as traverse cables at angles greater than 20°. LATTICE has successfully demonstrated a novel cable tensioning and transfer mechanism, which will be critical to the efficient movement of payloads across the Moon.

Long-term effectiveness testing, which is ongoing, will further demonstrate the capabilities of LATTICE for extended use. The results of this challenge are promising as LATTICE's scalability and modularity provide a key utility in to establishment of extended human habitation and activity on the lunar surface for the NASA Artemis III mission and beyond. Through the verification program, we have demonstrated that LATTICE has met the functional requirements outlined in this project and can be a long-lived robotic infrastructure and exploration system for extreme lunar terrain.

8 Detailed Timeline

Item	Date(s)	Description
First Team Meeting	11/14/21	Team met to discuss the 2022 BIG Idea Challenge and possible proposals
Notice of Intent Submission	9/24/21	Team submitted notice of intent
Concept Brainstorming	11/14/21 - 1/20/22	Brainstormed possibility of cabled transportation, LATTICE
Concept Design Review	1/20/22 - 1/28/22	Reviewed early design, system architecture and LATTICE mission concept with Caltech and JPL mentors
Proposal Submission	1/28/22	Team submitted proposal for LATTICE
Team Notified of Selection	2/24/22	LATTICE proposal accepted, $180k granted
Phase 1 Design Brainstorming	2/24/22 - 4/30/22	Brainstorming possible architecture for self-tensioning shuttle, extended cable system, driver mechanism. Established lab.
Phase 1 Low-Fidelity Prototype	4/30/22 - 5/24/22	LEGO prototype along string to demonstrate proof-of-concept of self-tensioning arms, overall structure of shuttle robot. Evaluated lunar deployment feasibility on Shackleton DEMs.
Mid-Project Report	5/24/22	Submitted Mid-Project Report to BIG Idea Panel
Team Notified of Pass Status	6/9/22	Team notified of passing status, second installment of funding
Phase 2 Design Brainstorming	5/24/22 - 6/12/22	Stake, Driver, Shuttle Redesign, ATRV-Jr Rover gifted by JPL
Phase 2 Mid-Fidelity Prototype Design/Testing	6/22/22 - 7/5/2022	Plywood/3D printed model of shuttle and stake transitions used to test self-tensioning on final cable. Mid-fi (steel pipe, COTS auger) stake testing in Lucerne Valley. ATRV Reverse Engineering
Phase 2 Design Review	7/6/22	Presented Phase 2 work to Caltech and JPL faculty advisors
Phase 2 Research/Testing	6/12/22 - 8/25/22	Research on self-tensioning physics, auger designs, and ATRV driving; tested stake transition, auger performance
Phase 2 Design Finalized/FEA Conducted	8/8/22 - 9/9/22	Shuttle components/assemblies finalized, FEA conducted, BOM created; driver system assembly finalized/integration completed, FEA conducted, BOM created; stake custom auger design completed
Team Critical Design Review	8/16/22	Full team presented design of subsystems and logistics to Caltech/JPL faculty advisors
Phase 2 Manufacturing	8/25/22 - 10/7/22	In/out-of-house manufacturing conducted for all subsystems
Phase 2 Assembly	8/29/22 - 10/7/22	Manufactured/COTS components assembled for all subsystems
Flume Verification Testing	10/10/22 - 10/14/22	Shuttle and stake transition tested in flume

Continued on next page

Table 11 – continued from previous page

Item	Date(s)	Description
Full System Dry-Run Test	10/15/22 - 10/16/22	All subsystems completed and fully integrated, full-scale execution of technology demonstration conducted in Lucerne Valley, CA
Technology Demonstration	10/22/22 - 10/23/22	Full scale system operating and videotaped for technology demonstration video
Technical Paper and Verification Demonstration	10/24/22	Final technical paper and technology demonstration video due to NASA BIG Idea Challenge Panel for final review
System Acceptance Review	10/31/22	Final system acceptance review with Caltech and JPL faculty advisors
Presentation and Poster Submission	11/13/22	Submission of final presentation and poster due to NASA BIG Idea Challenge Panel
BIG Idea Forum	1/14/22 - 11/17/22	Presentation of LATTICE at BIG Idea Forum and culmination of 2022 NASA BIG Idea Challenge
SciTech Conference	1/23/23 - 1/27/23	Presentation of the LATTICE paper at the AIAA International Student Conference

Table 11: Detailed Project Timeline

9 Detailed Budget

An overview of LATTICE's budgetary plan is outlined in Fig. 12. The largest change from our proposal is the increased cost of Student Research Fellowships. Twelve full-time 10-week student summer research positions were created through the Caltech SURF program to meet the significant work necessary to model, machine, assemble, and test LATTICE. In addition, the complexity of the LATTICE system called for six additional Freshman Summer Research Institute (FSRI) students to join the team and eleven team members were hired as "LATTICE Scholars" throughout September after the close of the SURF and FSRI programs. Because we were informed of our Finalist status after the SURF deadline, the SURF office was only able to cover half of the support we had expected. This and the additional cost of the LATTICE Scholars increased our personnel costs by more than $30k.

Categories	Spending	
Hardware	$	45,217.11
Lab equipment	$	11,249.67
Travel	$	3,990.22
Student Research Fellowships	$	66,591.43
Project Organization	$	1,585.49
Administrative Charge	$	33,263.80
Potential Costs	$	30,000.00
Total	$	191,897.72

Table 12: LATTICE budget breakdown

The budget requirements of the testing category have been incorporated into the hardware and lab equipment categories as our needs and constraints evolved with time. Our combined initial testing and hardware costs came to a total of $45k. Travel costs consist of gas and equipment for our 10 testing trips to Lucerne Valley. Project organizational costs totaled around $5k, which was used for funding for team meetings, team building events, and organizational software licenses (Jira and Confluence), which were used as internal wikis, project documentation, and order management.

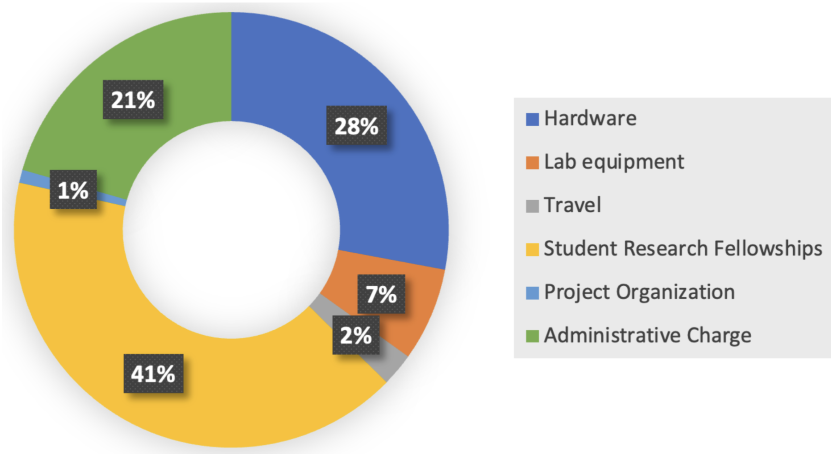


Fig. 19: LATTICE budget breakdown in a pie chart

Significant costs were saved with corporate sponsors. Hilltop, a company specializing in the manufacturing of custom aluminum and PVC hardware, saved machining costs. Maxon Motors discounted objecting model actuators used in our technology demonstration by about $10k.

This completion of this project would not have been possible without the establishment of an entirely new lab space, which was provisioned by the Caltech Engineering and Applied Sciences department in late April 2022. Equipment costs, including workbenches, electrical tools, a computer station, desks, and bench tools, were partially covered by $15k from the Caltech Student Investment Fund.

During phase 2 of this project, we received a $20k grant from the Graduate Aerospace Laboratories at the California Institute of Technologies (GALCIT) during phase 2, offering us more flexibility in this critical stage. As this project concludes, about $30k remains; a portion will be spent on the testing of our shuttle and on our final video.

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10 Appendix

10.1 Circuit Diagrams

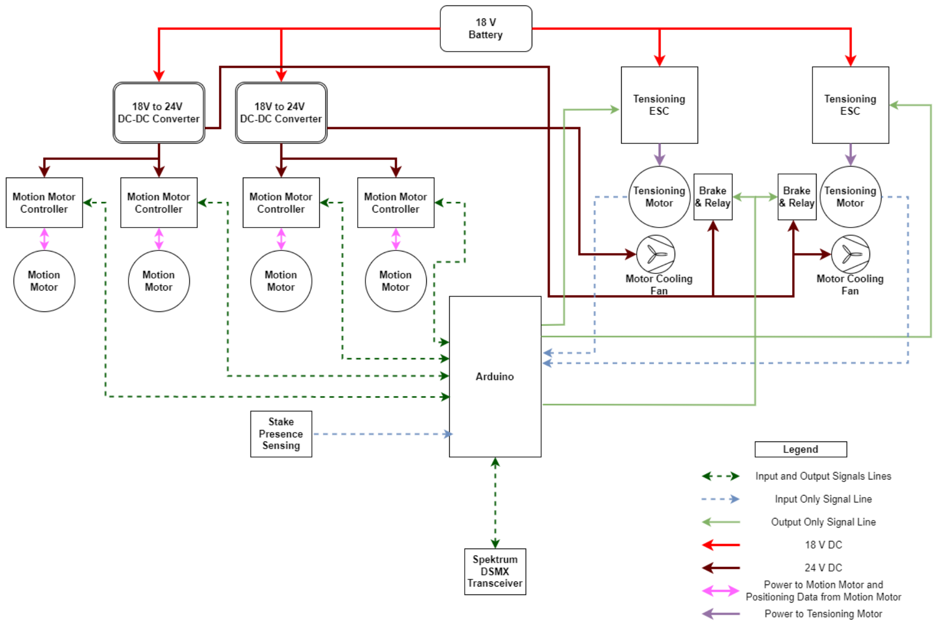


Fig. 20: Shuttle circuit diagram

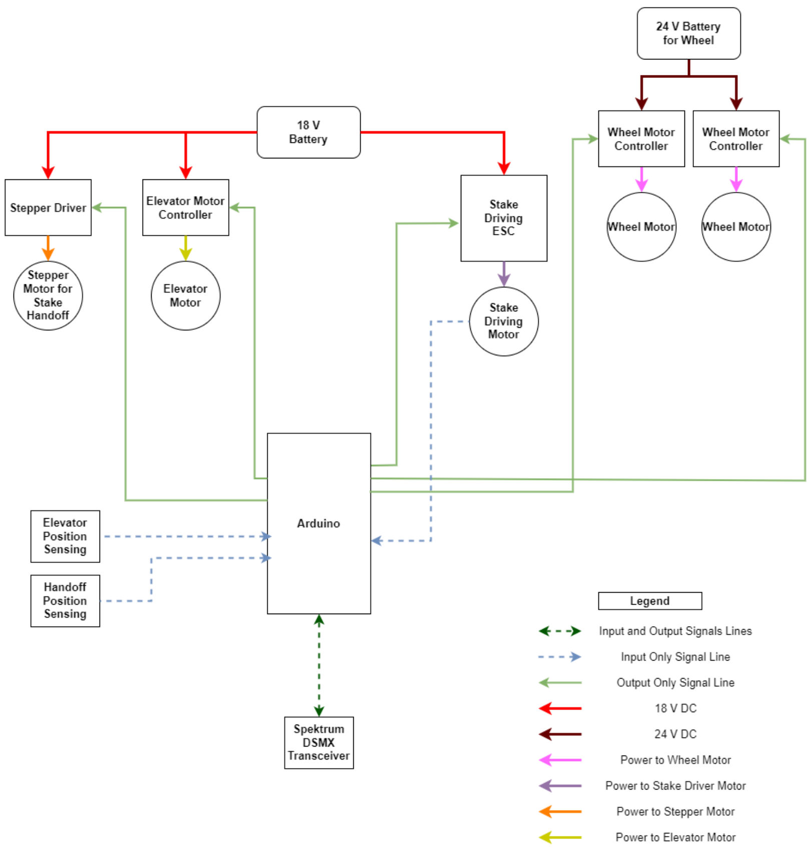


Fig. 21: ATRV-Jr circuit diagram

10.2 Hand-Off Mechanism Technical

The first system requirement is the clamping force needed to hold the stakes. This ranges from 24.5–49 N to maintain a safety factor of 2. However, the clamp has to be loose enough so that the stake slips through the clamp at about 100 N of force. To indicate whether each stake is directly aligned with the drill, photoelectric sensors are incorporated into the hand-off design. Lastly, the stakes must be released passively under a side load from the ATRV. Based on the weight of the stake and its radius (0.625 in), a clamp would exert 0.389 N·m of torque. The ATRV has the capacity to move at 300 N which equates to about 7 N·m of torque—enough to release the stake. The hand-off has two 5 mm-thick main plates manufactured from sheet metal. The first plate serves as a base to support the clamps while the second plate compresses the clamps so that they are wedged firmly between the plates. Each clamp can enact 24.5 N of clamping force and has a diameter capacity of 1.25 in. The clamps restrict the stake wobble to <1 cm to correctly align the stakes with the drill. The stakes must be directly attached to the cable as any misalignment would disrupt the shuttle's ability to traverse the line. The plates are equipped with lightning patterns and includes multiple mounting holes to the linear rail for any necessary adjustments. The clamp plate mounts to a 200 mm-long CNC linear motion rail powered by a NEMA 23 stepper motor. The 8 mm lead screw stepper motor allows for traceable movement and does not require a significant amount of torque (≤ 1.68 N·m) due to the need for deliberate motion.

10.3 Electronics

We used the HobbyStar Brushless Sensored ESC 120 A to control the HYTORC brushless motors. This reliably controls brushless motors in addition to handling the high currents that could come from high torque loads.

For the driver, we used the HiLetgo High Powered Motor Controller for driving the ATRV-Jr rover, the Cross Road Electronics (CTRE) VictorSPX for driving the elevator, and the StepperOnline DM542T Stepper Controller for controlling the hand-off mechanism.

To work around the issue of the non-functioning ATRV internal electronics, we used the HiLetgo motor controllers with the existing batteries to directly drive the drive motors at 24 V, shown in Fig. 21. The driver mechanism and hand-off mechanisms were part of another circuit powered by 18V LiPo. The Arduino commands both of those two systems.

For the shuttle we used the ESCON 50/5 Motor Controllers for the Maxon Motors and the HobbyStars for the tensioning arms.

10.4 Shuttle State Machine

The main control scheme of the shuttle is to maintain a constant take-up of cable. By doing so, the amount the shuttle will droop on the cable is limited to a desired value. Therefore, most of the control of the shuttle revolves around maintaining a certain take-up value throughout its various operations. A key challenge that must be autonomously navigated is the stake transition in which the shuttle goes from one section of cable to the other. The following state machines were used to accomplish all of these specified goals: constant take-up drive, arm transition, and stake transition.

Between stakes, the shuttle uses a constant take-up drive in which the shuttle uses both arms to take up equal amounts of cable. The shuttle drives until it reaches a stake, triggering the front limit switch and starting the stake transition. The stake transition covers the procedure for transitioning from one section of cable to another section of cable. The shuttle increases the cable take-up on the back arm and releases tension from the front arm, moving the front arm to avoid collision with the stake rail. Then the shuttle rides up the stake rail, until a magnet triggers a Hall effect sensor at the center of the rail. Now the shuttle takes up the cable with its front arm and releases the cable on the back arm so that the back arm can clear the rail. The shuttle then drives off the rail with tension only on the front arm. At the end of the stake rail, a back limit switch is triggered, and the shuttle returns to the constant take-up drive state machine with tension on both arms. Due to challenges in properly positioning the front and back limit switches on the current shuttle, these are currently triggered by manual inputs to simulate these switches.

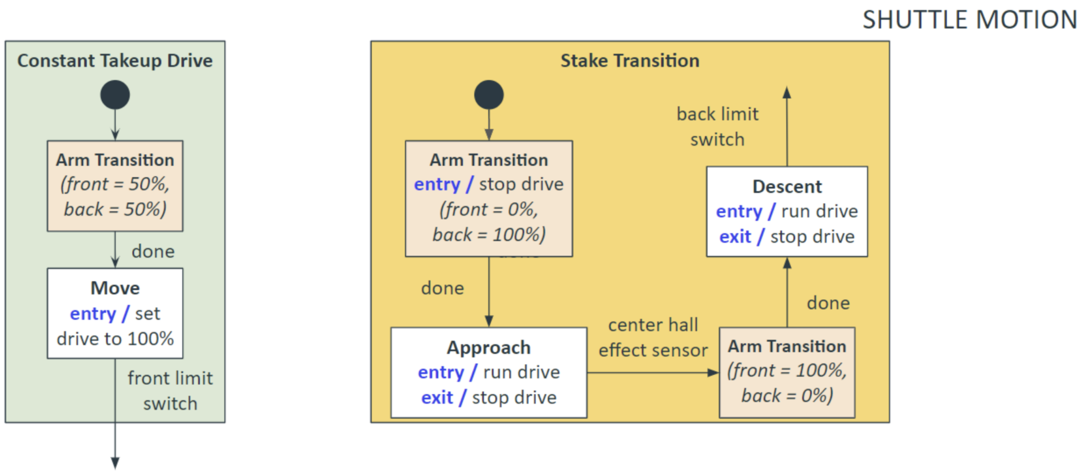


Fig. 22: Diagram of the shuttle motion state machine

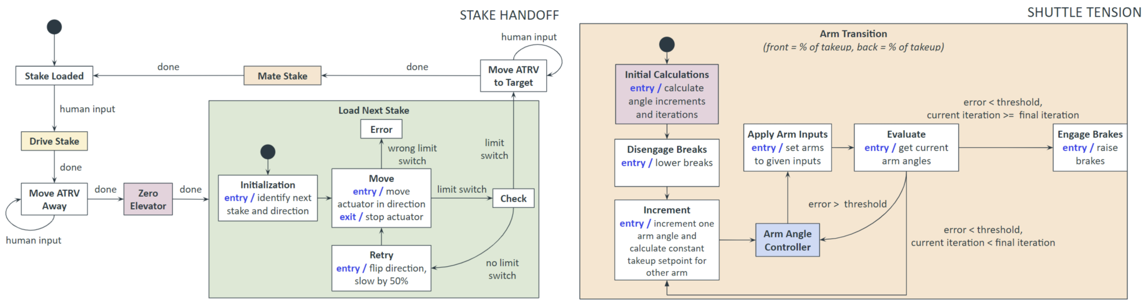


Fig. 23: Left: Diagram of the stake hand-off state machine. Right: Diagram of the shuttle tension state machine

10.5 Power Transmission

High Voltage Direct Current (HVDC) transmission is likely the best option due to compatibility with proposed power sources and power applications on the Moon. We found that for an assumed power draw of 30 W 10 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 conductor mass of only 200 g/km. such as in the Moon Diver mission [20].

10.6 Path-to-Flight, continued

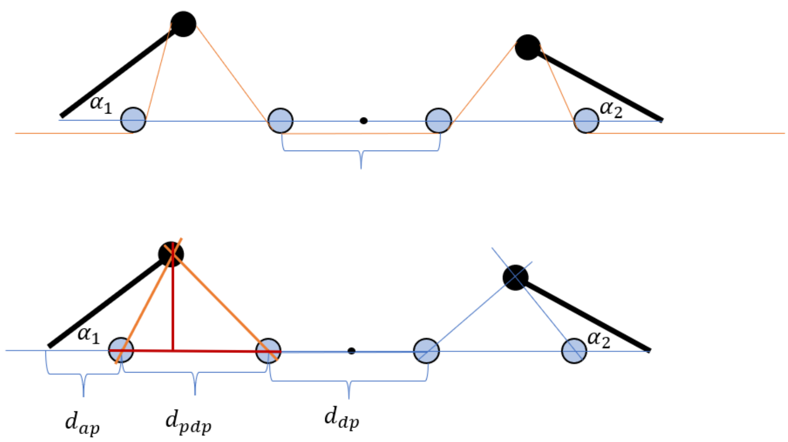
This chart outlines our plan for a continued path-to-flight.

Concept of Operations Stage	Current Operations Enabled via Prototype	Path-to-Flight Design Changes for Lunar Operation
Earth integration with lander	Shuttle bot positioning inside lander	None - deployment should be parallel in both environments, avoid gravity-based mechanisms
Lunar landing and surviving space environment	Shock testing and radiation exposure testing	Radiation hardware redundancy and electronics redesign
Post-landing pre-deployment test	Automated testing/comm with orbiter/earth	Test for functionality after landing for damage caused by landing shock
Driver and shuttle bot positioning in "waiting zone"	Local environment analysis and pathfinding	None - verify systems integrity after landing
Driver lays out initial cable	Stakes are pre-attached to cables during deployment	None - tensioning easier in low-gravity environment, verify dust and thermal performance
Driver lays stake	Staking module into soft regolith	Ensure consistency and mechanism sturdiness based on lunar regolith resistance
Driver tensions stake and connects cable	Stakes are attached to cables during deployment, rover itself provides the tensioning mechanism	None - easier in low-gravity environment, ensure consistency and cable integrity with lunar environment
Driver spools new cable	Stakes are attached to cables during deployment	None - verify capabilities in lunar environment, test cables for integrity after long-term radiation exposure before use
Shuttle bots move along cable	Shuttles will be based in the lander & autonomously deploy	Verification tests before deployment of shuttle bots to ensure functionality and maintenance
Shuttle bots move over stake junctions	Shuttle bots are capable of moving through stake junctions autonomously	None - ensure reliability of mechanism across long-term exposure
Shuttle bots transport cargo	Shuttle bots autonomously deploy after signal received from network	None - perform regular checks of bots to ensure no breakdowns throughout network

Fig. 24: Path-to-Flight Chart

Shuttle Math

1 Takeup Math



$$\sqrt{(L_{arm}\cos\alpha_1 - d_{ap})^2 + (L_{arm}\sin\alpha_1)^2} + \sqrt{(d_{ap} + d_{pdp} - L_{arm}\cos\alpha_1)^2 + (L_{arm}\sin\alpha_1)^2} +$$
$$\sqrt{(L_{arm}\cos\alpha_2 - d_{ap})^2 + (L_{arm}\sin\alpha_2)^2} + \sqrt{(d_{ap} + d_{pdp} - L_{arm}\cos\alpha_2)^2 + (L_{arm}\sin\alpha_2)^2} - 2\, d_{pdp}$$

Figure 1: Basic Take up derivation diagram

If we simplify the strings to connect the pulleys directly, we can see that certain right triangles begin to form, where the hypotenuse is the cable that is being taken up.

If we just consider one side, we see that there is one from the passive pulley to the arm, and there is one from the arm to the driver pulleys. We can perform pythagorean theorem on these triangles to get the rope length and then add them together to get the total takeup. However, since the cable was originally between the passive pulley and the driver pulley we have to remove that original cable length. It's the same procedure for the other side which gets us the expression above.

Thus we get the following equations:

$$T_{side}(\alpha) = \sqrt{(L_{arm}\cos\alpha - d_{ap})^2 + (L_{arm}\sin\alpha)^2}$$
$$+\sqrt{(d_{ap} + d_{pdp} - L_{arm}\cos\alpha)^2 + (L_{arm}\sin\alpha)^2} - d_{pdp}$$

$$T = \sqrt{(L_{arm}\cos\alpha_1 - d_{ap})^2 + (L_{arm}\sin\alpha_1)^2} +$$
$$\sqrt{(d_{ap} + d_{pdp} - L_{arm}\cos\alpha_1)^2 + (L_{arm}\sin\alpha_1)^2} +$$
$$\sqrt{(L_{arm}\cos\alpha_2 - d_{ap})^2 + (L_{arm}\sin\alpha_2)^2} +$$
$$\sqrt{(d_{ap} + d_{pdp} - L_{arm}\cos\alpha_2)^2 + (L_{arm}\sin\alpha_2)^2} - 2d_{pdp}$$

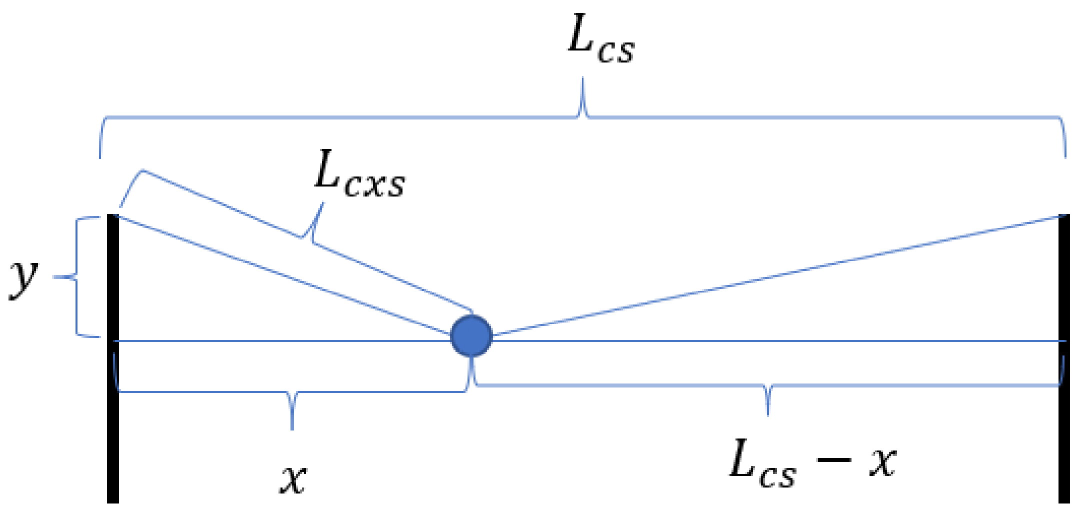


Figure 2: Shuttle position between stakes

2 Shuttle Position Math

Note: L_c is effective length of cable (with takeup accounted for) and L_{cs} is the stake span. We can derive the x and y positions of the shuttle based off of the displacement the shuttle traveled on the cable (L_{cxs}). We will assume that the shuttle is a point mass. We then setup a system of equations based off of the x and y positions and cable lengths:

$$L_{\text{cxs}} = \sqrt{x^2 + y^2}$$

$$L_c = \sqrt{x^2 + y^2} + \sqrt{(L_{cs} - x)^2 + y^2}$$

Thus, when we solve the equation we get that:

$$x = \frac{2L_c L_{\text{cxs}} - L_c^2 + L_{\text{cs}}^2}{2L_{\text{cs}}}$$

$$y = \sqrt{L_{\text{cxs}}^2 - \frac{(2L_c L_{\text{cxs}} - L_c^2 + L_{\text{cs}}^2)^2}{4L_{\text{cs}}^2}}$$

3 Tension Estimation

We know that the horizontal components of tension must cancel and that the vertical components must cancel the force of gravity on the shuttle. We can skip the trig and just use the side ratios to get the following terms:

$$T_L \frac{x}{L_{cxs}} = T_R \frac{L_{cs} - x}{L_c - L_{cxs}}$$

$$T_L \frac{y}{L_{cxs}} + T_R \frac{y}{L_c - L_{cxs}} = m_s g$$

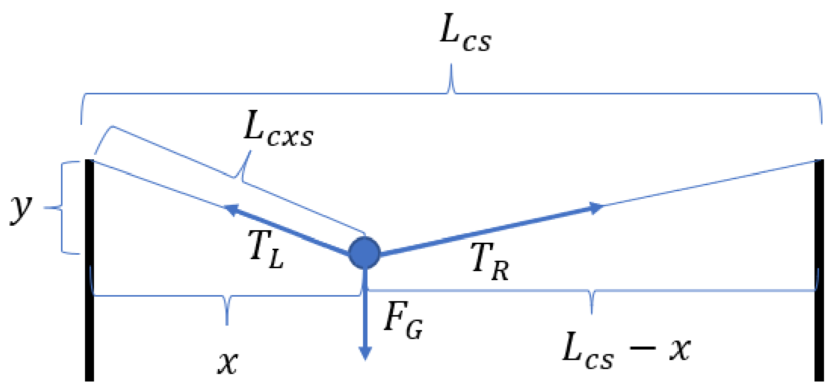


Figure 3: Free body diagram of the shuttle between two stakes

Solving the system gets us the following:

$$T_L = \frac{gL_{\text{cxs}}m_s\left(L_{\text{cs}} - x_s\right)}{yL_{\text{cs}}}$$

$$T_R = -\frac{-gL_{\text{c0}}m_sx_s + gL_{\text{cxs}}m_sx_s + gL_tm_sx_s}{yL_{\text{cs}}}$$

4 State space simulation of shuttle and take aways

Motivation

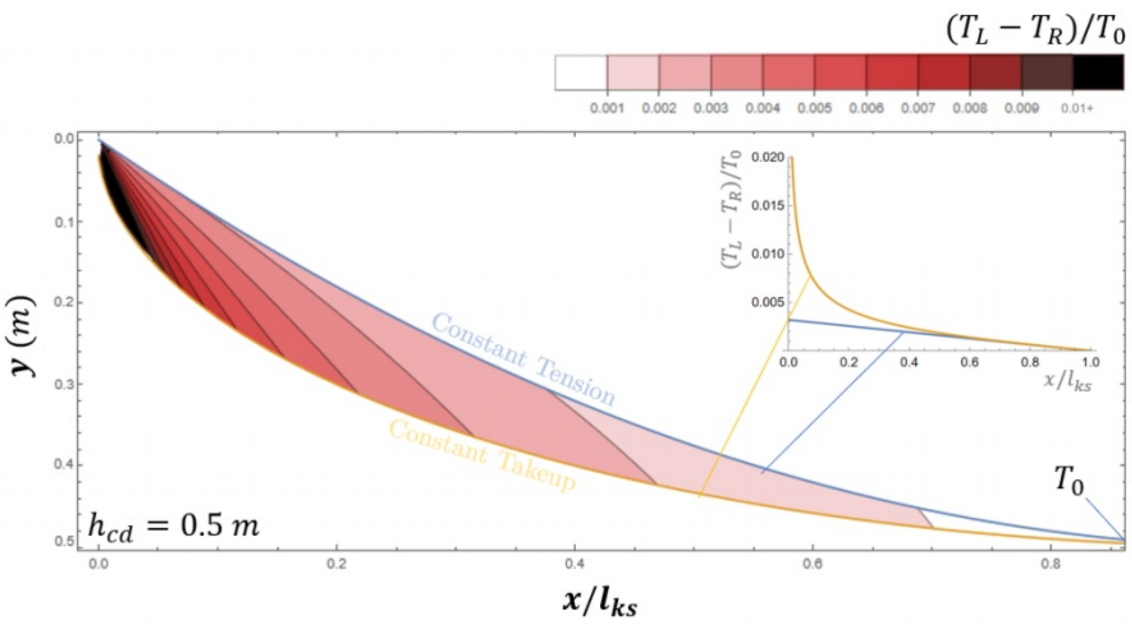


Figure 4: Constant Tension vs. Constant Take up approaches

The main motivation behind fully modeling the shuttle is to understand and determine an optimal control scheme. Initially, 2 approaches were identified. One in which we maintained constant tension and constant take up. Constant take up comes with the advantage that we can guarantee that we do not sink below a specified amount of droop. However, with this approach, the angle of approach skyrockets as we approach the stake. A constant tension approach, although with less guarantees, avoids the angle of approach issue immediately. However, as we will see with the state space simulation, constant take up sufficed and that the angle of approach issue is not a problem.

With all these equations defining the system, we can define a state space model with the following states and inputs:

$$x = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ L_t \\ L_{cxs} \\ x \\ y \\ T_L \\ T_R \end{bmatrix} u = \begin{bmatrix} \dot{\alpha_1} \\ \dot{\alpha_2} \\ \dot{L_{cxs}} \end{bmatrix}$$

This simplifies the math to setup the following function:

$$\dot{\begin{bmatrix} \alpha_1 \\ \alpha_2 \\ L_t \\ L_{cxs} \\ x \\ y \\ T_L \\ T_R \end{bmatrix}} = f(t, x(t), u(t)) =$$

$$\begin{bmatrix} u_1 \\ u2 \\ \dot{L}_t(\alpha_1, \alpha_2, u1, u2) \\ u3 \\ \dot{x}(L_t, L_{cxs}, \dot{L_t}, u3) \\ \dot{y}(L_t, L_{cxs}, \dot{L_t}, u3) \\ \dot{T_L}(L_t, L_{cxs}, x, y, \dot{L_t}, \dot{x}, \dot{y}, u3) \\ \dot{T_R}(L_t, L_{cxs}, x, y, \dot{L_t}, \dot{x}, \dot{y}, u3) \end{bmatrix}$$

We can setup a numerical integration to simulate the system dynamics for traversing the cable and for performing the arm transitions in preparation and after the stake transition.

Here are the following graphs from (note the time axis is not accurate to decrease the amount of time we were simulating the traversal of the cable, etc).

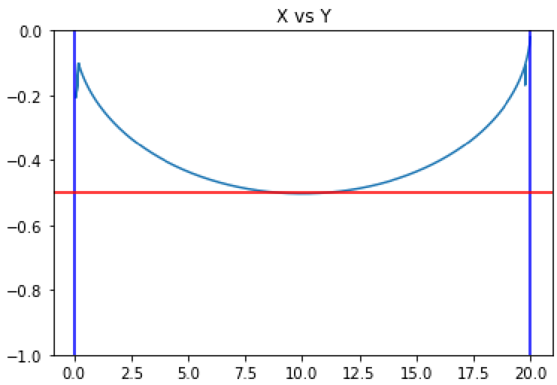


Figure 5: Simulated Shuttle Path

This first graph simulates the position of the shuttle while it: starts with only one arm (getting off stake rail), transitions to using both arms, traverses the cable, and then transitions back to one arm (to prepare to get on the stake rail again). It shows that we can limit the maximum amount of droop in our planned path of operations successfully.

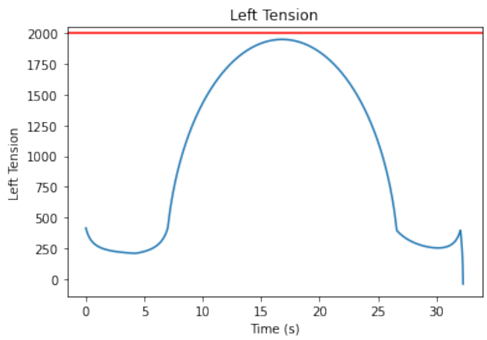


Figure 6: Left tension on shuttle

This graph shows the tension while the shuttle traverses the cables. We can expect around 2000N max tension and about 500N of tension when we're performing the stake transition.

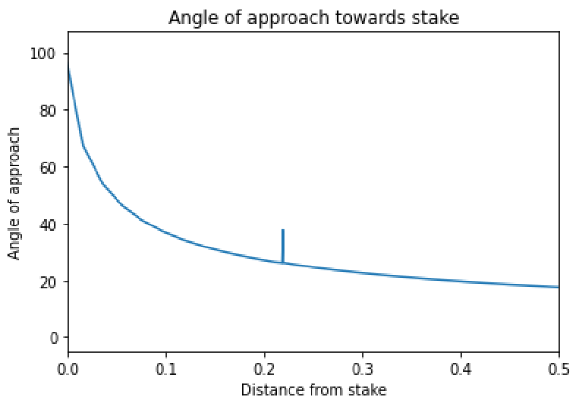


Figure 7: Angle of approach of the shuttle as it approaches the stake

This graph shows the angle of approach as we approach the stake rail. Note, that the vertical line around 0.2m of distance from the stake is when the shuttle moved from 2 arms to 1 arm. Our shuttle gets to the stake with somewhere between 40-50 degrees of an angle of approach. Therefore, if we maintain constant take up, we should be able to make it onto the rail.

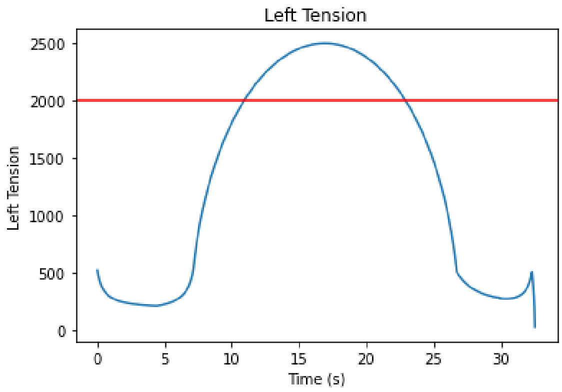


Figure 8: Left tension from 1 centimeter of overtension

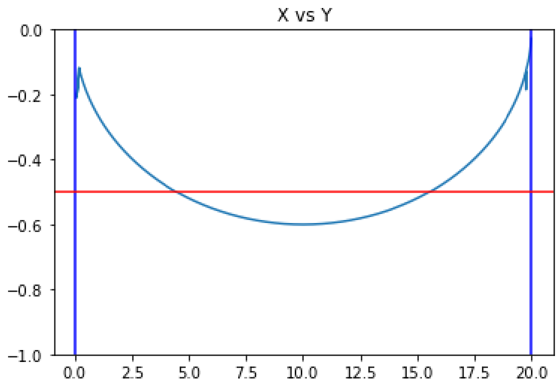


Figure 9: Simulated path from 1 centimeter of undertension

These two graphs demonstrate the need for high accuracy take up. A centimeter of undershoot leads to us drooping almost 10cm at the center and a centimeter of overshoot gives an additional 500N of tension which is significantly over the tension 2000N spec.

Ideally take up needs to be within a millimeter which means our take up setpoints and arm angle control have to be very accurate in a fully implemented system.

5 Torque Analysis

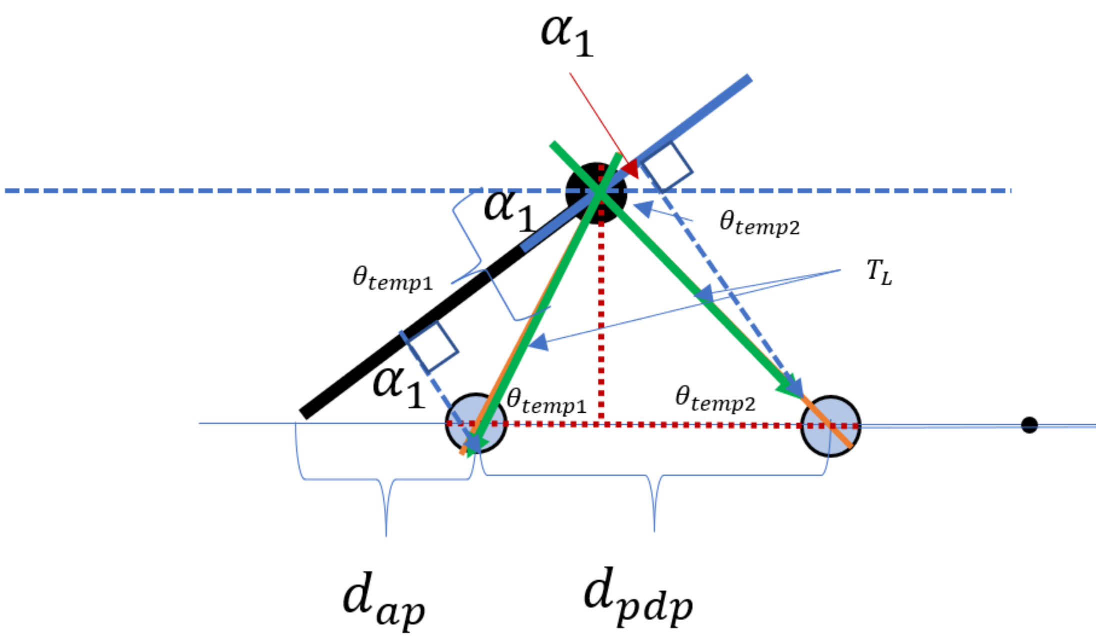


Figure 10: Free body diagram of an Arm

We will assume that the tension across the pulley is the tension being applied to the side of the shuttle we're interested in.

Then we get that

$$\tan\theta_{temp1} = \frac{L_{arm}\sin\alpha}{L_{arm}\cos\alpha - d_{ap}}$$

$$\theta_{temp1} = \arctan(\frac{L_{arm}\sin\alpha}{L_{arm}\cos\alpha - d_{ap}})$$

$$\tau_p = TL_{arm}\sin(\theta_{temp1} - \alpha)$$

$$\tan\theta_{temp2} = \frac{L_{arm}\sin\alpha}{d_{ap} + d_{pdp} - L_{arm}\cos\alpha}$$

$$\theta_{temp2} = \arctan(\frac{L_{arm}\sin\alpha}{d_{ap} + d_{pdp} - L_{arm}\cos\alpha})$$

$$\tau_{dp} = TL_{arm}\sin(\theta_{temp2} - \alpha)$$

$$\tau_{arm} = m_{arm}\frac{Larm}{2}\sin\alpha + \tau_p + \tau_{dp}$$

Graphing the torque with respect to angle at 2000N seems to indicate that the torque that will be put on the arms will be around 750 Nm. This informed our decision in high torque actuators.

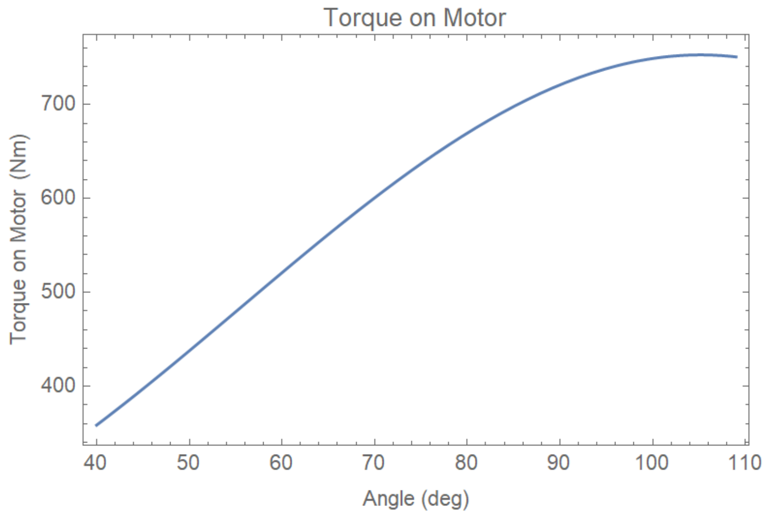


Figure 11: Plotting torque at 2000N at various arm angles

6 More accurate take up calculations

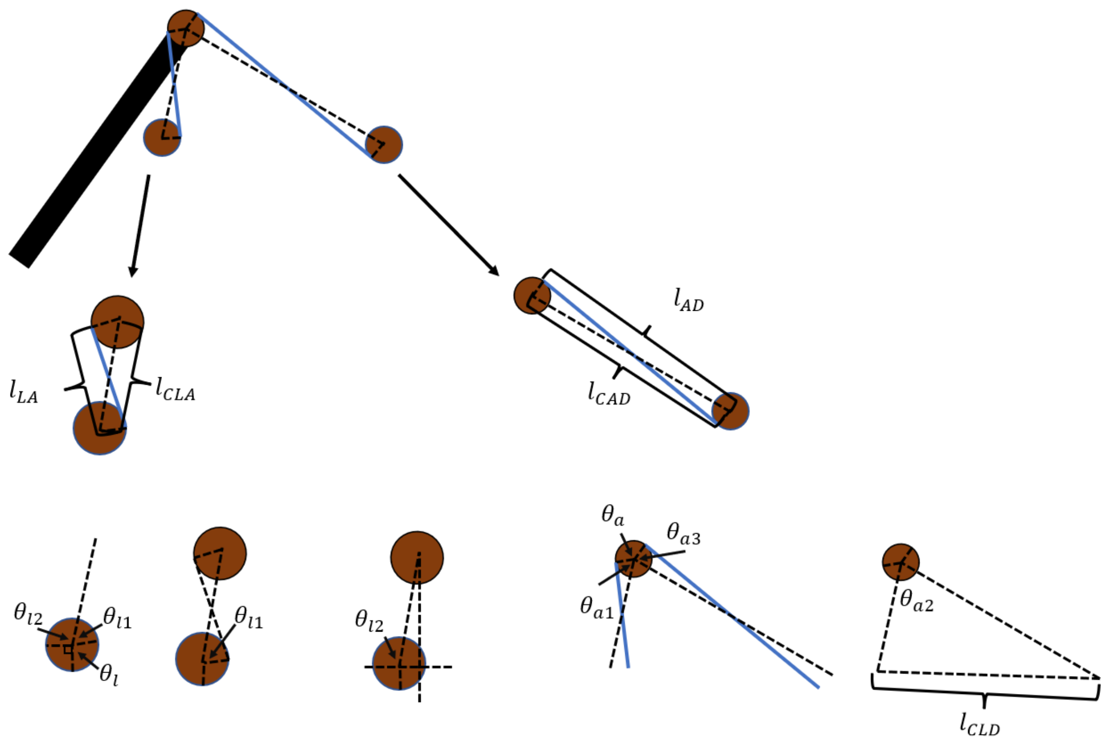


Figure 12: More accurate take up calculation

To get a better model of take up to inform our controls system, we split the take up into the leader pulley side and the arm pulley side. Each side has a cable connecting two pulleys and they have some arc of take up around the pulley. We will be ignoring the cable wrapped around the driver pulley because it has negligible change throughout the arm's range of motion compared to the other components.

First we will consider the leader side. Note that the cable is tangent to both pulleys, thus the radius that extends to the cable from the center of each pulley makes a right angle. Therefore, we know the radii are parallel which allows us to establish that the 2 triangles formed between radii, the cable, and the line between the two centers are congruent and right triangles. Thus, the length of the cable l_{LA} is as follows:

$$l_{LA} = 2 * \sqrt{\frac{l_{CLA}}{2}^2 - r_p}$$

Where, l_{CLA} is the centerdistance between the leader pulley and arm pulley and r_p is the radius of the pulleys. To get the arc of cable taken up by the leader pulley, we will solve for the arc between the vertical radius and the radius tangent to the cable. To do so we solve for two angles, θ_{l1} the angle between the center distance line and the radius tangent to the cable and θ_{l2} the angle between the center distance line and the horizontal. For θ_{l1} we know that we have a right triangle since the radius is tangent to the cable:

$$\theta_{l1} = \arccos \frac{r_p}{(\frac{L_{CLA}}{2})}$$

For θ_{l2} we have a right triangle with the horizontal radius and the vertical distance, and we can solve for θ_{l2} as its the external angle to the 90 degree of the triangle and the angle overlooking the base of the right triangle.

$$\theta_{l2} = \frac{\pi}{2} + \arcsin \frac{x_l - xa}{L_{CLA}})$$

Where x_l is the x position of the leader pulley and x_a is the x position of the arm. Note this only works when the arc of cable is greater than 90 degrees, which roughly corresponds to a 30 degree arm angle.

Thus the final angle we get is the remaining angle after subtracting the two angles we solved for and a 90 degree angle formed in the lower left quadrant of the circle:

$$\theta_l = 2 * \pi - (\theta_{l1} + \theta_{l2} + \frac{\pi}{2})$$

For the arm pulley and drive pulley we can solve for the cable in between them by doing the same thing we did for the other cable. Thus we get:

$$l_{AD} = 2 * \sqrt{\frac{l_{CAD}}{2}^2 - r_p}$$

For the cable around the pulley we need to solve for three angles θ_{a1}, the angle between the radius tangent to the pulley and the centerdistance from the arm pulley to the leader pulley, θ_{a2} the angle between the two center distance lines, and θ_{a3} the angle between the radius tangent to the cable and the center distance line from the arm pulley to the drive pulley. For θ_{a1} and θ_{a3} we use the same strategy we used for θ_{l1}:

$$\theta_{a1} = \arccos \frac{r_p}{(\frac{L_{CLA}}{2})}$$

$$\theta_{a3} = \arccos \frac{r_p}{(\frac{L_{CAD}}{2})}$$

For θ_{a2} we can solve for this angle using the law of cosines by using the center distances between the three pulleys as a triangle. Thus:

$$\theta_{a2} = \arccos(\frac{l_{CLA}^2 + l_{CAD}^2 - l_{CLD}^2}{2 l_{CLA} l_{CAD}})$$

Where l_{CLD} is the center distance between the leader pulley and the drive pulley.

With those three angles we can get the actual angle as the remaining angle of the circle:

$$\theta_a = 2\pi - (\theta_{a1} + \theta_{a2} + \theta_{a3})$$

Our final takeup value for a side is as follows:

$$T = l_{LA} + l_{AD} + r_p(\theta_l + theta_a)$$

When compared to the cad this take up estimation is within a millimeter for angles > 30 degrees.

11 Additional Images

Fig. 25: Manual stake test stand with applied downforce

Fig. 26: Stake planted in Lucerne Valley

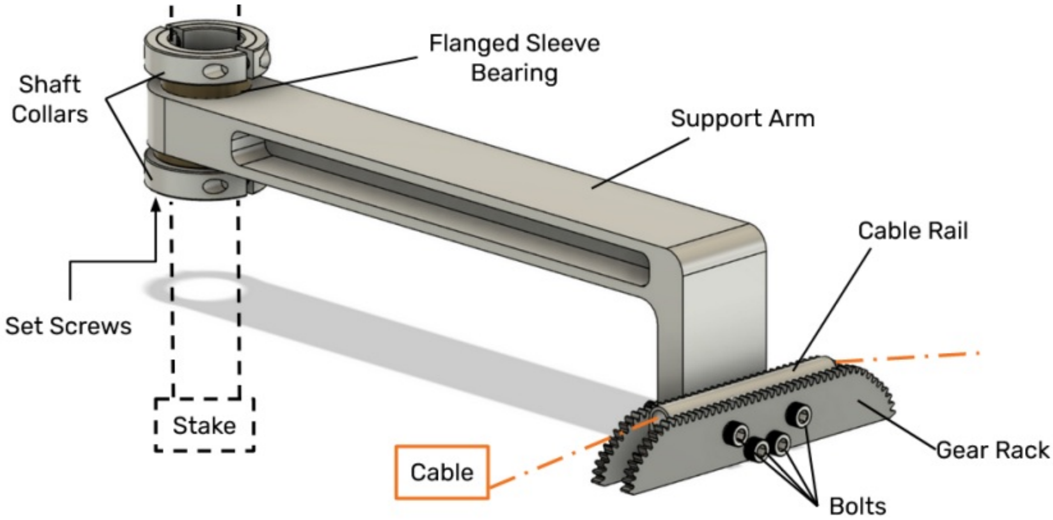


Fig. 27: CAD of stake rail

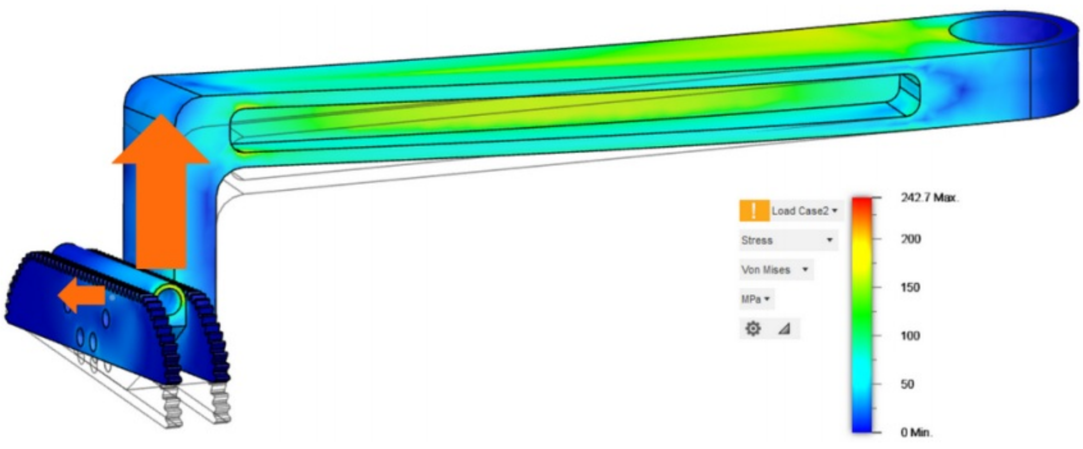
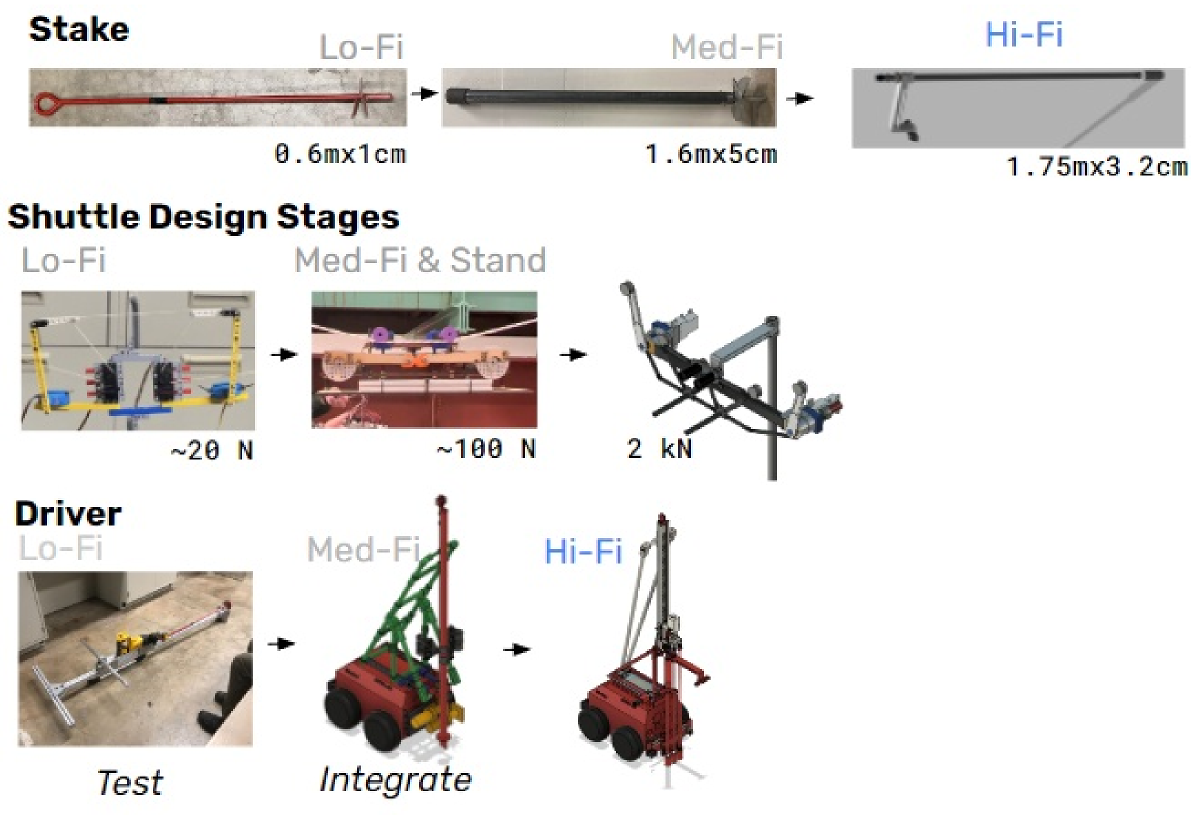
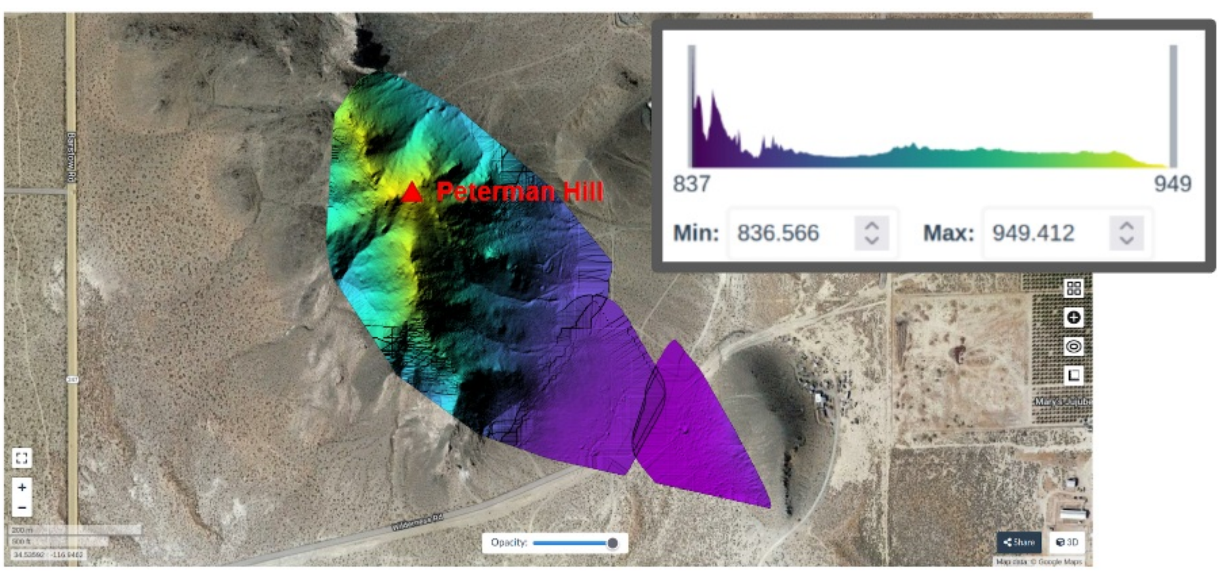


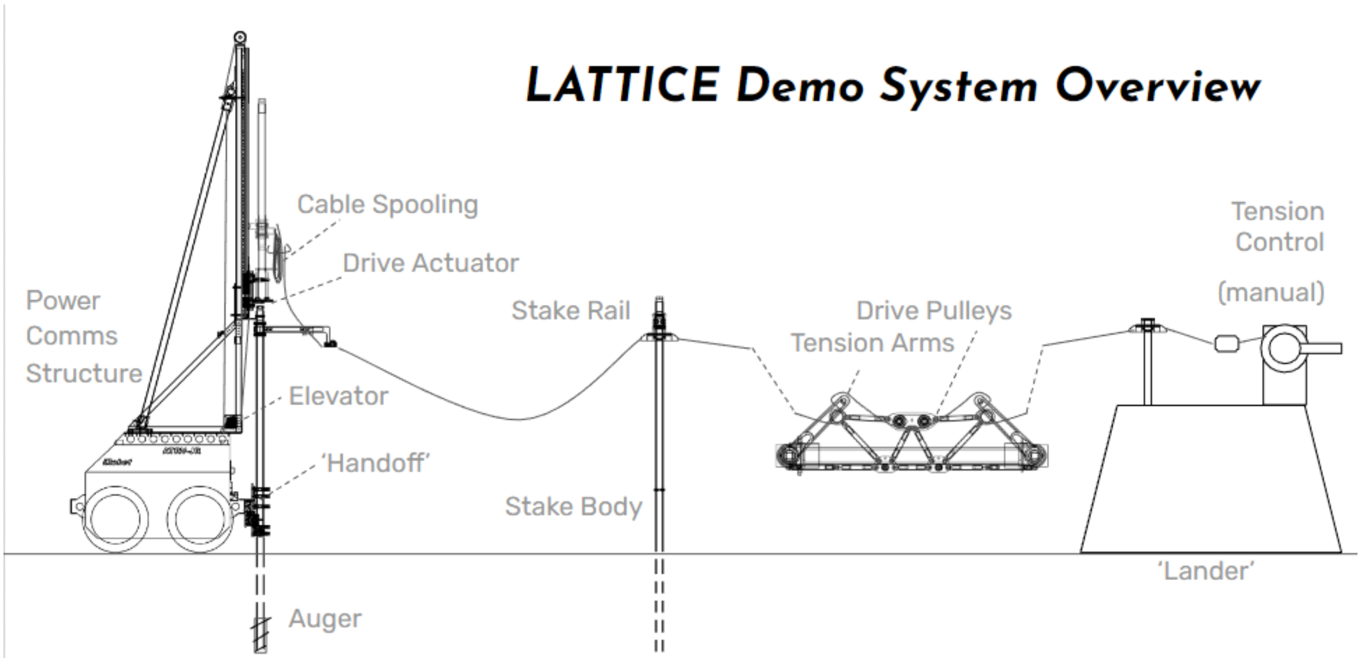
Fig. 28: FEA analysis of stake rail with 200 N lateral load and 2 kN upward load

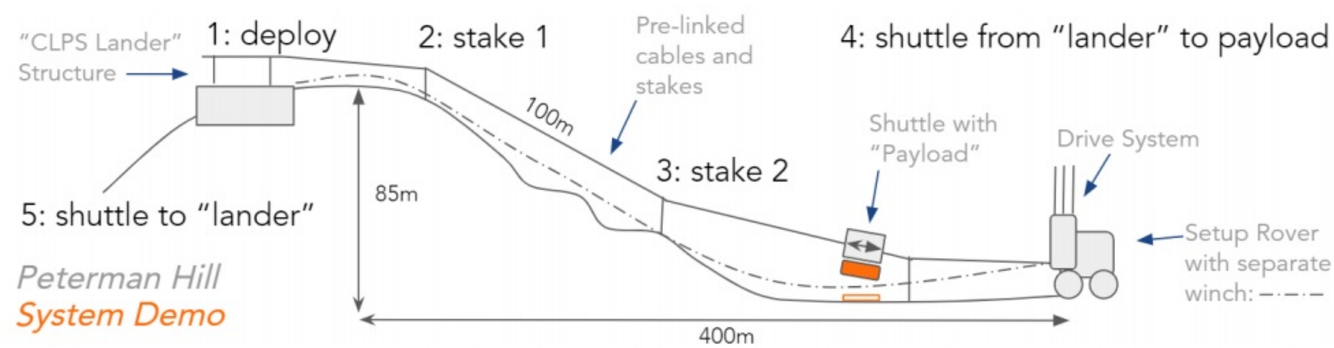


LATTICE Project Progression



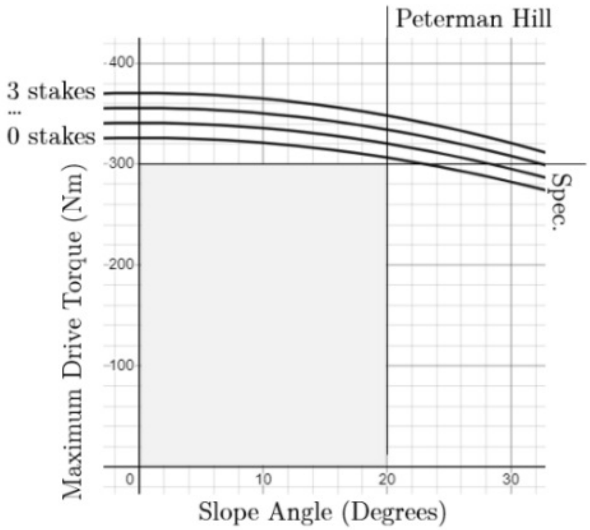
Peterman Hill DEM

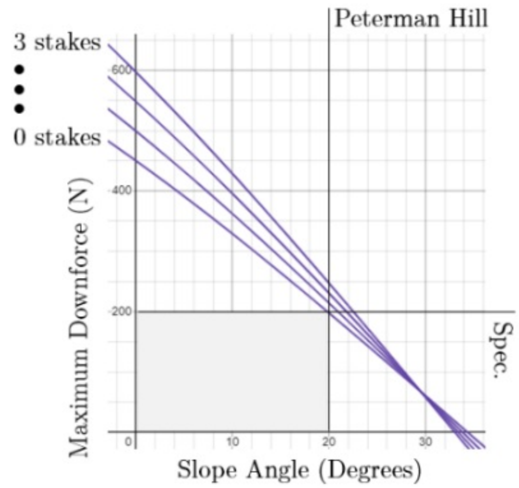




Early Manual Stake Test Stand

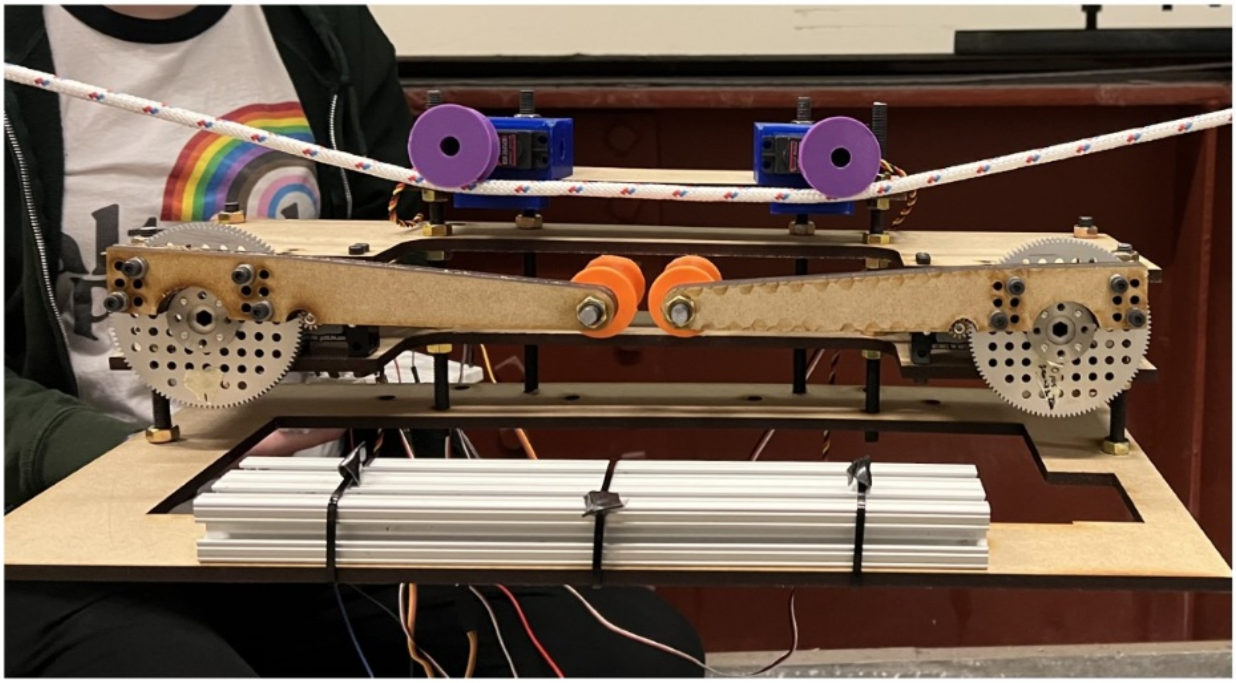
ATRV Drive Constraints

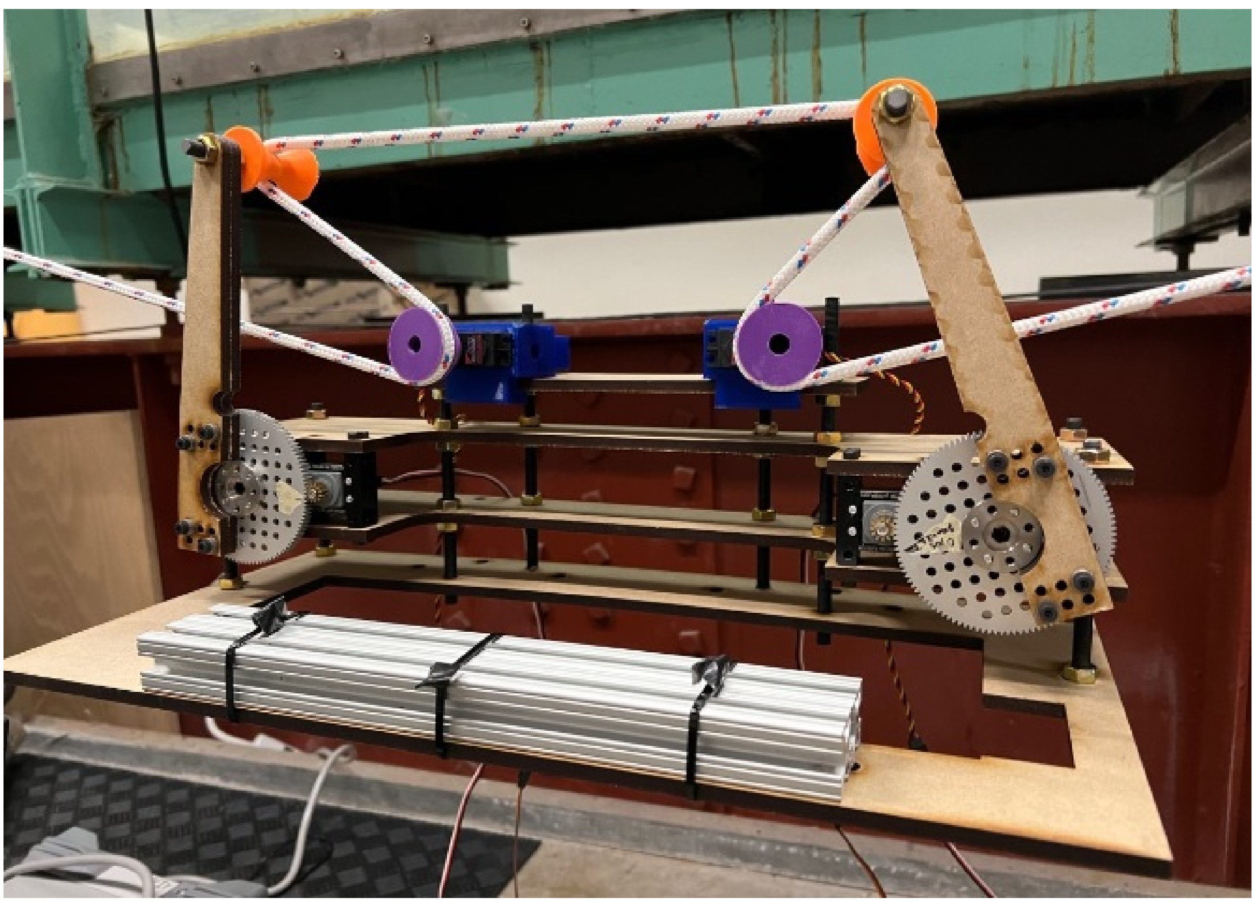


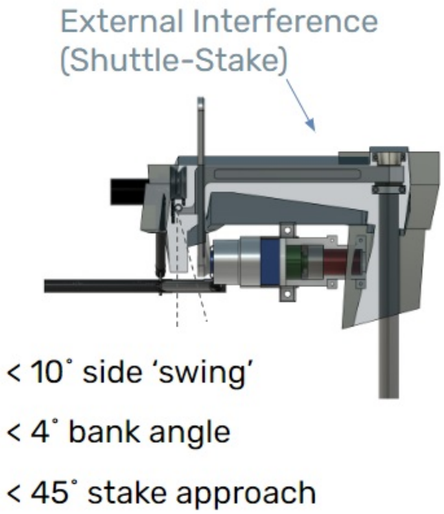


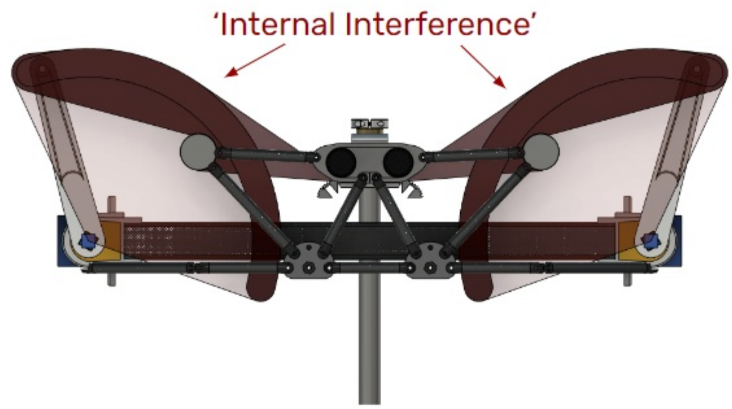
Early Handoff Clamp Prototype
3D Printed

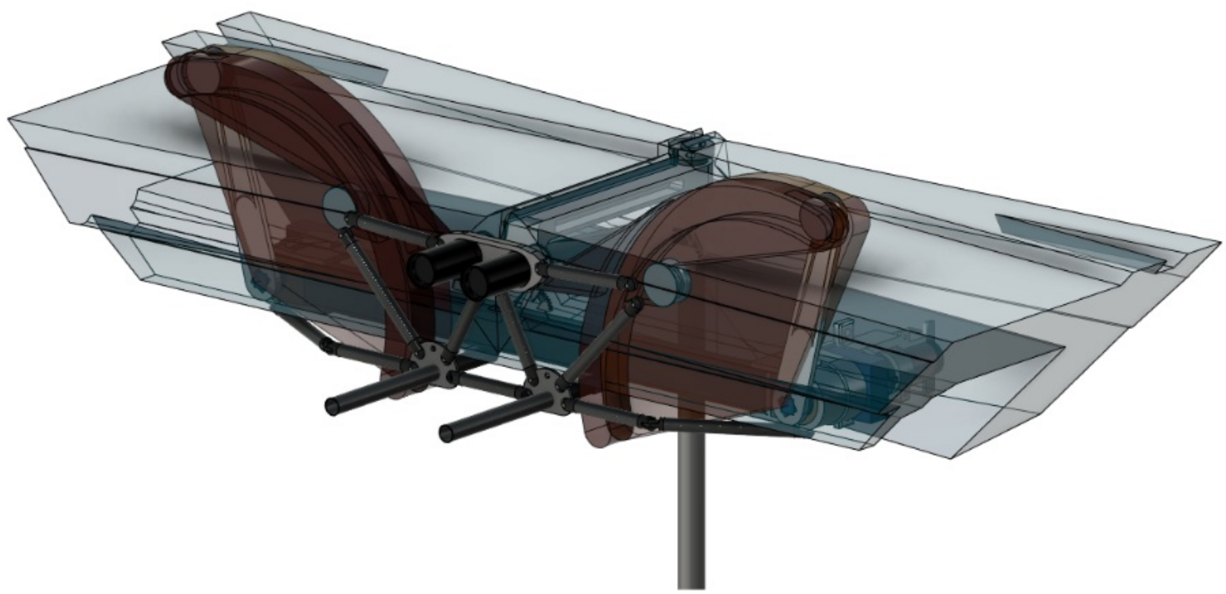
Med-Fi Prototype





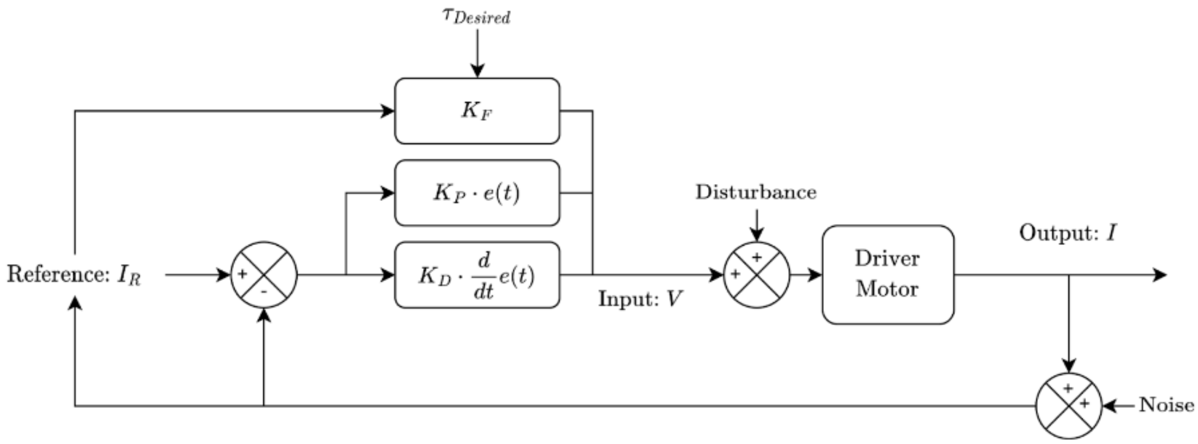




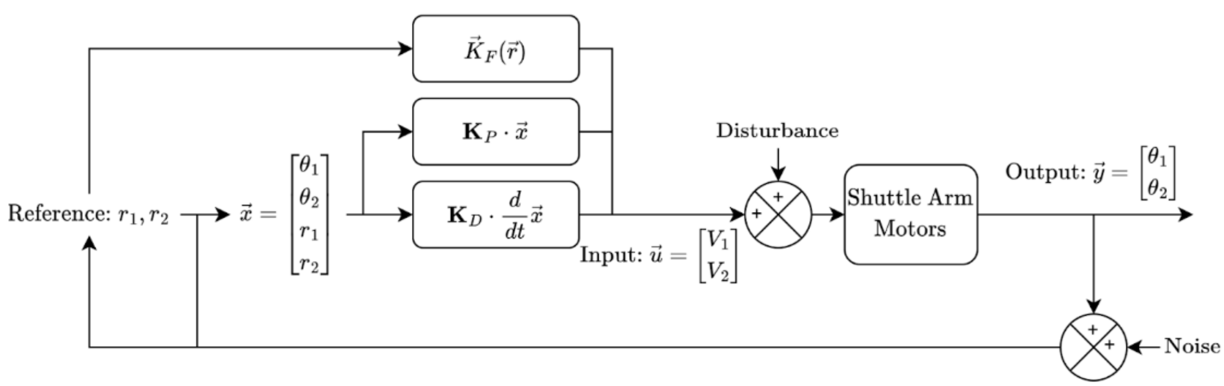


Shuttle Design Synthesis

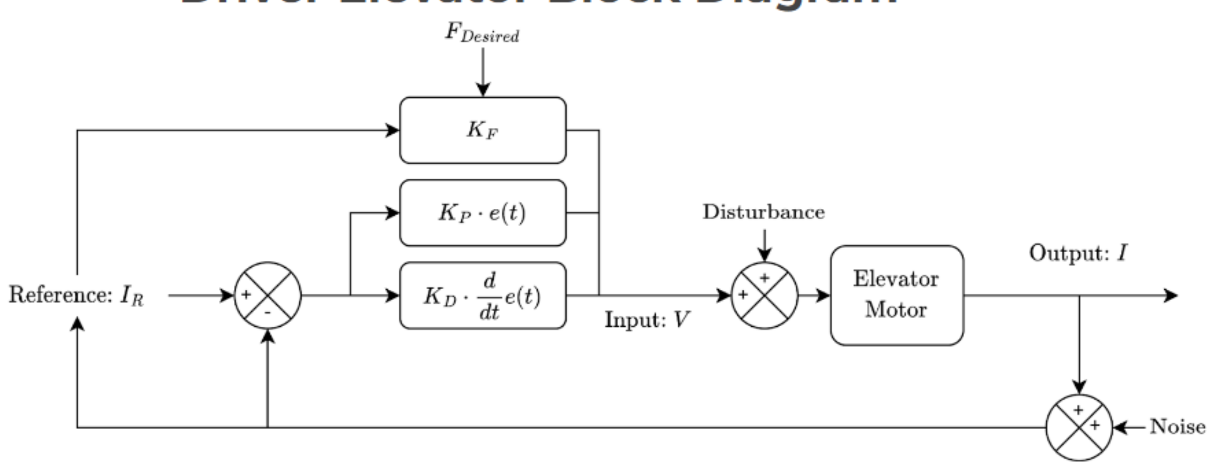
Driver Actuator Block Diagram



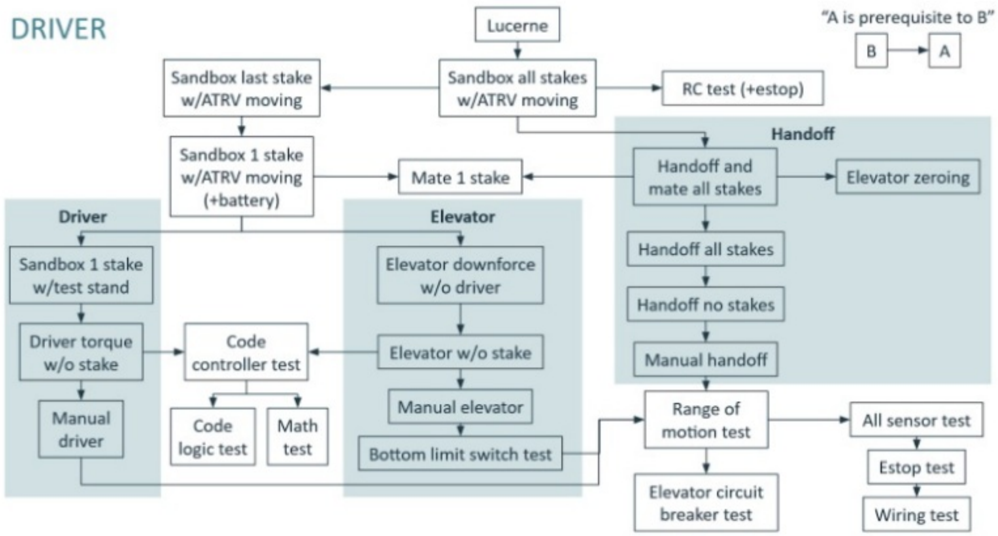
Shuttle Arm Block Diagram

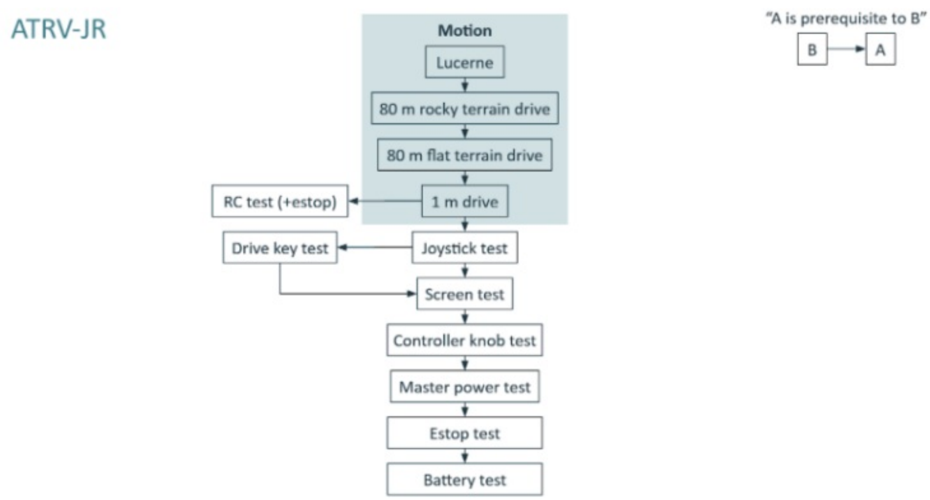


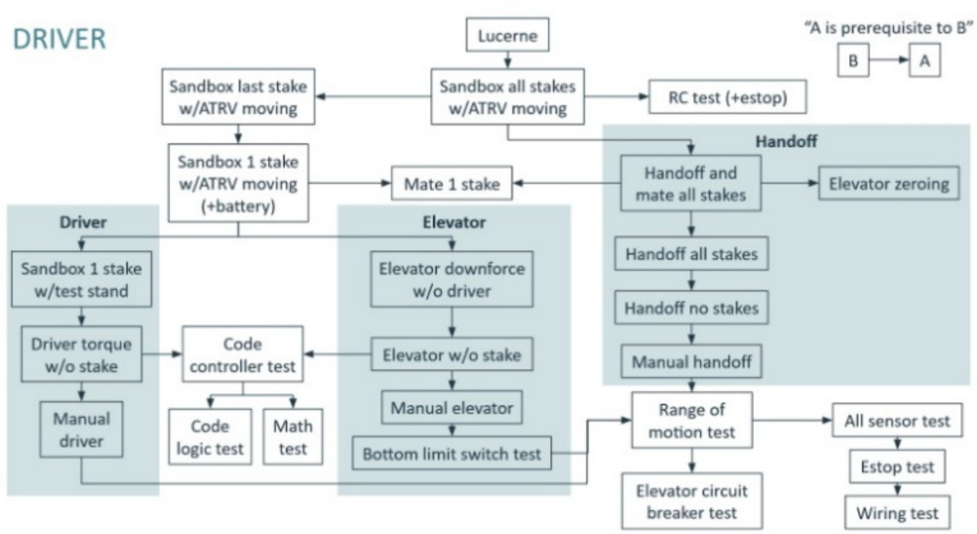
Driver Elevator Block Diagram

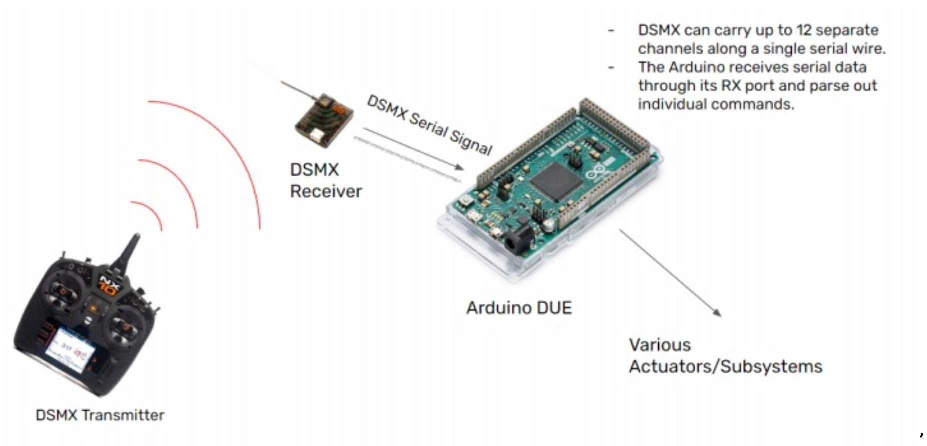


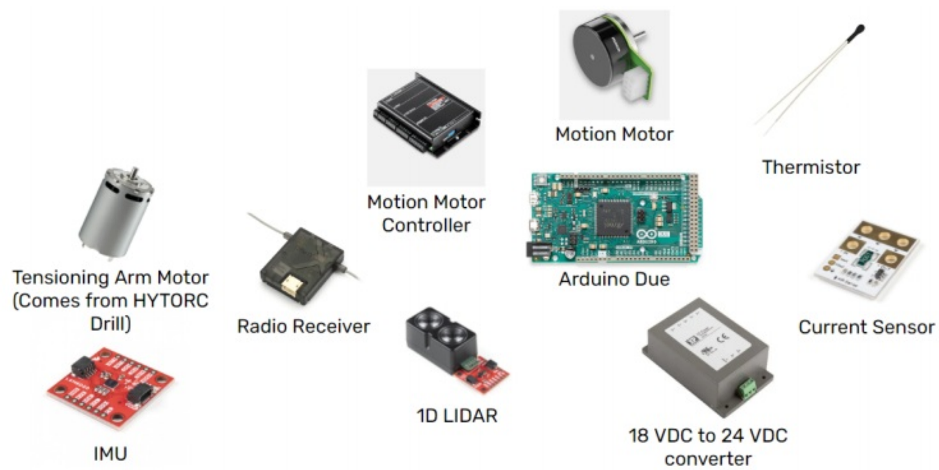
System Testing Plans



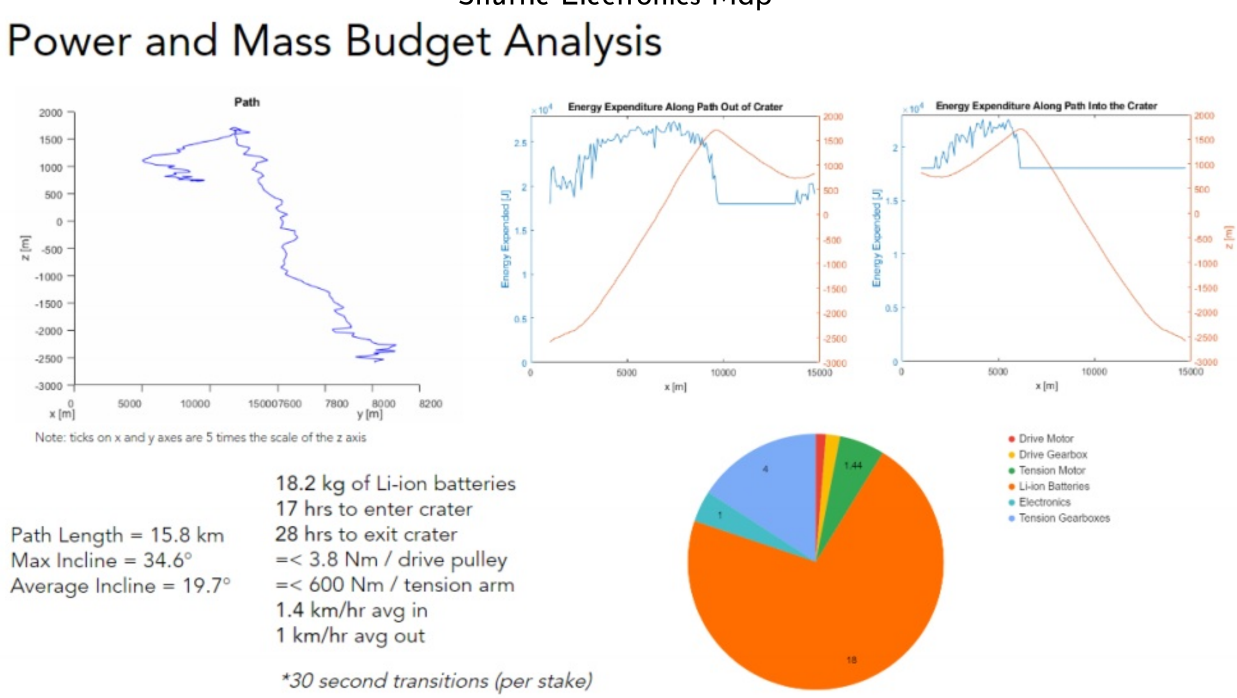




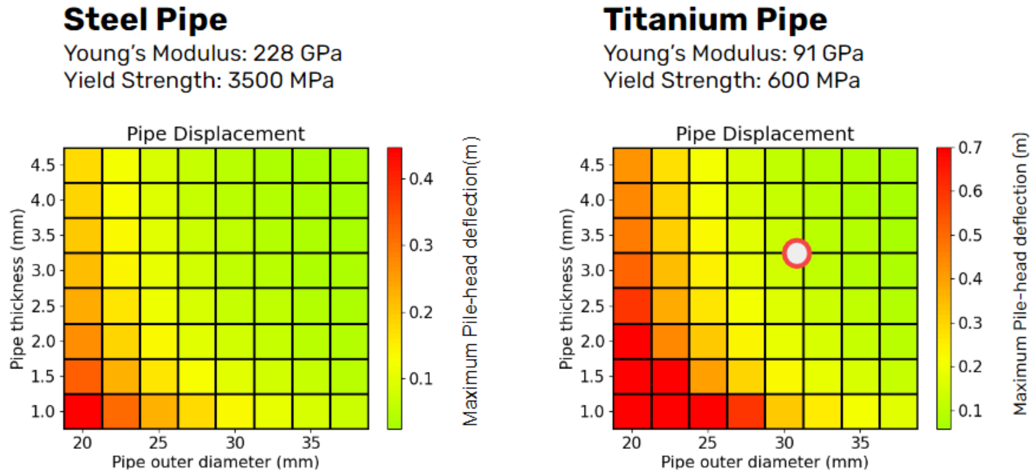


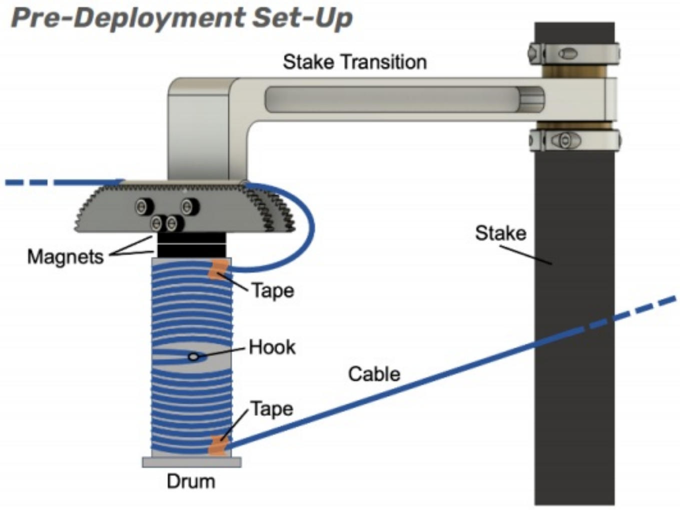


Shuttle Electronics Map



LPILE Stake Soil Deflection Simulations





25 m of cable (0.77 kg)

LATTICE Team vs Lucerne Valley