

LEAP – Legged Exploration Across the Plume

Phase I Final Report

Justin K. Yim¹, Ethan W. Schaler², Neil R. Wagner¹, David C. Bugby², Morgan L. Cable^{2,3}, Stephen Gerdts², Colin Creager⁴, and Ryan McCormick²

¹University of Illinois Urbana-Champaign, USA

²Jet Propulsion Laboratory, California Institute of Technology, USA

³Planetary Science Institute, USA

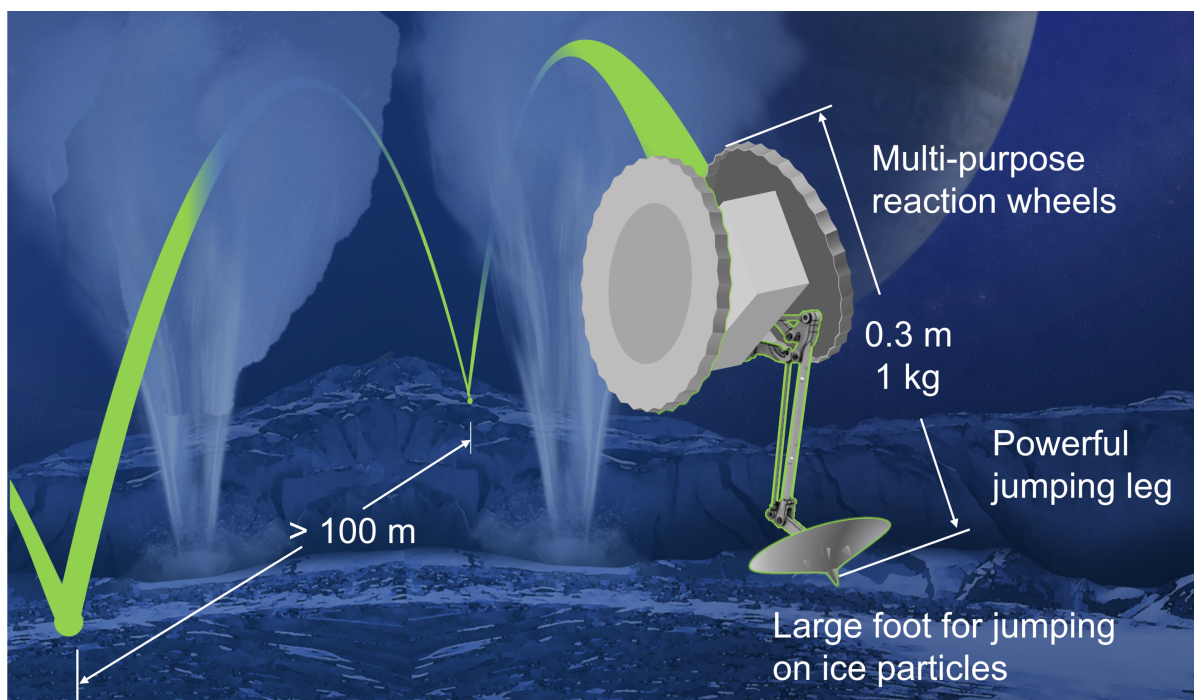
⁴Glenn Research Center, USA

ABSTRACT

We propose Legged Exploration Across the Plume (LEAP), based on the Salto jumping robot as a novel multi-jet robotic sampling concept for Enceladus to be deployed from Enceladus Orbilander. If successful, LEAP will enable collection of pristine, ocean-derived material directly from Enceladus's jets and measurement of particle properties across multiple jets by traveling from one to another. In low gravity, existing jump performance would be sufficient to leap 90 m vertically or 170 m horizontally in Enceladus's gravity allowing traversal of jets and collection of direct measurements otherwise not accessible to Orbilander. These measurements could be crucial for investigating the physics of how the plume is connected to the ocean.

Herein, we develop several key components of the LEAP concept. Our Science Traceability Matrix identifies key science objectives, investigations, and a corresponding set of potential instrument payloads. We identify suitable materials for key hardware subsystems, with a focus on accommodating energetic loads at cryogenic conditions and maintaining appropriate thermal boundary conditions. We study and coalesce on a viable Concept of Operations (ConOps), and include preliminary activities, power budgets, and mission duration. We report on thermal modeling implications for our robot design, material selection, and ConOps. We describe key takeaways from the robotic test campaign in engineered regolith simulants. Finally, we propose next steps for investigation of this exciting Enceladus mission concept, as well as highlight alternate applications.

Keywords: Enceladus, Surface Robotics, Hopping



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SUMMARY OF ACRONYMS

AFT Allowable Flight Temperature. 42, 52, 54, 64

CG Center of Gravity. 14, 15

ConOps Concept of Operations. 59, 60, 63–65

COTS Commercial Off The Shelf. 43

CTE Coefficient of Thermal Conductivity. 39

DTO Direct To Orbit. 64

ESC Electronic Speed Controller. 43

Fillite Fillite high-sinkage medium. 3, 22–24, 27, 29, 31, 35, 37

FSW Flight Software. 60

GRC-1 GRC-1 lunar simulant. 3, 22–26, 29, 31, 38

GRC-3 GRC-3 lunar simulant. 20

IMU Inertial Measurement Unit. 43

KOZ Keep Out Zone. 60, 63

MEMS Micro-Electro-Mechanical Systems. 10

MLI Multi-Layer Insulation. 41, 42, 50, 52, 53

MMLI Modular Multi-Layer Insulation. 42

MSR Mars Sample Return. 20

RHU Radioisotope Heater Unit. 42, 50, 64

SE+PM Series-Elastic Power Modulation. 12, 13

SME Subject Matter Expert. 39

SMLI Spacerless Multi-Layer Insulation. 42

SRL Sample Return Lander. 20

STM Science Traceability Matrix. 9

1 SCIENCE TRACEABILITY

1.1 Overview

Enceladus is unique among the high-value astrobiology destinations in the solar system, as it appears to meet all criteria for habitability [10], and material from this habitable ocean is directly accessible via the plume without the need to dig or drill [17]. The Enceladus Orbilander concept [43] would perform detailed science measurements of the plume during both a 1.5 year orbital phase and 2 year landed phase. Measurements would include compositional analysis of the plume vapor phase during orbit, and plume ice grains during both orbit and after landing. While the Orbilander would collect sufficient plume material to address key habitability and astrobiology questions, it would not have access to emissions of individual jets (which combine to form the mixed plume at higher altitudes) and potential diffuse eruptions immediately along the fissures that would enable optimal interpretation of those measurements, and provide key data on plume eruption mechanics (partitioning between the grain and vapor phase as the plume expands into space) and plume composition (comparing jet-to-jet variability of salts, organics and putative biomolecules). Further, access to plume material not exposed to UV radiation or other surface processing for extended periods of time will always be preferred from a science perspective [12], particularly for astrobiology investigations. Leaping robots could access jets by covering large distances in low gravity and circumventing challenging terrain features and even chasms. Jumping robots with small size / weight provide compounded benefits – both reducing cost and mass, and exhibiting high robustness to impacts like those experienced in jumping [34].

We propose Legged Exploration Across the Plume (LEAP), based on the **Salto jumping robot**, as a novel multi-jet robotic sampling concept for Enceladus (Fig. 1). LEAP combines large, controllable jumps that enable direct sampling of plume material along transects through jets or diffuse (curtain) eruptions at varying elevations, with long range that enables visits to multiple jets. Salto is a small, 118 gram, 30 cm jumping robot designed around one powerful, series-elastic, straight-line eight bar linkage leg [28, 29]. On Earth, Salto jumps 1.25 m, enough to leap 90 m vertically and 170 m horizontally at an optimal 45 deg angle on Enceladus.

Series elasticity allows Salto's leg to capture and return 60% of hopping energy to operate for over 10 minutes and 800 jumps with a small, 220 mAh, 16.8 V battery. The robust prototype has survived many thousands of jump cycles and hundreds of crashes over five years with only minor repairs. Minimal onboard processors and proprioceptive and inertial sensors are sufficient for autonomous operation outdoors [70], allowing LEAP to operate independently. Since its energy use depends most strongly on number of jumps and not jump distance, in Enceladus's gravity, its operating range could cover dozens of kilometers on one battery charge. Pronounced eruptions believed to be from individual jets are on average spaced 5 km apart along a fissure at Enceladus [32], so LEAP could explore multiple jets as well as any diffuse emission between them. Furthermore, the all-electric LEAP avoids contaminating potential sampling sites with propellant.

Salto's high-power, series-elastic leg uniquely enables three key capabilities for a LEAP mission: (1) continuous hopping with no wind-up, (2) energetically efficient locomotion over long distances via energy recapture, and (3) unique maneuvers like wall jumps on vertical surfaces that enable new, terrain-reactive exploration capabilities. In particular, Salto has demonstrated jumps on vertical surfaces [28] like ridge walls, soft dissipative surfaces [70] like accumulated ice particles, and narrow features [68, 69] like ledges. Interestingly, wall jumping on Earth has already demonstrated operation in conditions with near-zero gravity normal to the surface, which adds precedence for jumping on low-gravity worlds.

In developing LEAP, we will augment demonstrated Salto locomotion capabilities with two main mechanical systems: (1) a pair of reaction wheels that provide roll and pitch orientation control during the long flight phases over Enceladus, on-ground mobility on compacted regolith, and self-righting after tumbles and (2) design of a new broad and traction-enhanced foot for interaction with both slick icy surfaces and deep accumulations of uncompacted ice particles. In addition, we will evaluate a representative sensor payload / avionics, investigate hardware adaptations for the cryogenic environment, and theoretically analyze low-gravity jump dynamics.

1.2 Enceladus Representative Mission

LEAP's primary mission is to deploy from Enceladus Orbilander as a low-mass leaping "rover" to directly measure plume gas pressure, particle flux, and particle size distribution by repeatedly leaping through multiple jets along one or more "tiger stripe" features near the Enceladus south pole. A high-level concept of operations is provided in Fig. 1.

Important questions regarding the habitability and astrobiological potential of Enceladus' subsurface ocean, as well as the evolution and interplay of the moon's interior, can be addressed via measurements of plume vapor and ice grains. However, many of these questions depend on reliably tracing measurements of key species in the plume back to expected concentrations in the ocean. Different eruption mechanics could lead to fractionation via gas exsolution [46], vapor condensation (on conduit walls) and other processes, which may lead to species either being enriched or depleted in the plume. Current plume models are based on Cassini flythrough measurements of vapor and particle flux down to 49 km, above the altitude where individual jets combine to form a single plume (45 km). Measurements along a fissure at the surface, where the material exits the vents, would greatly improve understanding of how the plume connects to the ocean and enable robust derivations of ocean concentrations for species measured in the plume (e.g., CO₂, CH₄, H₂, NH₃, salts and biosignature molecules such as amino acids and fatty

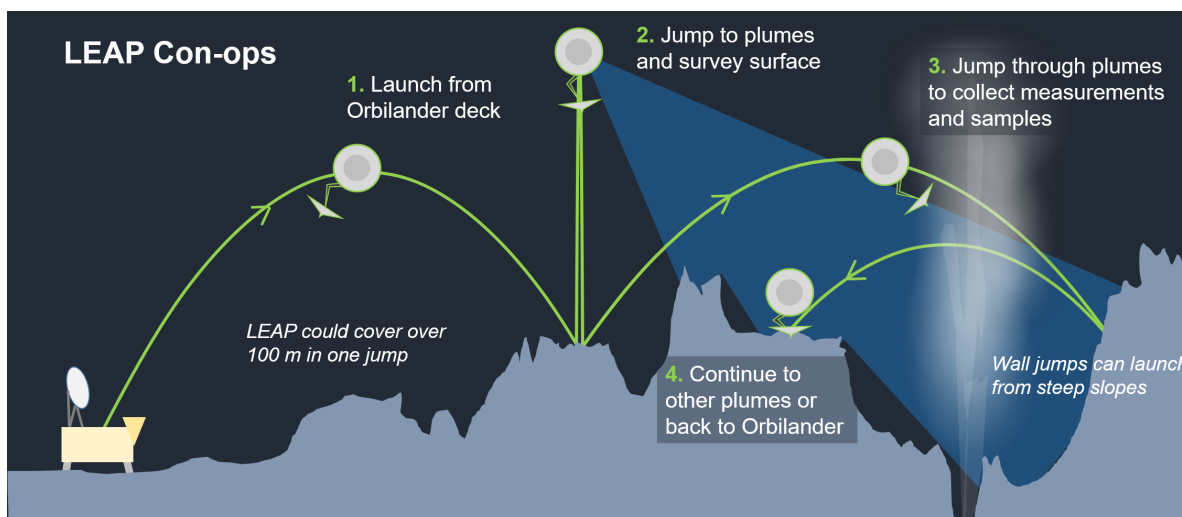


Figure 1. High-level concept of operations for small leaping rovers deploying from Orbilander to collect direct measurements from jets.

acids).

In situ measurements of jet properties would help constrain plume eruption mechanics. By quantifying the pressure and particle flux at different points, LEAP would provide the data needed to determine whether the jet model or curtain model is the dominant eruption mechanism. Collection of plume material would also be enabling: a sample of the plume gas and grains could help constrain how volatiles partition between solid and vapor phases, enabling much improved estimates of how concentrations of salts and key biomolecules in the plume trace back to concentrations in the ocean. In addition, samples from different jets could help address jet-to-jet variability which might lead to enrichment or depletion of certain species in the bulk plume.

The notional LEAP payload includes a pressure sensor to quantify jet gas emissions, an imager / LIDAR for high-resolution imagery and topography of fissures, and heat management for instruments and electronics. While our development focuses on this representative payload, we will explore alternative sensors such as particle flux sensors (e.g. HRD on Cassini). LEAP will self-launch from the Orbilander deck using its electrically actuated leg and will use orbital and descent imagery to reach a safe, hazard-free staging location (and avoid contamination of the Orbilander's surrounding workspace). For subsequent jumps, LEAP will use onboard imaging / ranging sensors to self-localize and refine orbital terrain maps as it navigates to pre-identified sample sites. Leaping vertically in place 10s of meters high over known terrain will allow LEAP to achieve long sightlines and extend high-resolution maps before planning subsequent jumps that progress to new targets. With sufficient contamination control mitigations, LEAP might return periodically to the Orbilander – either to drop off pristine plume particle samples for detailed analysis by Orbilander instruments or to recharge onboard batteries.

1.3 Enabling Other Planetary Science & Lunar Missions

The technology of LEAP has potential science benefits at other planetary destinations, in particular low-gravity environments with varied surface terrain types, challenging topography, and potentially no atmosphere.

On Ceres high-resolution LIDAR mapping of the domes and fractures within Occator Crater could better constrain their ages, and whether they formed from cryo-hydrologic or cryovolcanic processes [49], shedding light on an ocean world in its final stages.

On Pluto imaging transects along apparent compositional gradients could help distinguish between formation mechanisms (e.g., cryovolcanism versus impact for the Kiladze area [22]).

On Titan constraining the grain size and hardness of material comprising the equatorial dunes in steep areas inaccessible by Dragonfly would support saltation and transport models important for understanding Titan's evolution, and the ultimate sink of organics generated by photochemistry in the atmosphere [40].

On the Moon LEAP could perform rapid scouting to generate high-resolution terrain imagery / DEMs (substantially better than the 0.5-1 meter/pixel resolution of orbital maps) to support Endurance-A rover autonomous navigation across challenging terrain and when the rover arrives at each of the dozens of scientific sampling locations, similar to the pairing of the Perseverance rover and Ingenuity helicopter. LEAP can also serve as a rapid scout for astronaut-led missions on the lunar surface.

On Earth understanding jumping on unconsolidated granular materials also enables leaping on dust, regolith, sand, and similar materials. Jumping on ice particles specifically may enable efficient traversal of terrestrial snow and ice to support scientific missions or search and rescue in cold and remote environments like Earth’s mountains or polar regions. Jumping locomotors could exhibit multiple advantages compared to rotorcraft UAVs including avoiding the production of downwash that may fling snow, a lower sensitivity to wind, and avoiding the dangers of fast spinning blades.

1.4 Science Mission & Science Traceability Matrix

We have developed a preliminary Science Traceability Matrix (STM) (Table 1) that defines science objectives, measurements, and instruments for a multi-jet sampling mission that aligns with the goals of the Planetary Science and Astrobiology Decadal Survey [50]. Specifically, LEAP would address Decadal Q10.1: “Understand interior structures, tidal dissipation dynamics, and surface-interior exchange for icy shells of ocean worlds via measurement by spacecraft, theory, and modeling to determine the magnitudes and timescales of heating and persistence of liquid water.” While no landed Enceladus mission architecture was included in the Decadal Survey, one of the science objectives listed for the Enceladus Multiple Flyby (EMF) concept is appropriate to respond to this question: “Characterize Enceladus’s cryovolcanic activity to determine spatial and compositional variations in plume activity and the processes causing ocean material ejection and modification.” LEAP would address this science objective with sets of measurements covering plume activity and processes.

To constrain the spatial and compositional variability of the plume (LEAP Science Objective 1), LEAP will utilize the full payload (flux sensor, light optical aerosols counter (LOAC), mass spectrometer, pressure sensor and temperature sensor) to characterize the physical properties of diffuse (fissure)-sourced and collimated point (jet)-sourced emissions (LEAP Measurement Objective 1a) and measure the volatile composition and assess the vapor-to-particle ratio along a Tiger Stripe transect and as a function of Enceladus’ orbital period around Saturn (LEAP Measurement Objective 1b). By performing these measurements in at least three locations of diffuse emission and in at least two collimated jets along a Tiger Stripe, LEAP will enable comparison between these different emission sources over space and time.

To identify the primary mechanism driving ejection of plume materials and constrain the extent of fractionation of plume materials, LEAP will measure plume particle flux, abundance of volatiles (H₂O, CO₂, CH₄, NH₃ and H₂) and vent wall temperature. This will enable differentiation between the most likely models of eruption, namely static boiling/turbulent dissipation, sublimation, volatile exsolution or clathrate destabilization. If the static boiling/turbulent dissipation model dominates, we would expect fractionation at the boiling interface, latent heat release from condensation, and an ice/vapor ratio in the range 0.01-0.1 [48, 33, 38]. If sublimation is the primary mechanism, we would see higher abundances of volatiles, fractionation, and an ice/vapor ratio <0.4 [26, 35]. For volatile exsolution, we would not expect any fractionation, high levels of H₂, CO₂, and CH₄, and an ice/vapor ratio of ~6 in the collimated jets [46, 45]. Finally, clathrate destabilization would result in high levels of CH₄ but little if any H₂ [13]. Distinguishing between these various eruption mechanisms will be critical to tracing plume compositional measurements back to true composition in the subsurface ocean.

Measurement requirements for LEAP are based on current state-of-knowledge from in situ plume measurements made previously by Cassini, as well as remote sensing and telescopic observations. The plume gas velocity is predicted to be approximately 400 m/s for the diffuse emission sources (thermal velocity) and 800 m/s for the collimated jets [23]. The vertical gas velocity derived from measurements made by Cassini UVIS’s high speed photometer (HSP) is 609 m/s [30], within this same range. Converting gas velocity to pressure with Bernoulli’s principle:

$$p_d = 1/2 * \rho * v^2 \quad (1)$$

we predict the dynamic pressure (p_d) in a collimated jet with gas velocity of 800 m/s and gas density of 1×10^{-14} H₂O/m³ to be 9.6×10^{-10} kPa. For plume production rate, we used 4×10^{11} to 8×10^{11} particles/sec for diffuse sources, 1.5×10^{12} to 3.8×10^{13} particles/sec for collimated jets [23]. Based on this same model [23], the expected dust density at an altitude of 100 m above the surface of Enceladus should be $\sim 4.5 \times 10^{-8}$ g/m³.

Thus, even within the high-speed collimated jets, the estimated gas pressure (9.6×10^{-10} kPa) and particle density (4.5×10^{-8} g/m³ 100 m above the surface) is extremely low. This is significant and enabling for the LEAP mission:

1. LEAP robots (at 1 kg / 100s cm² cross-sectional area) will experience minimal disturbance, enabling accurate jumps / landings even when jumping directly through the densest collimated jets (and the robots will not be blasted off the Enceladus surface)
2. Onboard optical sensors (cameras / LIDAR) will be able to see through the collimated jets, enabling mapping, hazard identification, and planning of safe jumps across the Tiger Stripe fissure

Number of Robots A single, sufficiently capable LEAP robot carrying all 5 instruments and given sufficient time should be able to perform all identified tasks in the STM (Table 1). However, the top-level LEAP mission requirements instead baseline 2 robots (science-motivated), and there are compelling reasons to instead send 4 robots (operations-motivated).

Operating **2 robots** enables each robot to be dispatched directly to a separate active collimated jet, with measurements of the diffuse plume emissions at requisite intervals along the Tiger Stripe on the way to / from the collimated jet location. This maximizes science return, minimizes time / risk to meeting the LEAP mission requirements, and allows measurements to be collected at different times across Enceladus’ orbital period at each jet (2a2). If one robot fails, the second robot can continue to complete measurements at both collimated jet locations.

Operating **4 robots** enables pairs of robots to be dispatched directly to the two active collimated jets, while working together to overcome mapping / navigation challenges (e.g. environment illumination) and return valuable science data to Orbilander if one robot fails. Operating paired robots also introduces new capabilities, including: (1) the ability to perform coordinated scientific measurements (e.g. particle image velocimetry, by having one robot illuminate the collimated jet while jumping through it, and the other robot recording the illuminated particles from a fixed vantage point), and (2) the ability to share greater variety of science instruments across the two robots. This enables new science return and further minimizes time / risk to meeting the LEAP mission requirements.

Sample Return to Orbilander The size, mass, and power constraints of the LEAP robots drive significant concessions in the capabilities / quality (e.g. sensitivity, accuracy, range) of the Micro-Electro-Mechanical Systems (MEMS) scientific instruments that will directly measure the plume. While LEAP’s instruments will be sufficient to meet the “Instrument Functional Requirements” in the STM (Table 1), the Orbilander will support significantly superior instruments. Unfortunately, the Orbilander is immobile after landing on the surface near a Tiger Stripe, and the Orbilander instruments are limited to measuring ejected material that falls on / around Orbilander.

Future work will identify potential benefits of a plume sample retrieval, enabled by LEAP, to enhance the science return of the Orbilander concept. Access to pristine plume sample will be balanced against complexity of interfaces for sample delivery to Orbilander and additional functional requirements on LEAP.¹ A viable sample return capability requires defining, designing, and implementing a hardware system capable of: capturing a minimum viable sample volume (potentially requiring multiple jumps through a collimated jet), adhering to planetary protection and sample handling constraints, preserving captured sample for the duration of transport, and delivering the sample to Orbilander in a pristine state.

1.5 Science Payload

The total science instrument payload is highly constrained on all spacecraft, but especially so on LEAP, where we will directly trade payload mass for jump height / range. For the 1 kg LEAP robot, we can reasonably allocate only 10% of total spacecraft mass (100 grams) to science payloads. Conventional laboratory versions of each instrument in the STM are often on a similar size- / mass-scale to the full LEAP robot, so LEAP must leverage sufficiently capable MEMS sensors / instruments to meet the combined science and mass requirements. We conducted a preliminary investigation of relevant MEMS instruments that meet each instrument functional requirement, and found a viable technology for each.

Particle Flux is measured by a MEMS ultra-fine particle (UFP) detector [37].

Particle Size Distribution is measured by a MEMS light optical aerosol counter (LOAC) [56].

Volatile / Gas Composition is measured by a MEMS quadrupole mass spectrometer [60].

Gas Pressure is measured by a MEMS squeeze film absolute pressure sensor [57] or a touch-mode MEMS capacitance diaphragm gauge [41].

Plume / Surface Temperature is measured by a Cernox temperature sensor [15] or a thin-wire thermocouple [47]. Non-contact thermal infrared sensors (used on the Mars Perseverance Rover [47]) were also considered, but lose effectiveness below 220K.

¹The current LEAP implementation attempts to minimize interfaces between LEAP and Orbilander, in a manner inspired by the Ingenuity helicopter / Perseverance rover combination on Mars. Sample return requires a significant expansion of interfaces, and a potential redesign of the Orbilander science payloads itself to accommodate sample handling and delivery to the Orbilander instruments. For this reason, we have deprioritized this study for Phase I, but do aim to explore this capability in future work.

OWLS Decadal Survey Goal (Q10.1)	EMF Science Objective (OWLS)	LEAP Science Objectives	Measurement Objectives	Measurement Requirements	Flux sensor	LOAC	Mass Spectrometer	Pressure sensor	Temperature sensor	Instrument Functional Requirements					LEAP Mission Requirements (Top Level)
										Flux sensor	Light Optical Aerosols Counter	Mass Spectrometer	Pressure sensor	Temperature sensor	
										[Particle flux]	[Particle size distribution]	[Volatile / gas composition]	[Gas pressure]	[Plume or surface temperature]	
Understand interior structures, tidal dissipation dynamics, and surface-interior exchange for icy shells of ocean worlds via measurement by spacecraft, theory, and modeling to determine the magnitudes and timescales of heating and persistence of liquid water.	Characterize Enceladus' cryovolcanic activity to determine spatial and compositional variations in plume activity and the processes causing ocean material ejection and modification.	ACTIVITY	1. Plume activity: Constrain the spatial and compositional variability of the plume.	1a. Constrain the spatial variability of the plume by characterizing the physical properties of diffuse (fissure)-sourced and collimated point (jet)-sourced emissions.	1a1. Plume particle flux for grains $\leq 0.3 \mu\text{m}$ (diam), particle size distribution (1-30 μm) and gas velocity (pressure) and temperature in at least three locations of diffuse emission and in at least two collimated jets along a Tiger Stripe.					Particle size range: 0.05-0.30 μm	Particle size range: 1-30 μm Particle size uncertainty: 10 %	Mass range: 2-44 u (H_2 to CO_2) Mass resolution: 18 m/ Δm (to distinguish NH_3 from H_2O) Sensitivity: 1000 ppm (0.1 % mixing ratio for CH_4) Precision: 500 ppm (50 % at 1000 ppm)	Pressure range: 0 to 1e-6 kPa Pressure precision: 10%	Temperature range: 50-280 K Temperature precision: ± 10 K	Mission Design: - Land within 1 km of a Tiger Stripe, between two active jets (each within 3 km of the landing site). - Deploy 2 LEAP hoppers, one to each active collimated jet. - Perform ≥ 3 jumps through the diffuse plume emission at 3 m/s horizontal velocity and 50-100 m altitude, at a distance of ≥ 250 m apart. - Perform ≥ 5 jumps at different points in Enceladus' orbit period in diffuse plume emission. - Perform ≥ 2 jumps through two different collimated jet emissions at 3 m/s horizontal velocity and 50-100 m altitude. Operations: - Operate payload while in plume during jumps. - Operate pressure/temperature sensor while in plume during jumps and at crevasse edge prior to jumps.
				1b. Constrain the compositional variability of the plume by measuring the volatile composition and assessing the vapor-to-particle ratio along a Tiger Stripe transect and as a function of Enceladus' orbital period around Saturn.	1b1. Abundance of H_2O , CO_2 , CH_4 , NH_3 and H_2 in at least three areas of diffuse emission and at least two collimated jets in a horizontal transect along a Tiger Stripe and as a function of Enceladus' orbital period around Saturn.					Velocity range: 1-800 m/s Production rate: $4\text{e}11 - 3.8\text{e}13$ particles/sec Particle density: $4.5\text{e}-8 \text{ g m}^{-3}$	Velocity range: 1-800 m/s Particle concentration uncertainty: 50%				
					1b2. Plume particle flux for grains $\leq 0.3 \mu\text{m}$ (diam), particle size distribution (1-30 μm) and gas velocity (pressure) in at least three areas of diffuse emission and at least two collimated jets in a horizontal transect along a Tiger Stripe and as a function of Enceladus' orbital period around Saturn.										
		PROCESSES	2. Eruption mechanism: Identify the primary mechanism driving ejection of plume materials to constrain the extent of fractionation of plume materials.	2a. Determine if plume eruptions are driven primarily by static boiling, sublimation, volatile exsolution, clathrate destabilization or another mechanism by measuring the physical properties, volatile composition and vapor-to-particle ratio of diffuse (fissure)-sourced and collimated point (jet)-sourced emissions.	2a1. Plume particle flux for grains $\leq 0.3 \mu\text{m}$ (diam), particle size distribution (1-30 μm) and gas velocity (pressure) and temperature in at least three locations of diffuse emission and in at least two collimated jets along a Tiger Stripe.					Flux sensor (MEMS UFP Detector)	Light Optical Aerosols Counter (LOAC)	Mass Spectrometer (mQMS)	Pressure sensor (Squeeze Film)	Temperature sensor (Cernox)	
					2a2. Abundance of H_2O , CO_2 , CH_4 , NH_3 and H_2 in at least three areas of diffuse emission and at least two collimated jets in a horizontal transect along a Tiger Stripe and as a function of Enceladus' orbital period around Saturn.					Particle size range: 0.02-0.30 μm Production rate: $320 - 1\text{e}6 \text{ cm}^3$	Particle size range: 0.2-100 μm Particle (p) size uncertainty: $\pm 0.025 \mu\text{m}$ ($p < 0.6 \mu\text{m}$) 5 % ($0.7 < p < 2 \mu\text{m}$) 10 % ($p > 2 \mu\text{m}$) Velocity range: $1.3 - 2.7 \text{ L/min}^*$ Particle (p) concentration uncertainty: $\pm 20 \%$ ($> 1 \text{ p/cm}^3$) $\pm 60 \%$ ($< 0.01 \text{ p/cm}^3$) Sampling rate: 40 kHz	Mass range: 1-200 u Mass resolution: 50 m/ Δm Sensitivity: 500 ppm Precision: 20 %	Pressure range: 10e-7 to 0.1 kPa Pressure sensitivity: 2e-7 kPa	Temperature range: 0.1-325 K Temperature precision: $\pm 13-60 \text{ mK}$ Response time: 0.05-2 sec Radiation tolerance: Yes	
					2a3. Temperature at or near the walls of the crevasse in close proximity to diffuse and jet emissions.										

*Based on LOAC pump for operation in Earth's atmosphere; need to confirm if modifications would need to be made for operation in vacuum.

Table 1. LEAP Science Traceability Matrix. Candidate MEMS sensors have been identified to perform all requisite measurements of the Enceladus plume, including particle flux [37], particle size distribution [56], volatile / gas composition [60], gas pressure [57, 41], and plume / surface temperature [15].



Figure 2. Isometric view of robot platform displayed in CAD

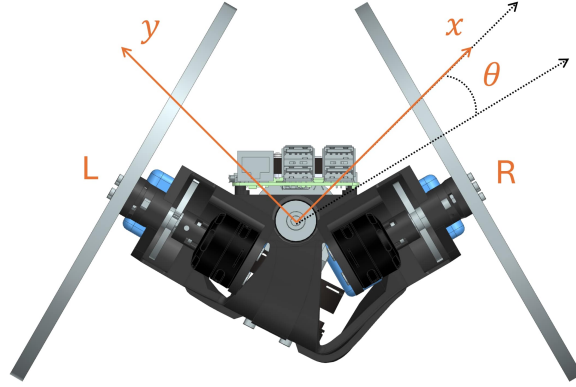


Figure 3. Robot platform from above. The 15-degree cant angle, θ , of the wheels allows for balancing and aerial reorientation while maintaining differential drive features.

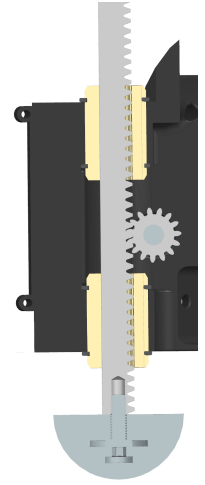


Figure 4. Rack and pinion design for jumping leg

2 MULTIMODAL JUMPING AND ROLLING

We built a testbed platform shown in Fig. 2 with one leg and two multi-purpose wheels to explore combinations of rolling and jumping locomotion. On flat surfaces, its two wheels enable it to roll like a typical differential drive mobile platform using its wheels. On granular media and uneven terrain, the platform can stand up and balance on its single leg, then lean and jump in desired directions. In flight, the platform can reorient itself with its reaction wheels and point its leg in any direction to land precisely. This platform could be uniquely suited to explore small bodies like Enceladus where the low gravity enables enormous jumps to cross gaps and fissures, collecting data and surveying the landscape. Using the two locomotion modes, it could provide an efficient and versatile method of traveling. Development of this prototype and its controllers was published in the 2026 IEEE International Conference on Robotics and Automation (ICRA) [65].

2.1 Locomotion Design

For the platform, two wheels are needed to serve as reaction wheels to balance and as differential drive wheels. The wheels cannot be parallel so that there is control authority in two directions, while both are perpendicular to the jump axis as to not induce yaw while balancing. The angle between the wheels adjusts the capability of the rolling and balance modes as the closer to parallel they are, the more efficient the rolling is and the less authority the platform has over balance and reorientation. The cant angle used on the prototype is shown in Fig. 3.

The prototype developed consists of two wheels that are at a cant angle of 60° and perpendicular to the z-axis which the leg drives along. The leg of the prototype actuates in a straight line using a rack and pinion described below in section 2.2.1. The cant angle was chosen to allow for both strong rolling control and enough balance control to sustain impacts, directionally lean, and reorient in the air quickly. The prototype's mass is 1.25kg with a leg stroke of 0.2m. The overall size of the robot is about 27cm^3 .

2.2 Jump Propulsion

2.2.1 Direct-drive testbed

The prototype's single leg is a rack and pinion shown in Fig. 4 driven by a Vertiq 40-06 370Kv motor. It uses a 300 mm long circular steel rack and 1.5 cm diameter 15 tooth pinion. The simple rack and pinion, instead of a linkage-based design of other robotic jumping platforms [39, 73, 29], allows evaluation of custom torque profiles for the jump mechanism. While torque profiles were held constant in phase I tests, in future work, we plan to simulate candidate linkage mechanisms to evaluate which are most suitable. The rack and pinion leg stores no elastic energy on landing, making our design less efficient but more versatile for evaluating the future design of the leg.

2.2.2 Series-elastic Power Modulation

The jump height of electric robots is often limited by the peak power of the jump motor, maximum energy storage in devices like springs, or by the peak allowable force dictated by leg or substrate material strength. We therefore compared the peak electrical power consumption and peak force transmitted to the ground in simulations of different designs. In parallel to construction and testing of the direct-drive physical prototype, we also simulated Series-Elastic Power Modulation (SE+PM) leg propulsion

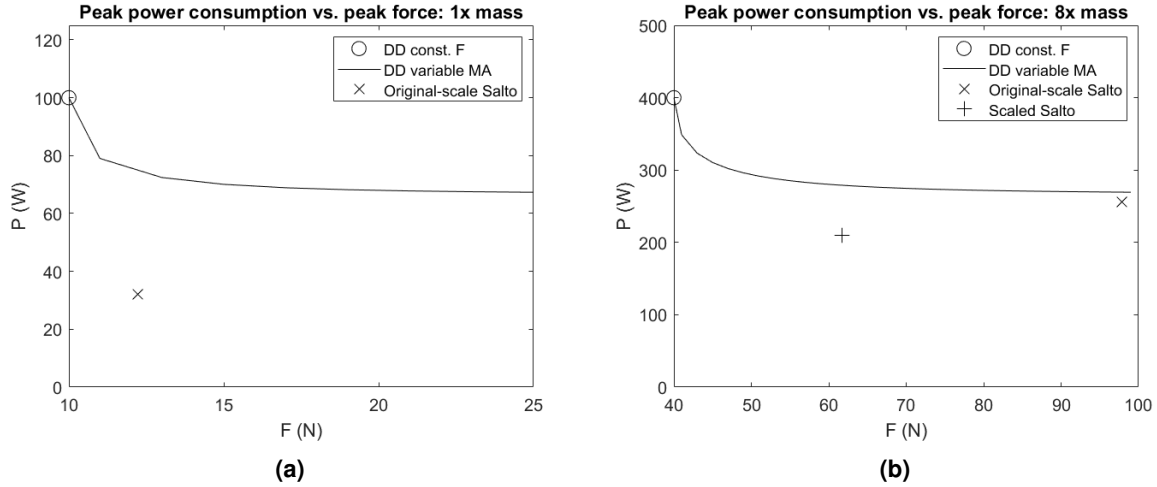


Figure 5. Simulation comparison of series-elastic power modulating and direct-drive (no additional energy storage) electric jumping leg designs' peak power and force at different size scales.

based on the Salto leg scaled up to the size of the LEAP concept [28]. SE+PM (termed power amplification in biological literature) enables a small jumper's leg to briefly output a higher power than its actuator's peak mechanical power output by storing and then releasing elastic potential energy during the jump. Since the time during which a jumper can accelerate its body is limited by the length of its leg, smaller jumpers with shorter legs generally require higher power to make high jumps and thus SE+PM can help reduce actuator peak power requirements for particularly small jumpers.

Since the LEAP concept is enlarged from the previously developed Salto robot to carry greater onboard computation and instruments, we analyzed the relationship between jumping robot scale, power, and force. We developed two simulations in Matlab, one based on prior Salto publications and one based on a rack and pinion leg transmission. To analyze the effect of scale, we assumed a fixed target liftoff velocity of 5 m/s (a 110 m high jump) and varied leg length in the simulations while assuming isometric scaling of the robot geometry so that mass increases as the cube of leg length scale. With cubic increase in mass and constant liftoff velocity with length, jump energy increases cubically with length but force scales quadratically since propulsion force is applied over the length of the leg stroke.

The choice of mechanical advantage profile over the extension of the leg determines the peak force and peak power in a direct-drive leg without auxiliary energy storage mechanisms like springs. The lowest force jump that reaches a given liftoff velocity is achieved by a mechanism that holds the force at a constant value. However, this design requires significantly more power at the end than the start of the jump since mechanical power rises linearly with velocity in this case. The optimal variable mechanical advantage transmission to minimize power requires extremely high force at the start of the jump. Since mechanical power is force times velocity, the optimal mechanical advantage is near infinite at the start when the velocity is near zero. Our direct-drive simulations thus consist of two phases: first, the robot accelerates at constant force until a peak power is reached, then the robot accelerates according to a constant power profile. In our direct-drive simulations, we set varying maximum force limits and numerically find the required peak power to reach the target liftoff velocity. To calculate peak electrical power consumption, we assume a leg transmission design for which the motor operates at its peak power point of one-half free running speed when the mechanical power demand is at its peak. DC electric motors are 50% efficient at the peak power point so peak electrical power consumption is double the peak leg mechanical power according to this assumption.

As shown in Fig. 5a, Salto's SE+PM achieves a dramatically lower combination of peak force and peak power at its original scale of 0.15 m leg extension and 0.12 kg mass. For a Salto leg design scaled up to the size of the LEAP concept with a 0.3 m leg extension and 1 kg mass, the combination of peak force and power are still lower than that achievable by optimal direct-drive designs, but the difference is less dramatic as shown in Fig. 5b. Note that the Salto design at its original 0.15 m length carrying the scaled up 1 kg robot mass requires both higher power and force than the scaled-up design, highlighting the benefit of the longer leg stroke. The benefit of decreased power and force demands with a larger sized leg presents an interesting tradeoff against impact robustness which favors smaller robots as described in [34].

2.3 Flight Orientation

2.3.1 Orientation Control

In flight, the platform must reorient from its launch attitude so that it can land on its foot. To do this, the platform should be able to point its foot in any direction while accommodating residual angular momentum retained at takeoff. This is particularly difficult with only two reaction wheels since they do not fully actuate the platform's attitude in the same manner as

a conventional combination of three reaction wheels; they lack direct control of rotation about the body-fixed z-axis that is perpendicular to both wheel axes. However, we chose to use only two wheels since this configuration avoids a third wheel obstructing rolling motion, reduces system weight and complexity, and is still sufficient to achieve the desired pointing control as described below.

Previous robots achieve in-flight foot pointing in varying ways, such as Salto-1P's thrusters directly applying torque about the z-axis to counteract any non-zero angular momenta encountered at launch [29]. Other jumping robots use a two degree of freedom servo joint at the base of the leg, like the Raibert Hopper [55] or the 3D bow-legged hopper [72]. This method would severely limit the range of motion that our leg could aim in and require additional actuators, increasing complexity and power consumption. Using the reaction wheels that will also be used in the balancing and rolling modes, we can increase the capability of our underactuated system without adding additional components. While they do not provide direct control over rotation about the body-fixed z-axis, controlling this rotation is not strictly necessary since the alignment of the leg and foot with the system's z-axis means that rotation about this axis does not change the direction that the foot is pointing.

The aerial controller commands motor torques for the left and right reaction wheel τ_R and τ_L respectively in order to drive the vector from the platform's Center of Gravity (CG) to the foot (along the leg axis) to align with a desired unit vector v_{foot}^0 with respect to the world-fixed frame 0. Since we are interested in controlling the direction of the leg, rotation around the axis of the leg during flight is acceptable since it does not change the leg's direction. Rotation about the leg axis may be induced by nonzero angular momentum at liftoff remaining from the dynamics or disturbances during launch. Thus, we first derive reaction wheel torque commands that cancel out gyroscopic precession induced by angular momentum of the reaction wheels in order to stabilize the leg pointing axis. Since the wheels are designed to have identical inertia tensors and spin about the tensor's major axis, the compensatory torque commands are given by:

$$\begin{aligned} \tau_{gyro,R} = & I_{wheel} \cdot \omega_R \cdot \omega_{b,z}^b \cdot \tan(2\theta) \\ & + I_{wheel} \cdot \omega_L \cdot \omega_{b,z}^b / \cos(2\theta) \end{aligned} \quad (1a)$$

$$\begin{aligned} \tau_{gyro,L} = & I_{wheel} \cdot \omega_L \cdot \omega_{b,z}^b \cdot \tan(2\theta) \\ & - I_{wheel} \cdot \omega_R \cdot \omega_{b,z}^b / \cos(2\theta) \end{aligned} \quad (1b)$$

where $\omega_{b,z}^b$ is the component of the angular velocity of the chassis relative to the world frame about the body-fixed z-axis, I_{wheel} is the moment of inertia of a wheel about its axle, ω_R and ω_L are the angular velocities of the left and right reaction wheels about their axles respectively, and θ is the cant angle as shown in Fig. 3.

After applying the precession cancellation torques, we can linearize the rotational dynamics about the desired pointing vector to derive a simple proportional-derivative feedback law. Expressing the desired pointing vector with respect to the body frame $v_{foot}^b = R_0^b v_{foot}^0$ using rotation matrix R_0^b from the world frame to the body frame yields the following expression for the controller:

$$\begin{aligned} \tau_R = & -k_p \cdot v_{foot,y}^b + k_d \cdot \omega_{b,x}^b + \tau_{gyro,R} \\ \tau_L = & k_p \cdot v_{foot,x}^b + k_d \cdot \omega_{b,y}^b + \tau_{gyro,L} \end{aligned} \quad (2)$$

where $\omega_{b,x}^b$ and $\omega_{b,y}^b$ denote components of vectors relative to the body-fixed x and y axes respectively.

2.3.2 Experimental performance

In experiments the prototype has achieved reorientation accuracy within 2° . This level of accuracy allows the system to conduct multiple jumps and land after jumping. The aerial reorientation is displayed in both Fig. 7 and 11.

2.4 Jump Aiming

2.4.1 Balance Control

To address balancing on the ground, we propose using two planar controllers, given in previous experiments [19], in the roll and pitch directions, respectively. To do this with two rotating masses that are not aligned with the coordinated planes aligned with roll and pitch, we combine the effects of each rotating mass such that they are coordinated for each controller in their component directions. The equations of motion of a planar reaction wheel pendulum given by the controller [19], is

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \ddot{q}_b \\ \ddot{q}_w \end{bmatrix} = \begin{bmatrix} mcg \sin(q_b) \\ \tau \end{bmatrix} \quad (3)$$

where H_{ij} are the elements of the joint space inertia matrix, $\ddot{q}$, are the joint acceleration variables with subscript w indicating the reaction wheel, and b indicating the body. τ is the joint torque that acts on the reaction wheel. c is the distance from the foot

to the CG of the robot, m is the mass of the robot, and g is the acceleration due to gravity. For the 3D robot, the equations of motion that we use for balance controller derivation are

$$\begin{bmatrix} H_{11} & 0 & H_{13} & H_{14} \\ 0 & H_{22} & H_{23} & H_{24} \\ H_{31} & H_{32} & H_{33} & H_{34} \\ H_{41} & H_{42} & H_{43} & H_{44} \end{bmatrix} \begin{bmatrix} \ddot{q}_x \\ \ddot{q}_y \\ \ddot{q}_R \\ \ddot{q}_L \end{bmatrix} = \begin{bmatrix} mcg \sin(q_x) \cos(q_y) \\ mcg \sin(q_y) \cos(q_x) \\ \tau_{R,w} \\ \tau_{L,w} \end{bmatrix} \quad (4)$$

where q_x and q_y refer to the angle of the chassis's tilt from vertical about the corresponding axis. Furthermore, as in the original controller, $\ddot{q}_x$ and $\ddot{q}_y$ can be replaced by the non-dimensionalized triple derivative of the angular momentum of the body about the foot's point of contact with the ground, $\ddot{M}_x$ and $\ddot{M}_y$. Rearranging the matrices, one can solve for the joint accelerations for the reaction wheels

$$\begin{bmatrix} H_{13} & H_{14} \\ H_{23} & H_{24} \end{bmatrix}^{-1} \begin{bmatrix} mcg \sin(q_x) \cos(q_y) - \ddot{M}_x H_{11} \\ mcg \sin(q_y) \cos(q_x) - \ddot{M}_y H_{22} \end{bmatrix} = \begin{bmatrix} \ddot{q}_R \\ \ddot{q}_L \end{bmatrix} \quad (5)$$

and therefore solve for the reaction wheel joint torques obtaining

$$\begin{bmatrix} H_{33} & H_{34} \\ H_{43} & H_{44} \end{bmatrix} \begin{bmatrix} \ddot{q}_R \\ \ddot{q}_L \end{bmatrix} + \begin{bmatrix} \ddot{M}_x H_{31} + \ddot{M}_y H_{32} \\ \ddot{M}_x H_{41} + \ddot{M}_y H_{42} \end{bmatrix} = \begin{bmatrix} \tau_R \\ \tau_L \end{bmatrix} \quad (6)$$

Now the two planar balance controllers use two sets of commands given by the control law to balance in 3D space on a point.

$$\begin{aligned} \ddot{M}_x &= k_{dd}\dot{M}_x + k_d\dot{M}_x + k_M M_x \\ \ddot{M}_y &= k_{dd}\dot{M}_y + k_d\dot{M}_y + k_M M_y \end{aligned} \quad (7)$$

The gains are found using the pole placement method discussed in the planar case [24], eq. 31-33. Using the small-angle approximation, $M_{x,y}$, $\dot{M}_{x,y}$, and $\ddot{M}_{x,y}$ become $T_{c,x,y}^2(\dot{q}_{x,y} - G_{\omega,x,y}\dot{q}_{R,L} - G_{\omega,y,x}\dot{q}_{L,R})$, $q_{x,y}$, and $\dot{q}_{x,y}$, respectively, with $T_{c,x,y}$ being the time constant of toppling and $G_{\omega,x,y}$ being the velocity gain in their respective planes.

2.4.2 Experimental performance

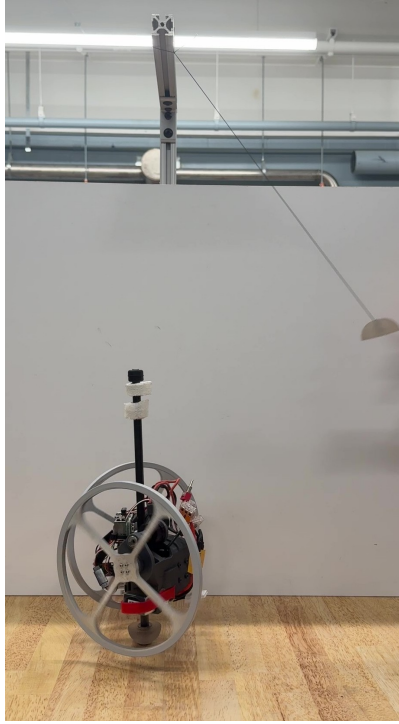
While the testbed is balancing, it may encounter outside forces from unknown sources. The ability to resist and reject disturbances demonstrates the robustness of the balancing controller. Fig. 6b displays known impact magnitudes to the testbed and the respective responses. In these tests a pendulum swings into the body of the testbed while it balances as shown in Fig. 6a. Due to the cant angle of the wheels, the balance controller has greater control authority over the forward and back directions than it does over left right directions.

In these experiments the balance controller rejected impulses of 0.01 *Nms* in both the forward-back and side-to-side directions. Fig. 6b displays the response to an example trial of an impact to the top of the testbed in the forward-back directions. The theoretical optimal control for this reaction wheel inverted pendulum system derived following [19] could reject a disturbance of 0.054 *Nms* but this theoretical value is not achieved due to measurement noise and other nonidealities.

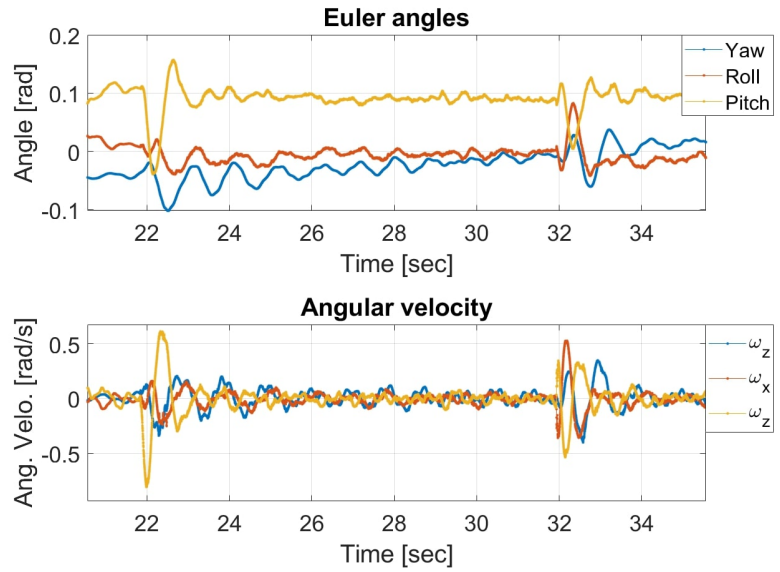
While balancing, the balance controller can lean the testbed to “point” towards a desired jump target. Upon reaching the desired angle, the leg motor quickly accelerates the testbed to make a lateral jump. During launch, leg encoder and IMU angular velocity measurements are fused to estimate the achieved liftoff velocity vector. After liftoff, the aerial controller aims the testbed's leg along the velocity vector in preparation for landing, though during the initial portion of flight, the leg angle is limited not to point above a threshold angle since landing is expected only after apex when the testbed's vertical velocity is negative. This aligns the leg so that after touchdown it can dissipate the energy of the jump using an impedance controller simulating a damper. The landing dissipation allows for a soft tumble, from which the robot can continue rolling or balancing immediately. Shown in Fig. 8a, the testbed launches at an angle of 20° from upright, jumping 0.59 *m* high and 0.82 *m* long and the aerial controller aligns the leg along the velocity vector as the testbed falls. After touchdown, the leg dampens the impact from the jump to land softly as shown in Fig. 8b. Note that on Enceladus with its weaker gravity, this jump performance would enable jumps over 40 *m* high and 60 *m* long. Since the launch and landing acceleration magnitudes are much greater than gravity on Earth, gravity can be considered a minor disturbance in the dynamics during the high-acceleration phases of motion and their behavior in lower gravity environments would be similar. However, residual velocity that results in a bounce after landing could cause longer flight times in lower gravity; in this case, aerial control could be again re-engaged for subsequent attempts at landing or the robot could self-right after coming to rest.

2.4.3 Jumping Accuracy

To accurately land in a position, the platform must be able to lean and jump accurately. The prototype demonstrates a sub-degree precision for straight and lean jumps on hard surfaces as shown in Fig. 27 and 29. This level of precision demonstrated the ability of the balance controller with leaning capabilities. This level of accuracy on jumps results in a landing accuracy of < 2cm on vertical jumps and about 6cm on a lean jump of 15°, both with a launch velocity of 3.2m/s.



(a) Test set-up for determining impulse rejection of the balance controller. Here the testbed is hit by a mass at the end on a pendulum against the highest point of the testbed.



(b) Euler angles and angular velocity of the testbed in balance disturbance experiments. A pendulum struck the testbed in the front-back direction at 22 and 32 s with impulse magnitudes of 0.013 Nms and 0.009 Nms respectively. The offsets from 0 in the Euler angles are due to the balance offset of the testbed since the center of mass is not located exactly along the leg.

Figure 6

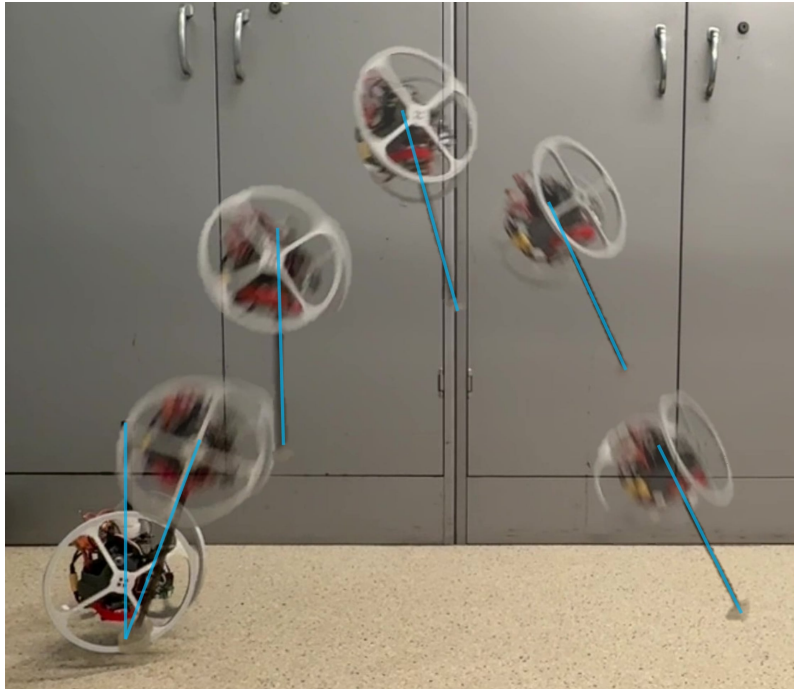
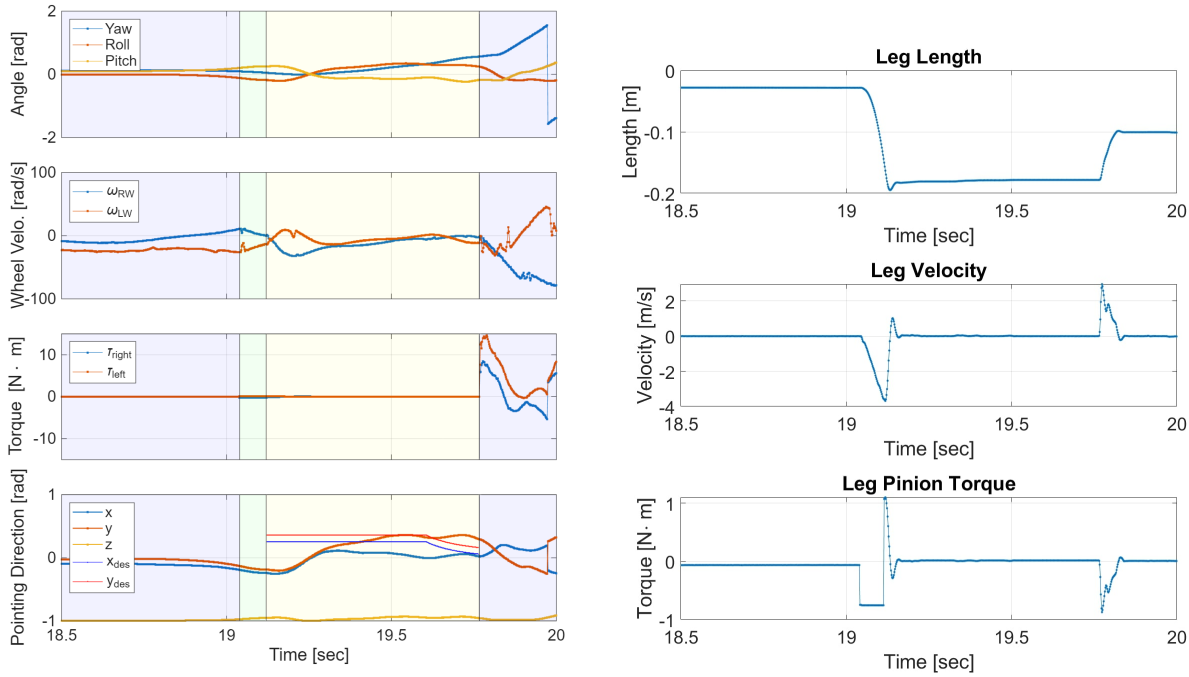


Figure 7. Testbed leaning and jumping, then reorientating itself in the air to point along the velocity vector. The data collected in this test is shown in Fig. 8a and Fig. 8b.



(a) Data traces from the lean jump depicted in figure 7. Chassis orientation Euler angles, wheel velocity and torques, and leg pointing direction are displayed. The colored regions indicate the change in testbed state: blue is balancing, green is jumping, and yellow is aerial.

(b) Leg position, velocity, and commanded torque from the leg motor. The first peak is the platform jumping by extending the rack and pinion. The second peak is the landing as the leg motor provides a counter torque to dampen the impact force.

Figure 8

2.5 Rolling

On its side, the platform can roll and steer like a differential drive system. Shown in figure 9, the prototype rolls in a figure eight shape showing ability to control its path on the ground. The prototype is able to drive when flipped over on the side with the narrower wheel base but usually drives on the side with the wider wheel base for greater stability. The platform can follow a pre-planned trajectory as shown here or accept input from a human user through a joystick.

2.6 Self-righting

To transition from rolling to jumping, a multimodal platform must self-right, orienting its leg down and initiating balance control. This behavior also provides robustness to crashes after a jump, since if it ends in a fall, the platform can land on a side and roll from there or re-right itself and jump again. Fig. 10a depicts self-righting, and Fig. 10b displays the associated Euler angles of the testbed. To get itself upright, it brakes quickly while moving forward to flip over. Then it extends its leg to shift its mass so that it tips upward. Lastly, it stands up on its leg and begins balancing.

The testbed can combine the above behaviors using the methods described to navigate complicated environments. Fig. 11 shows rolling and self-righting into the balance position at the base of a large step. Then, it leaps onto the step and damps out the impact of landing, perching itself on top of the ledge ready to roll away or initiate another leap. Fig. 12 shows the state machine states throughout the demonstration sequence through rolling, balancing, jumping, flight, and rolling again.

2.7 Conclusion

We demonstrated that despite underactuation, the LEAP concept can perform rolling and targeted jumping locomotion. The concept explores ways that future space platforms may explore the rough terrain and exotic conditions presented on extraterrestrial bodies, such as Enceladus. The two reaction wheel controllers allow the platform to balance on a point and reorient in the flight while using only two reaction wheels in a 3D space. This allows the platform to perform complex maneuvers while minimizing mechanical complexity. Specifically, we demonstrate the ability to roll, balance, self-right, and jump while having only three actuators in the entire platform. Each of these abilities show the potential of the LEAP concept.

In the future we plan to further develop the platform for extraterrestrial exploration by optimizing the efficiency of the systems, replacing the leg with a linkage that better suits the exploration domain, and introducing new maneuvers such as wall jumps, vaulting off of the leg, and instrument pointing to further increase this platform's ability. Additionally, the inclusion of vision capabilities will allow this platform to scout areas that may be desirable for exploration or safe to land and jump again.

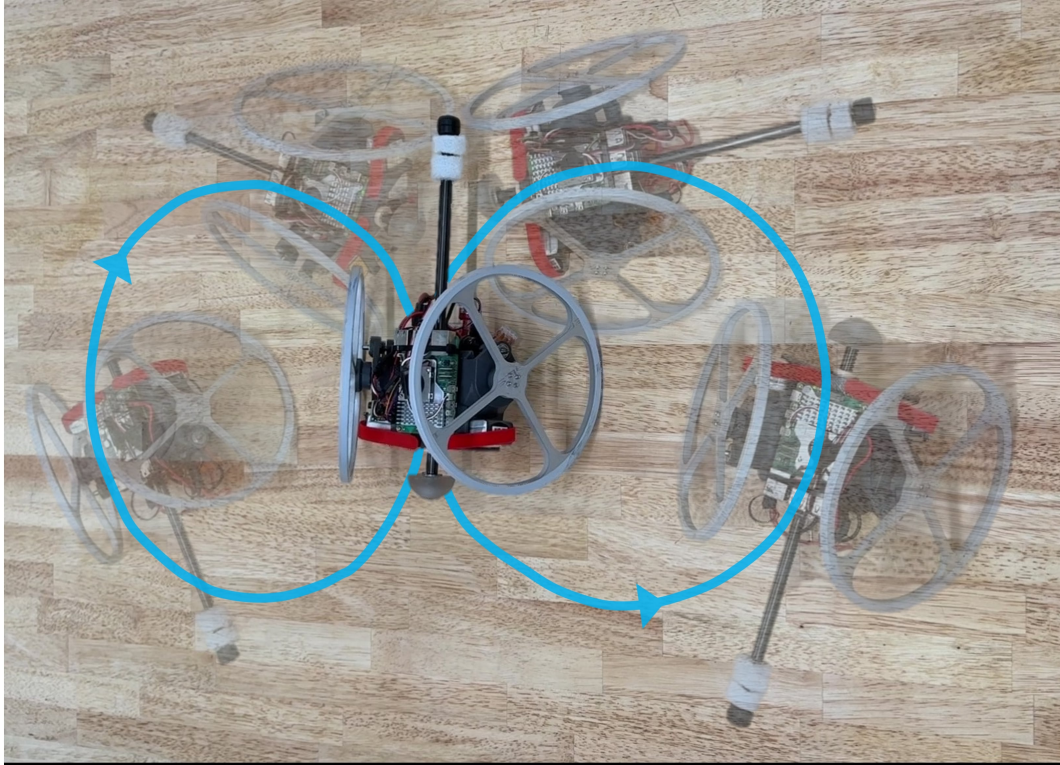
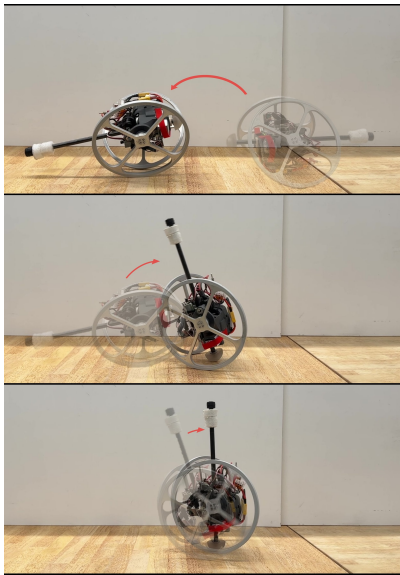
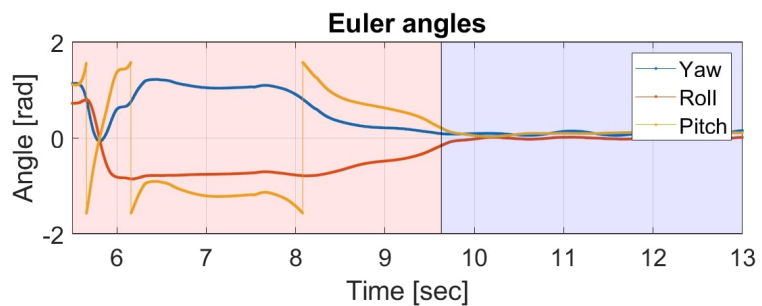


Figure 9. Prototype rolls on the ground in a figure-eight path, blue trajectory overlaid from camera tracking.



(a) Overlay of self-righting from rolling to balancing. Top: testbed rolls forward and stops suddenly to flip over. Middle: testbed extends leg to shift weight backwards and tip upright. Bottom: testbed lifts itself off the ground and begins balancing.



(b) Euler angles during self-righting shown in figure 10a. The red background denotes the system in rolling phase, and the blue background denotes the system in balancing phase. The discontinuity in pitch is due to the system passing the domain limits of $\pm\pi/2$.

Figure 10

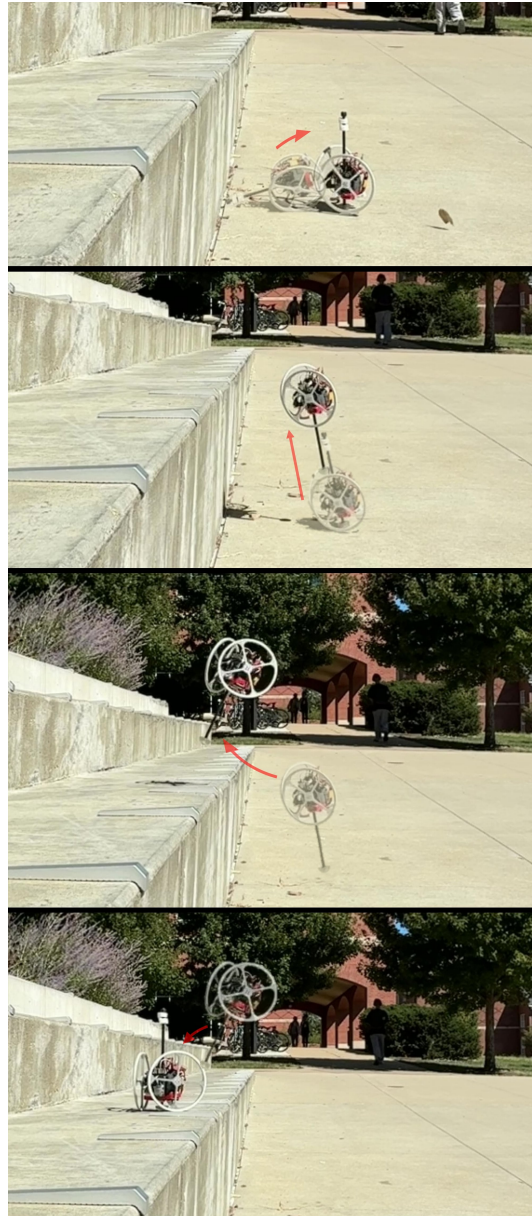


Figure 11. Overlay of combined behaviors: Rolling and self-righting into balancing mode, then leaning and jumping up. After jumping it reorients to point along the velocity vector, and finally lands softly, returning to rolling.

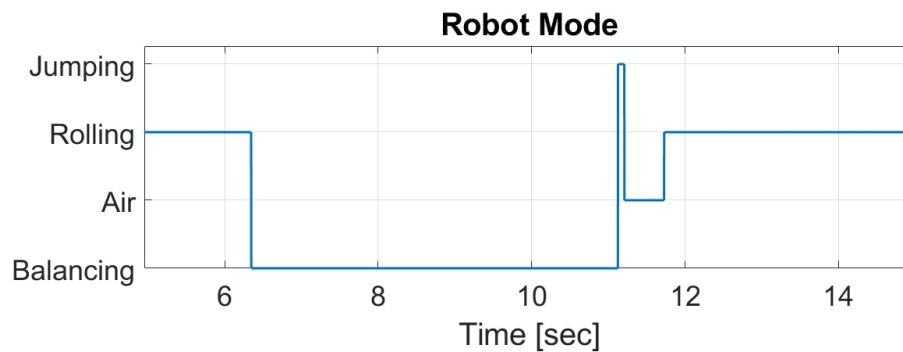


Figure 12. Testbed modes during the trial shown in Figure 11. The testbed goes from rolling to balancing, then to jumping into the air, and then landing and rolling again.

3 JUMPING IN REGOLITH

Jumping in regolith is a challenging endeavor, with complex foot-terrain interactions during both launch and landing that can have a significant impact on jump energy delivery / recovery, jump height, landing accuracy, and foot slip. How well we are able to understand and control these interactions will determine the viability of the LEAP mission concept, and so we conducted work in three main areas:

1. Terramechanics modeling of foot / regolith interactions, in Section 3.1
2. Mobility testing of the foot / regolith interactions, through an extensive hardware testing campaign at the NASA Glenn SLOPE lab, in Section 3.2
3. Hardware improvements for jumping in regolith, in Section 3.2.4

3.1 Foot + Regolith Modeling

Terrestrial research into terramechanics for various forms of robotic locomotion does include wheeled, legged, hopping, and burrowing robots, however space-focused terramechanics research is primarily divided between wheeled rovers and spacecraft landing legs / footpads. Landing spacecraft on regolith under reduced-gravity conditions, in particular, is an area of important historical research that can partially inform work on LEAP. This has included work for the NASA Lunar (Lander) Module [66] and a discrete element model for foot interactions with granular media during an Enceladus landing [31].

Other work has investigated slow impacts into granular materials at a range of collision velocities and gravity levels [59], with a focus on the applications for robotic missions to small bodies (moons / asteroids). This study focused on low Fr numbers (< 10), but did make some extrapolations up to $Fr < 100$. Separately, researchers at Georgia Tech developed a Matlab model with regolith modeled more simply as a spring + damper and calibrated to the height of the robot jump itself [3].

Here, we leveraged the Lunar Module Soil Mechanics Study developed by the Bendix Corporation [66] to provide a mathematical basis for foot-regolith interactions, and guide preliminary efforts on jumping foot design. There is a significant caveat to using this model: we don't know how Enceladus regolith material actually behaves, so it's hard to reliably tune this model's parameters and have high confidence in real-world results [31].

The Bendix model was originally developed for the Apollo Lunar Module, to better understand lander foot / regolith interactions. Our version of this model was initially developed to study Mars Sample Return (MSR) Sample Return Lander (SRL) foot / regolith interactions, including ground pressure and sinkage under a range of vehicle landing conditions and regolith densities. It relates these terms with the Froude number:

$$Fr = v / \sqrt{g \cdot L} \quad (2)$$

where v is the velocity, g is the gravity, and L is a characteristic length, often the footpad diameter at the ground contact.

The Bendix model used here was calibrated to GRC-3 lunar simulant (GRC-3), and to the relevant dimensions for the SRL lander footpads, with $Fr \ll 1$. The LEAP robot is significantly smaller and launches / lands with significantly higher velocity, resulting in a Fr of $1.6 \sim 2.0$ (on Earth) and Fr of $\sim 13+$ (on Enceladus). The discrepancy between the calibrated range of Froude number in this model versus our expected operating conditions limits the quantitative accuracy of the results, but provides qualitative information. Testing done at Glenn to measure actual soil properties and determine force vs. sinkage for our range of Fr will help us refine this model in the future.

Fig. 13 provides the force vs sinkage plot from the Bendix soil model for the following set of input parameters: gravity (0.113 m/s^2), impacting mass (1 kg), footpad diameter (10 cm), impact initial velocity (0.2 m/s), soil bulk density (460 kg/m^3), soil relative density (74%), and soil internal friction angle (34 deg). Note that we decreased the impacting velocity to 0.2 m/s to achieve a Froude number (Fr) ~ 1.9 , which is more consistent with subsequent regolith testing on Earth (Fr of $1.6 \sim 2.0$). In reality, the impact velocity would be the same on Earth and Enceladus, and the Enceladus case would have a $Fr \sim 13$. The model gives a final sinkage of 7.5 mm and a peak vertical force of 5.6 N.

Additional simulations were performed to model behavior of a 5 cm and 8 cm footpad impacting into GRC-3 at 1.4 m/s under Earth gravity (9.8 m/s^2), to inform subsequent testing at the NASA Glenn SLOPE Lab.² Comparing the results of a 5 cm diameter footpad impact (Fig. 14, $Fr = 2$) and an 8 cm diameter footpad impact (Fig. 15, $Fr = 1.6$), we see that the smaller footpad results in greater sinkage (22 mm vs 10.5 mm) and a lower peak force (145 N vs. 270 N). A larger area foot is therefore preferable to minimize robot foot sinkage into loose regolith, and maximize force transmission from the foot to the terrain during launch.

3.2 Regolith Testing Campaign

LEAP mobility testing – both legged jumping and wheeled driving – was successfully demonstrated in relevant regolith simulants at the NASA Glenn SLOPE Lab [67].

²Note that the NASA Glenn SLOPE Lab uses GRC-1 regolith instead of GRC-3.

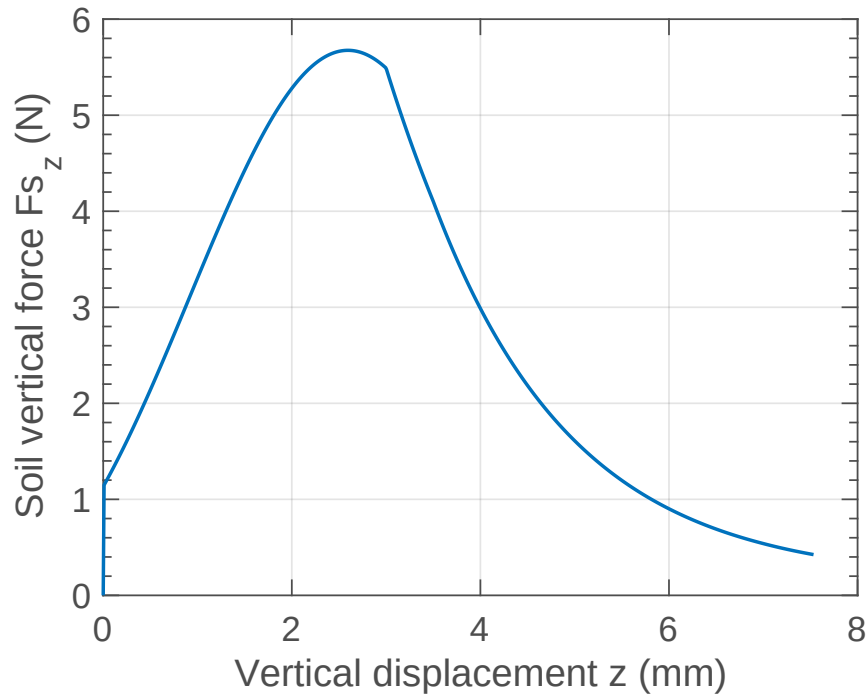


Figure 13. Soil vertical force versus vertical displacement (sinkage) for a 10 cm radius footpad impacting at 0.2 m/s ($Fr = 2$), on Enceladus.

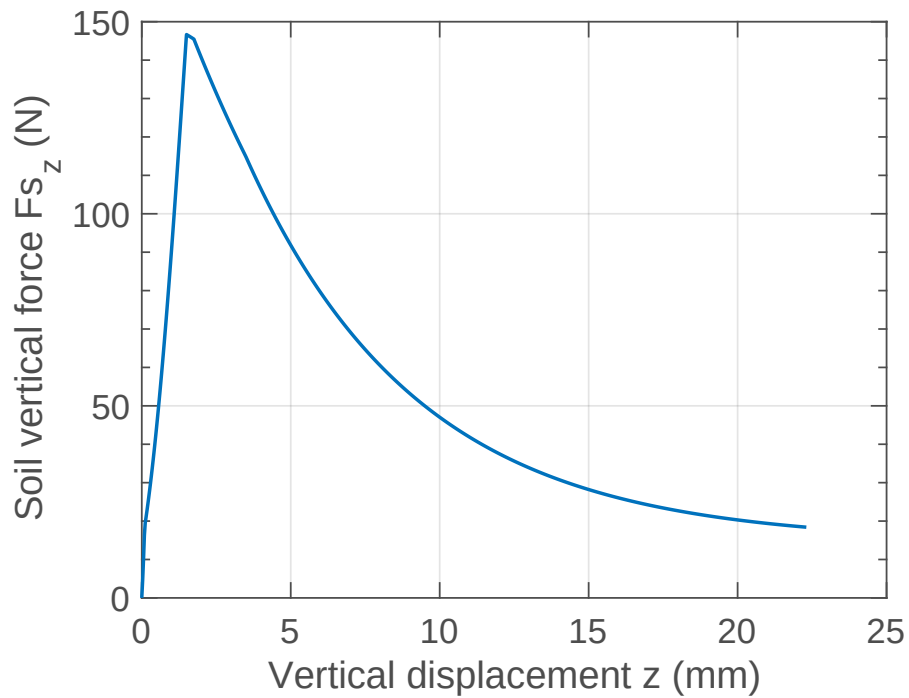


Figure 14. Soil vertical force versus vertical displacement for a 5 cm radius footpad impacting at 1.4 m/s ($Fr = 2$), on Earth.

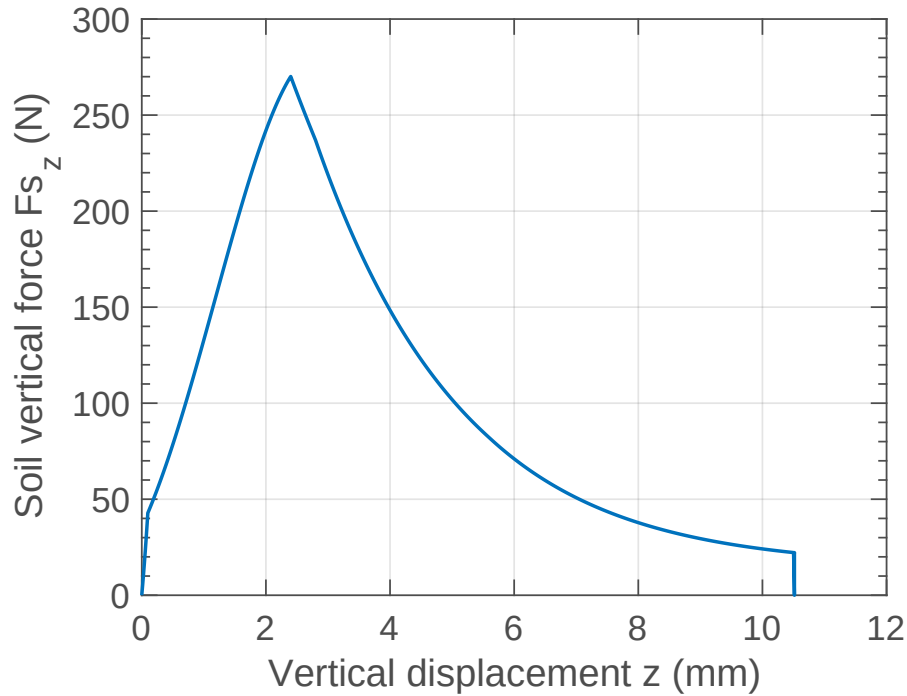


Figure 15. Soil vertical force versus vertical displacement for a 8 cm radius footpad impacting at 1.4 m/s ($Fr = 1.6$), on Earth.

3.2.1 Testing Facilities

Testing was conducted at the NASA Glenn SLOPE Lab over 1 week, with experiments performed in two soil tanks:

- 6m x 5m x 0.3m adjustable tilting soil tank, filled with GRC-1 (Fig. 16)
- 12m x 3m x 0.6m sink tank, filled with Fillite (Fig. 17)

Per [67], the **GRC-1 simulant** is a “custom poorly graded soil consisting of semi-angular silica particles. It was developed to match the bulk strength properties of the equatorial lunar terrain explored during the Apollo missions, with a focus on targeting the ‘softer,’ more conservative range of properties with respect to vehicle mobility. The soil density can be controlled, providing a range of conditions.” GRC-1 is a well-characterized simulant and allows our team to investigate jumping on regolith varying levels of compaction / density, which we are able to control through a series regolith preparation steps (discussed in Section 3.2.2). Using a hydraulic lift system, the tilt-bed is adjustable up to 45 degrees of inclination for sloped surface operations; however, the maximum angle is typically limited by the angle of repose of the simulants in the bed and our testing was limited to a maximum slope of 20 degrees.

In comparison, the **Fillite medium** consists of “hollow alumino-silicate microspheres and is intended to mimic the wind-blown dune soil found on Mars that has produced entrapped conditions for rovers. Though the material is not a high-fidelity simulant, it has low bearing and shear strength and produces a very challenging case for roving vehicles.” Fillite provides a high-sinkage, low-cohesion medium that can partially approximate a cryogenic snow environment that LEAP might encounter on Enceladus. Due to its particle shape, this material mimics the wind-blown dune soil on Mars and has extremely low shear strength, which produces a very challenging traversability case for roving vehicles.

3.2.2 Regolith Preparation

The team worked with two regolith testbeds – a GRC-1 simulant testbed (Fig. 16) and a Fillite simulant testbed (Fig. 17). The GRC-1 testbed also supports testing at a controllable slope. We tested the GRC-1 at two primary levels of simulant compaction – loose and compact – and the Fillite in its standard, uncompacted state.

Unprepared GRC-1 was used for initial LEAP robot checkout tests, and was produced by raking the existing testbed surface smooth without modifying the underlying particle cohesion from prior activities unrelated to the LEAP project. Relative density (ρ_d) of the unprepared GRC-1 was measured to be approximately **47%** (Fig. 19).

Loose GRC-1 was prepared by methodically shoveling the entire workspace to a depth of 10-15 cm to reduce particle cohesion, followed by lightly raking the surface smooth. It had a relative density (ρ_d) of **12-24%** (Fig. 20).



Figure 16. GRC-1 simulant testbed, in loose prepared state at a tilt of 10 deg. Numbers indicate approximate locations of the cone penetrometer measurements detailed in Section 3.2.3.



Figure 17. Fillite simulant testbed, in prepared state. Numbers indicate approximate locations of the cone penetrometer measurements detailed in Section 3.2.3.

Compact GRC-1 was prepared in a three-step process: (1) dragging a weighted roller across the workspace to pre-compact the GRC-1 simulant, (2) covering the surface of the workspace with a tarp and plywood boards, and (3) operating a vibratory plate compactor on top of the plywood boards (4+ passes across all areas of the workspace) to compact the underlying GRC-1 simulant. The plywood boards were critical when operating the vibratory plate compactor to ensure smooth translation across the workspace and avoid embedding the compactor in the regolith simulant. The plywood boards effectively transmitted vibrations down to the regolith simulant, and ensured a flat surface after compaction. The tarp was used to control / mitigate dust generation during the energetic compaction activity.

This process produced a workspace with a relative density (ρ_d) of **80-100%** (and exceeded the standard model for ASTM-D4253) (Fig. 21). The reason for this could be excessive compaction force that altered the simulant by breaking down larger particles and increasing the quantity of fine particles that can pack within voids in the original particles.

Fillite was prepared by simply spreading / leveling the material within the entire workspace using a board on rollers, with no additional compaction steps (see Fig. 22). This produced a workspace with a cone index of 0.30 (0-0.15 meters) and 1.20 (0-0.39 meters), but without a direct mapping to relative density.

3.2.3 Regolith Characterization

After each of the above regolith preparations and before testing the LEAP robots, a series of cone penetrometer measurements were collected at 6-8 locations distributed across the testbed. The locations of these measurements are approximately illustrated in Figs. 16 and 17.

The cone penetrometer measurement produces a single value that combines the soil shear strength and compressive strength based on depth (i.e. a continuous measurement of soil strength vs. depth). This measurement is produced by pressing a cone with known cone angle and cross-sectional area into the regolith, and measuring the ground reaction force (a combination of shear and compressive loading on the cone based on the cone angle) vs. depth using an integrated load cell. Pressure is derived from the measured force and cone cross-sectional area. The slope of this pressure vs. depth plot is the cone index gradient (G), and values for the cone index across a range of depths is reported for each regolith preparation in Figs. 19 to 22.

Multiple cone index values are provided to more clearly highlight nonlinear regions in the regolith strength (typically cone index gradient / regolith strength increases at greater depths). A standard area cone was used for the majority of the cone penetrometer soil measurements, but a smaller area cone was required for the highly-compacted GRC-1 testing to reach sufficient depth.

Due to the number of tests executed during the 1 week test campaign at the Glenn SLOPE Lab, and the need to perform each jump on untouched / unmodified regolith, we required 4 preparations of the GRC-1 testbed in the Loose state, 3 preparations of the GRC-1 testbed in the Compact state, and 1 preparation of the Fillite testbed. We re-performed the cone penetrometer measurements after each fresh preparation, but have only provided results for a single preparation of each testbed / state in Figs. 19 to 22.

Two established relative density strategies are used to map a cone index into a relative density measurement: Modified Proctor (ASTM-D1557, impact compaction from tamping [1]) and vibratory compaction (ASTM-D4253 [2]), along with published work in this area [53, 52]. Our relative density measurements are computed using a linear model derived from vibratory compaction in [53] Fig. 6.11 (and reproduced here in Fig. 18):

$$G = 0.0823(D_R) + 1.6464 \quad (3)$$

where G is the cone index gradient (kPa/mm) and D_R is the relative density (%). This linear model of relative density is fit to data with D_R of 0-75%, however the data does show likely nonlinear behavior at both low D_R ($< 30\%$) and high D_R ($> 65\%$) that deviate from the model's single slope.

Due to this likely nonlinearity not captured in the model, we compute a relative density that exceeds 100% for the highly compacted GRC-1 produced with the vibratory compactor. The actual max cone index gradient that we measured was $G = 25 kPa/mm$ – significantly higher than what is captured in the model. Our strategy to estimate relative density in these highly-compact states was to instead peg the max measured cone index gradient at approximately 100% relative density, and renormalize smaller, but still highly compacted measurements relative to this $25 kPa/mm$ value. Using this process, we estimate achieving 80-100% relative density in across the various test locations and preparations.

Due to the minimal cohesion of Fillite, the team is not aware of established relative density measurements for this material based on cone index gradients, and thus only cone index gradients are reported.

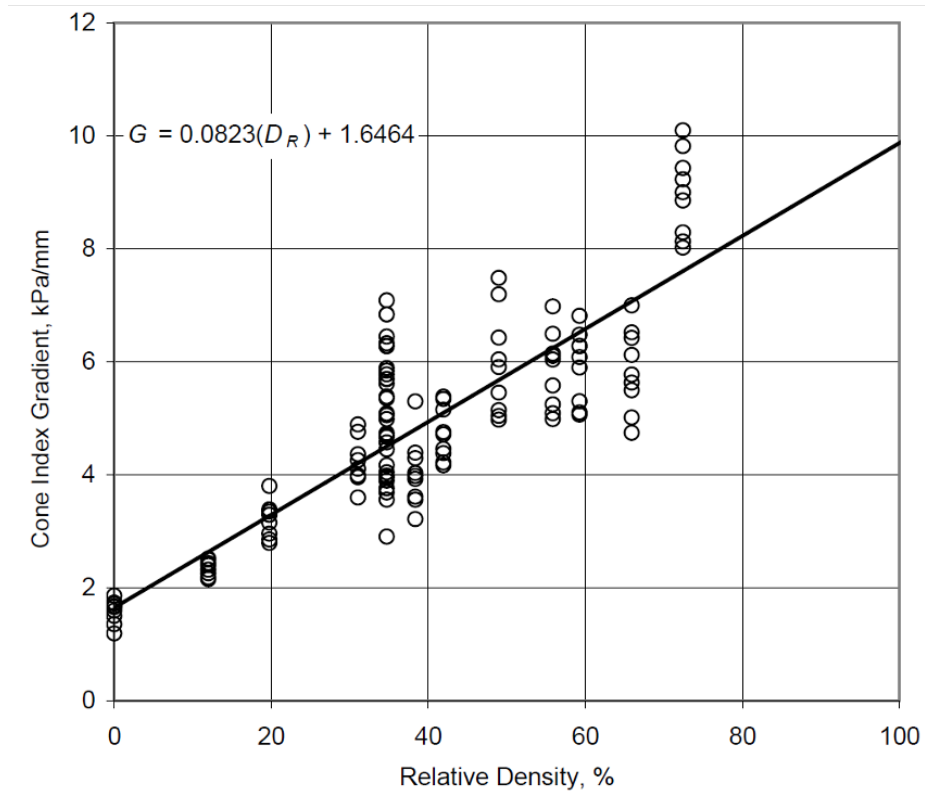


Figure 18. Cone index gradient versus relative density of GRC-1, reproduced from Fig. 6.11 in [53].

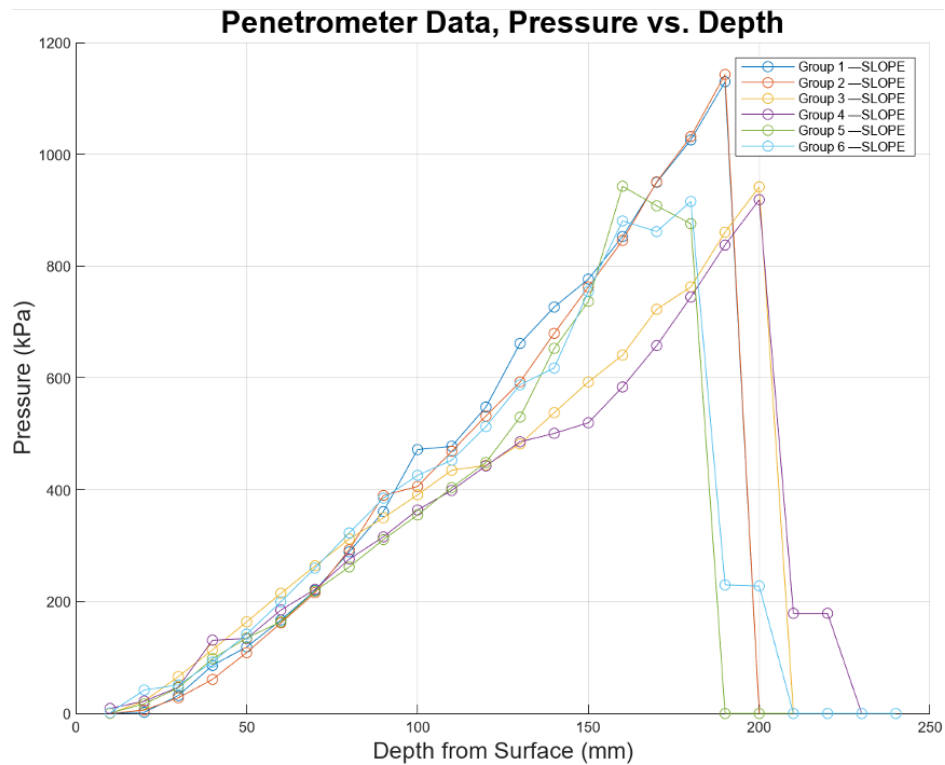


Figure 19. Cone penetrometer data for unprepared GRC-1, with an average cone index of 3.43 (0-0.05 meters) and 5.55 (0-0.19 meters), and a relative density (ρ_d) $\sim$ 47%.

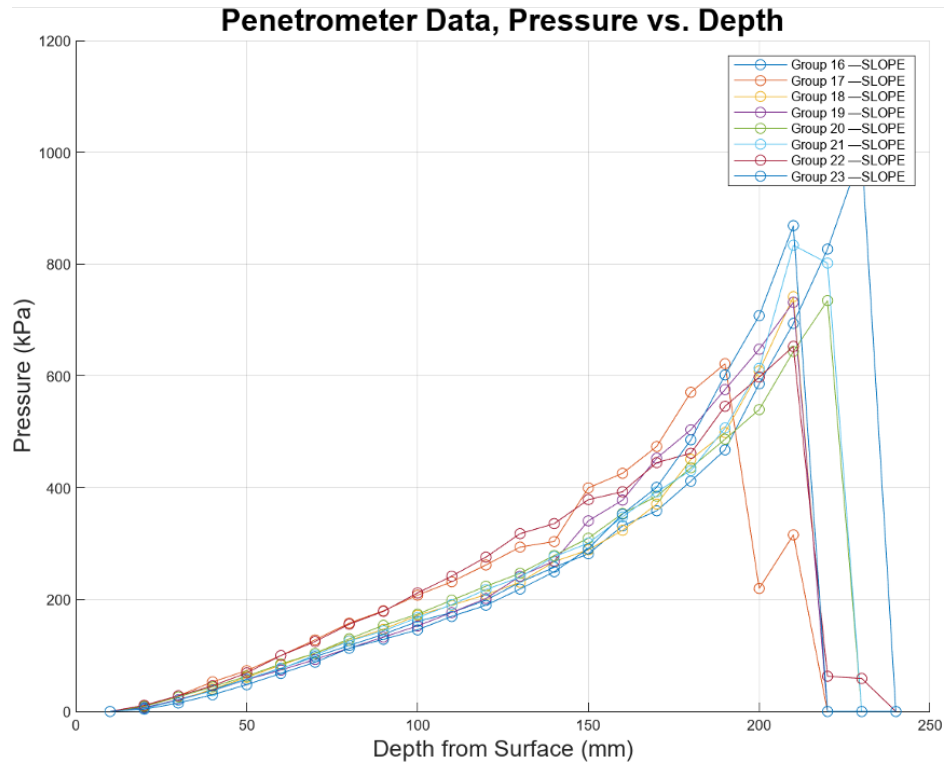


Figure 20. Cone penetrometer data for loose GRC-1, with an average cone index of 1.55 (0-0.05 meters), 2.63 (0-0.18 meters), and 3.34 (0-0.23 meters), and a relative density (ρ_d) $\sim$ 12-20%. Additional loose preparations yielded relative density (ρ_d) $\sim$ 12-24%.

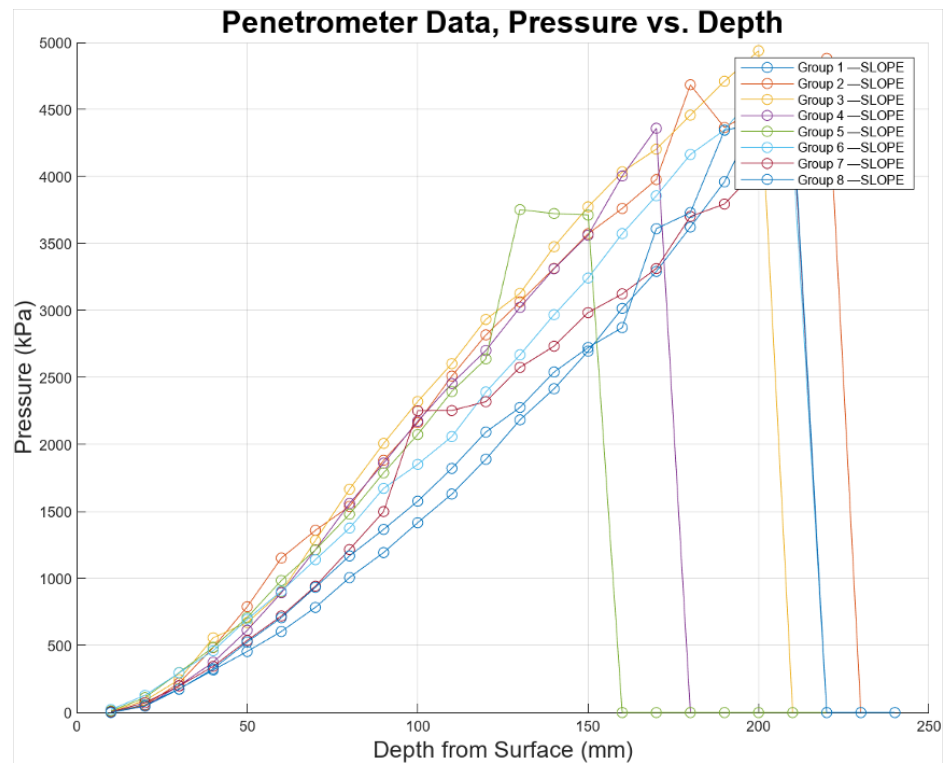


Figure 21. Cone penetrometer data for compact GRC-1, with an average cone index of 15.6 (0-0.05 meters) and 25.6 (0-0.20 meters), and a relative density (ρ_d) $\sim$ 80-100%.

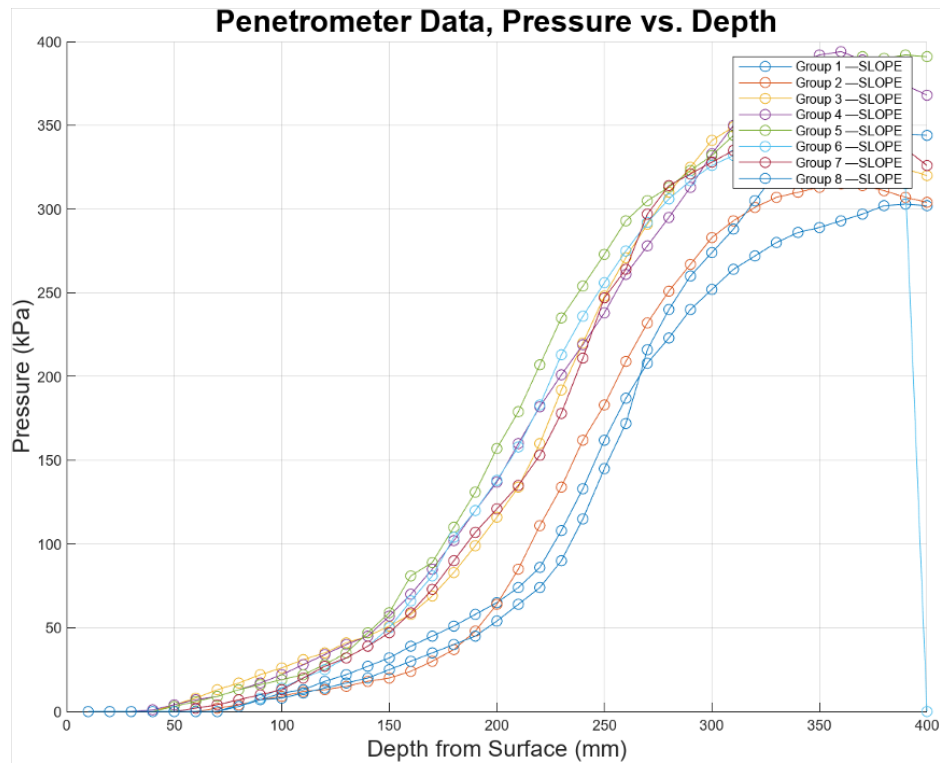


Figure 22. Cone penetrometer data for Fillite, with an average cone index of 0.30 (0-0.15 meters) and 1.20 (0-0.39 meters). No relative density calculation was available for Fillite.



Figure 23. LEAP-S1 platform used for testing of jumping on granular media. Dual reaction wheels keep the platform balanced on the ground and oriented in the air. A single rack and pinion is used to drive the leg to jump and hop of varying terrain.

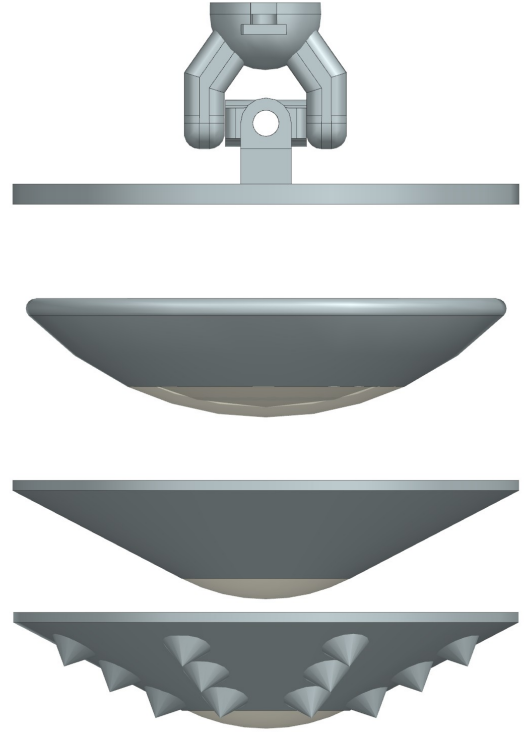


Figure 24. Different foot designs used during the test campaign. From top to bottom: flat, hemisphere, cone, and hybrid. The all have a radius of 10 cm and all used a universal joint shown on the flat foot.

3.2.4 Robot Preparation and Measurement

Pose estimation for robot experiments was recorded by a motion capture system in the SLOPE lab and onboard the prototype. Markers were attached to detect the current position of the prototype and by comparing the expected and resultant data streams, the energy lost into the media by the jumping mechanism due to changes in parameters can be measured. Energy is calculated by taking the apex height of the data as potential energy and horizontal velocity as kinetic energy and the total energy is measured in Joules. The accuracy of jumping is also measured by analyzing the data streams and repeated tests of each parameter set. It is determined by the deviation in launch angle variation and derived by the arc tangent of the launch horizontal velocity, a constant in the air, and the launch vertical velocity, obtained from the max height. The prototype was refined from the version in section 4 with sealed actuator housings protecting motors and gearboxes as shown in Fig. 23. This additional sealing slightly increased the mass of the prototype. We also changed the wheels to Delrin from Aluminum to increase compliance for impact absorption and clad them in foam tires to increase their surface area to better distribute load over granular substrates. A list of the prototype's physical parameters are listed in Table 2.

Platform Parameters	
Mass (<i>kg</i>)	1.43
Leg Length (<i>cm</i>)	27
Leg Throw (<i>cm</i>)	20
Wheel Mass (<i>kg</i>)	0.185
Wheel Inertia (<i>kg · mm²</i>)	1365

Table 2. Platform physical parameters. Leg throw is the difference of fully retracted and extended leg lengths. The wheel inertia is the inertia about its rotation axis.



Figure 25. LEAP-S1 jumping on GRC-1 Compacted in the SLOPE Lab.

We varied the platform's jump power between a constant $0.6 \text{ N} \cdot \text{m}$ and $1.0 \text{ N} \cdot \text{m}$, the lean angle of the jump between 0° , 10° , and 20° degrees, and the behavior of the jump. Behaviors were as follows: stationary jump, stationary hop, straight lean and jump, straight lean and hop, and directional lean and hop between hop sideways and hop backwards. Jumping implies a singular jump, where hoping implies jumping twice. Any directional hopping was performed by changing the direction of the leg pointing vector in the air so that the next jump will propel the system into a desired direction. Lean magnitude of the jumping controller was set at 15° and 30° from upright.

Several foot profiles were used including: flat, cone, hemispherical, and hybrid. These designs were modeled from the foot profiles presented in [31]. Each of these designs were attached to the main rack and pinion of the prototype with universal joint so that the prototype could balance around the common rotation point while the foot stays planted into the granular media. Without the joint, the media would “hug” the foot and generate ground reaction torques that the controller cannot handle. Each foot varied in size to tests the contribution of contact area to the dynamics of jumping on granular media. The foot profiles are shown in Fig. 24.

Once the data from the motion capture instruments was collected, it was processed into trials. The jump were taken and fit to a ballistic trajectory and using trials with an R^2 value over 0.90. We used this method with no smoothing to provide the jump velocity and peak heights which were then turned into jump energy and accuracy. We removed outliers outside three standard deviations of the mean.

The bar charts shown below compare jump energy to different subsets of the testing campaign. The number of trials of each bar is shown in the middle of each bar. The individual test points are shown as opaque gray dots on each bar. The bar height is the mean of the data and the error bar is 1 standard deviation of the data. The launch angle and velocity plots display the launch velocity mean and standard deviation as the line that passes through the outer arc of the secant. The secant is the standard deviation of the launch angle and the center angle is the mean launch angle of that subset. The text on the plot shows the mean and standard deviation of the launch angle and launch velocity.

3.3 Jumping Performance

To characterize the behavior of jumping with differing simulant material and preparation, substrate slope, leg power, lean angle, and foot shapes, we ran a series of tests varying these parameters and comparing the locomotion performance (energy and accuracy) as described above.

3.3.1 Jump energy vs. simulant type

Varying granular material and preparation has a large effect on jump energy. As shown in Fig. 26 and 28, as the GRC-1 compaction level increases the jump energy increases. As presented in Table 3, high compaction GRC-1 offers similar performance to the rigid setting (both slightly above 7 J); as the compaction level decreases to unprepared and loose GRC-1 the jump energy decreases. In the uncompactable Fillite, the jump energy is at its lowest, losing over 1 Joule in stationary jumping and nearly 2 Joules with a lean of 15° . Compared to the mean rigid test energy, compacted GRC-1 loses 0.7%, uncompact GRC-1 loses 6.6%, loose GRC-1 loses 14.1%, and Fillite loses 15.5% in vertical jumps. For lean jumps (15°), as compared to the mean rigid test energy, GC, GU, GL, and F lose 1.5%, 4.4%, 11.5%, 22.3%, respectively.

This shows the lower the compaction, the more energy is needed to compress the media to produce a ground reaction force

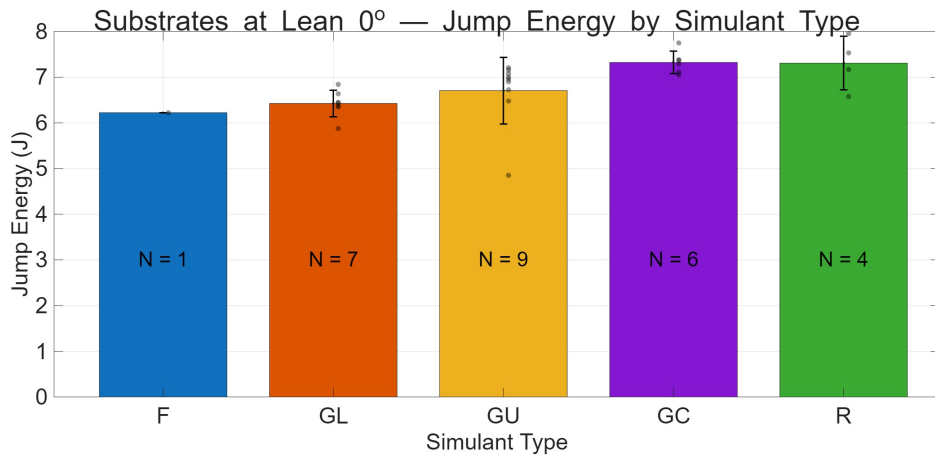


Figure 26. Comparison of jump energy versus simulant type with a jump power of $1N \cdot m$ and a vertical jump. The number of sample of each corresponding trial are noted within each bar.

Launch Angle Means by Simulant Type

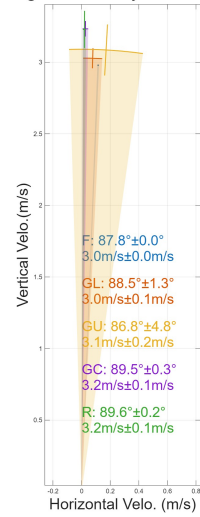


Figure 27. Accuracy of vertical jumps on varying simulants.

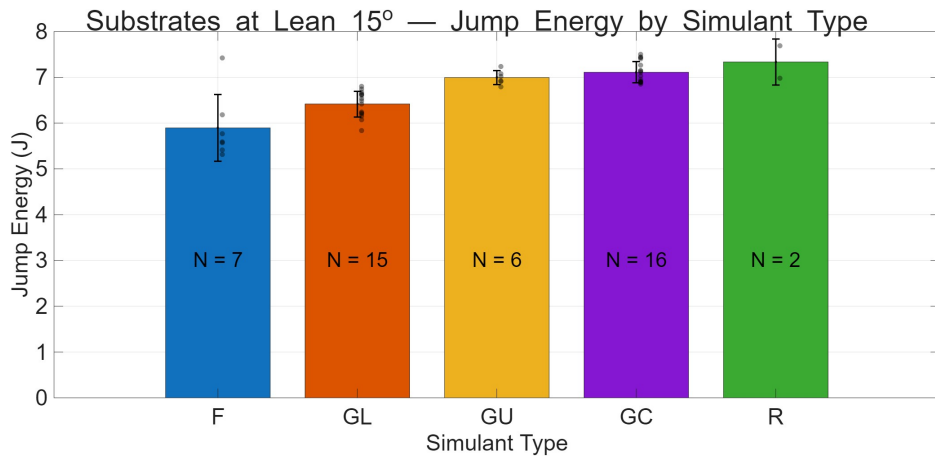


Figure 28. Comparison of jump energy versus simulant type with a lean of 15°.

Launch Angle Means by Simulant Type

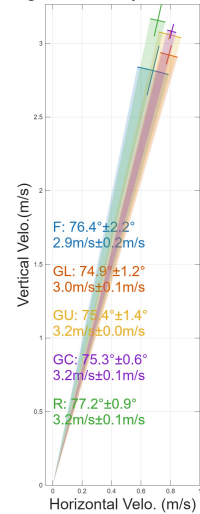


Figure 29. Accuracy of vertical jumps on varying simulants.

to launch the prototype. Since the prototype's leg is commanded to produce a constant force, there is a critical compaction level that can support the jump. Loss of energy into the substrate lowers the max jump distance and therefore increases the cost of transportation of jumping locomotion. Notably as the lean angle increases past 25° , the loss of jump energy increases as well, indicating a greater level of deformation involved in a jump horizontally. Different kinds of observed soil deformations are described below.

In the slope beds, only loose GRC-1 was tested however the same trend would be expected as the same compression phenomenon would be present. We would also expect to see this effect compound with the relative angle to the ground, needing larger compression levels to jump.

3.3.2 Jump accuracy vs simulant type

Jump accuracy of the platform, measured by deviation in launch velocity angle, stays relatively unaffected by changes in the granular media when launch angle is not excessive. The mean and standard deviations of stationary and lean jumps are shown in Fig. 27 and 29. In vertical jumps there is little to no difference between simulant in the launch angle, and therefore compaction levels of the simulant have little effect. This may be because vertical jumps on flat terrain are rotationally symmetric about the vertical axis and there are few asymmetries to cause perturbations to angle. In lean jumps, there is some reaction force from the ground to rotate the foot, which the compaction/cohesion level can affect. As a result, simulants with a lower cohesion between particles have a larger spread of jump angles, with the high compaction media varying less than 1° and the lower compaction media $> 1^\circ$. The lowest compaction level media, Fillite, has a variation of 2.2° , more than double the high compaction media.

The jump velocities shown in both lean and vertical jumps follow the same relationship as shown in the bar charts above. Notably, the effect of decreasing jump velocity or energy with decreasing compaction is exacerbated with lean jumps. This may be due to an increase in substrate deformation for lean jumps, as the material near the surface next to the foot is also displaced in addition to the media below the foot.

We expect that with the slope beds this effect is more prominent as the relative angle, the angle of the platform to the ground normal, can be larger when the surface normal is deflected relative to gravity and the foot force has a correspondingly larger component tangential to the surface.

For leaning jumps on sloped terrain as shown in Fig. 36, the same phenomenon is present. As the slope increases, the jump accuracy lowers and the jump energy variation widens. In addition the higher slope becomes far less efficient to jump on, showcasing the effect of the shearing behavior at high slopes.

3.3.3 Jump Energy vs. Foot Profile

The jump energy of the platform is not heavily affected by the foot profile. As shown in Fig. 38 and Fig. 39, all feet had comparable jump performances. In vertical jumps, Fig. 30, the cone profile provides consistent jump energies over flat and hybrid designs. Hemisphere provides the largest jump energy over unprepared and compacted GRC-1 but has the least jump energy on the loose GRC-1. Notably, the compacted media is comparable to a rigid surface with a rubber foot showing that when compacted, granular media can act as solid surfaces for low mass jumping locomotion.

Looking at accuracy of vertical jumps, in Fig. 31, the consistency of the cone profile has less spread over trial than both flat and hybrid, along with higher takeoff velocities. The flat and hybrid designs have greater variability than other designs, with more variability the less compacted the media. Hemisphere has a low number of trials so no spread were calculated.

With lean jumps the same trends are present as the vertical jumps. The cone, hemisphere, and flat profiles offer similar performance and distributions for lean jumps at 15° . Similar trends of variability of the foot profiles are also present as show in Figs. 32 and 33.

On average the flat performed the worst in vertical jumps, a reduction of 11.7%, the hemisphere performed the worst on horizontal jumps, a reduction of 8.6%. This analysis shows little significant difference between foot profiles, and reduction in jump energy can be attributed to the comparison to the rubber foot only being tested on rigid surfaces. For lean jumps and vertical jumps on a slope, the flat foot profile becomes the best between the cone and hemisphere. Only at the highest slope and lean angle does the flat become slightly worse than the cone but the variation is lower. Overall, the flat foot is the most consistent and highest jump energies. At high slope and lean it may start to suffer from slipping, described in the jumping phenomena section below. Tabulation of the foot profile energy and accuracy data is shown in Table 4 below.

3.4 Jumping performance on sloped terrain

Sloped terrain has an effect on jumping locomotion, with the jump consistency decreasing as the slope increases as shown in Fig. 34. This correlates to the increase risk of failure for jumping on slopes as it can lead to slipping/shearing of the slope, contact with the slope, and feet tripping in the terrain. In straight jumps, there is an increase in the jump energy with the increase of slope, but also a higher variability of jump energy. This could be explained by jumping on a smaller area due to tilt in the foot. In turn, the pressure increases and less force needs to go into compacting the grains and therefore more energy transfers into the jump. The accuracy of vertical jumps on sloped terrain is relatively unaffected and the launch velocity is comparable, as shown in Fig. 35.

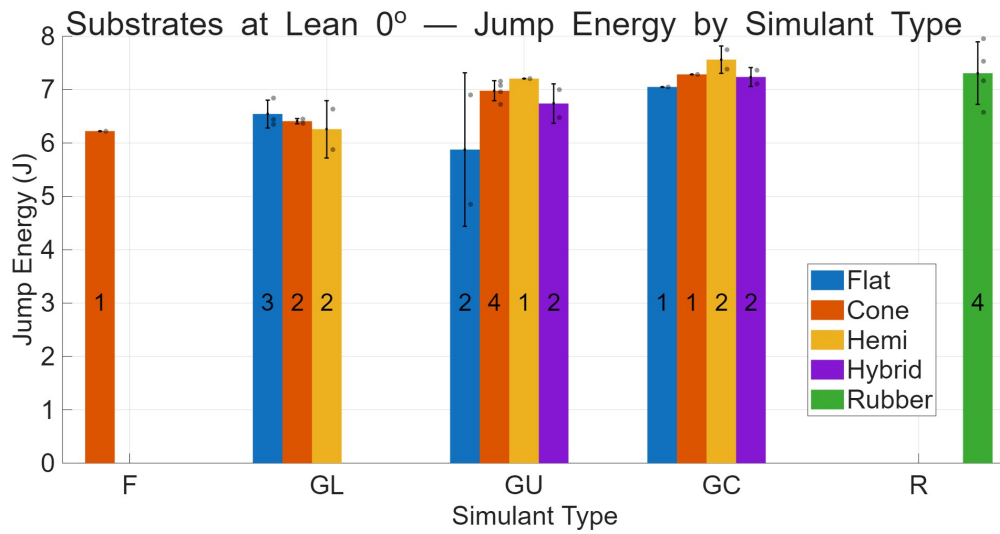


Figure 30. Jump energy comparison of different foot profiles versus granular media.

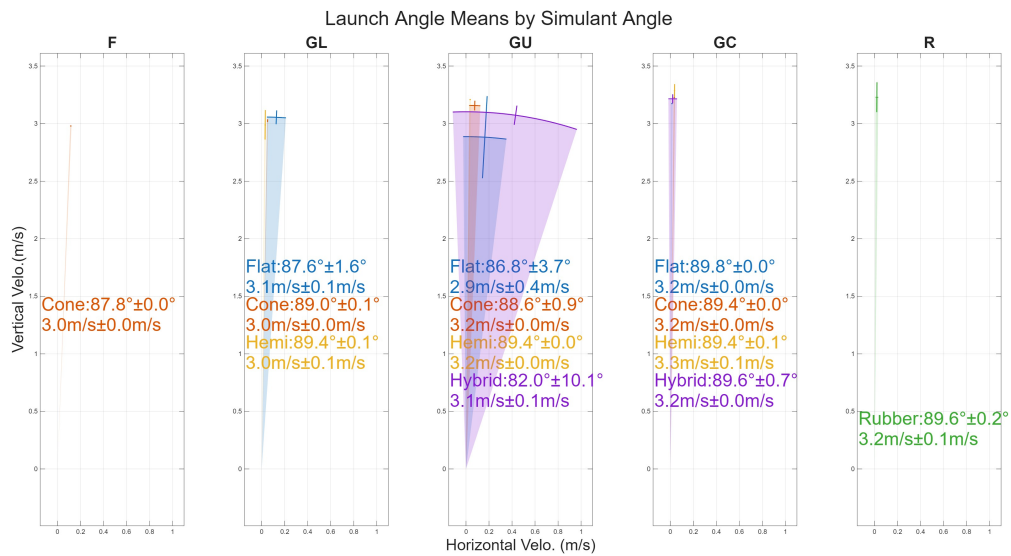


Figure 31. Accuracy comparison of foot profiles on differing simulants for vertical jumps.

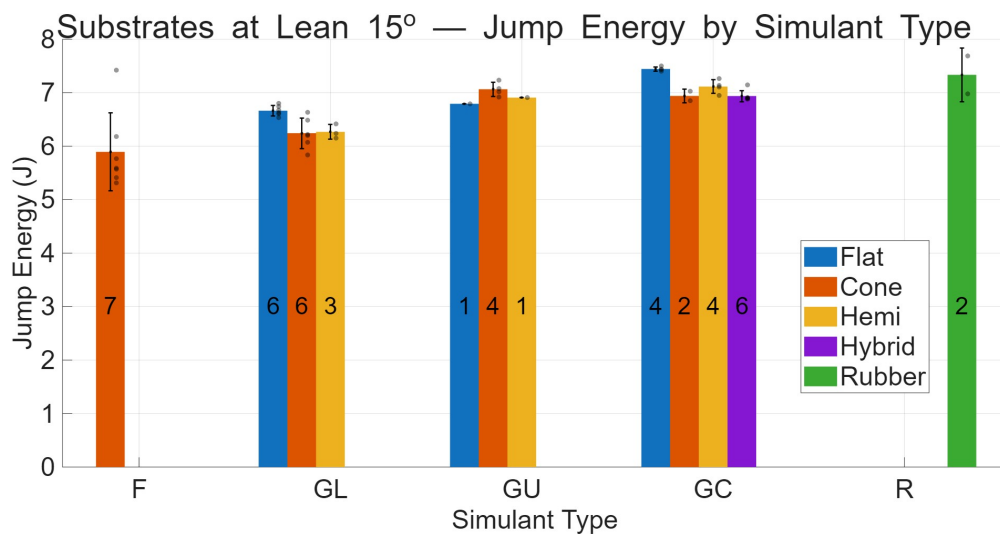


Figure 32. Jump energy comparison across foot profiles on different simulants with a 15° lean.

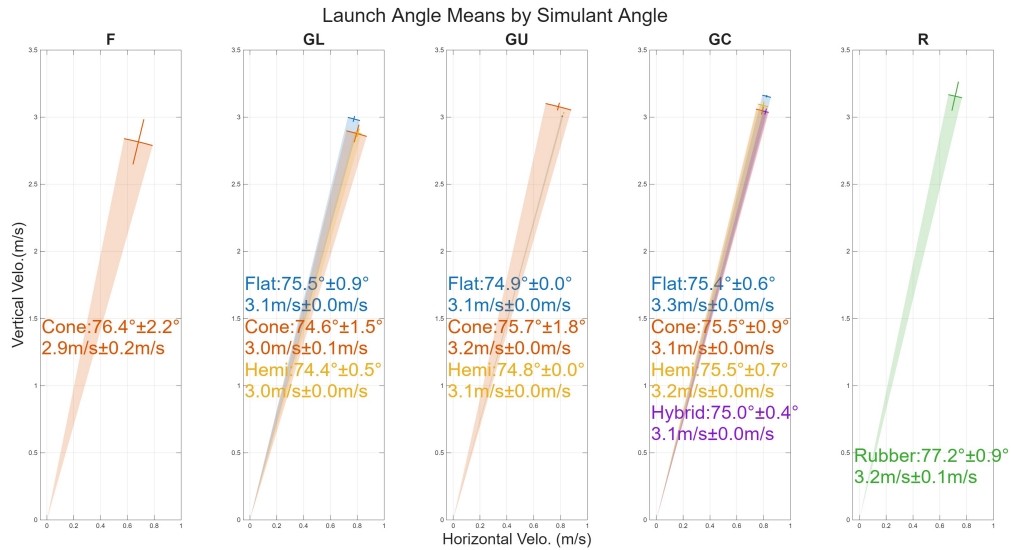


Figure 33. Launch accuracy comparison of foot profiles on different simulant with a 15° lean.

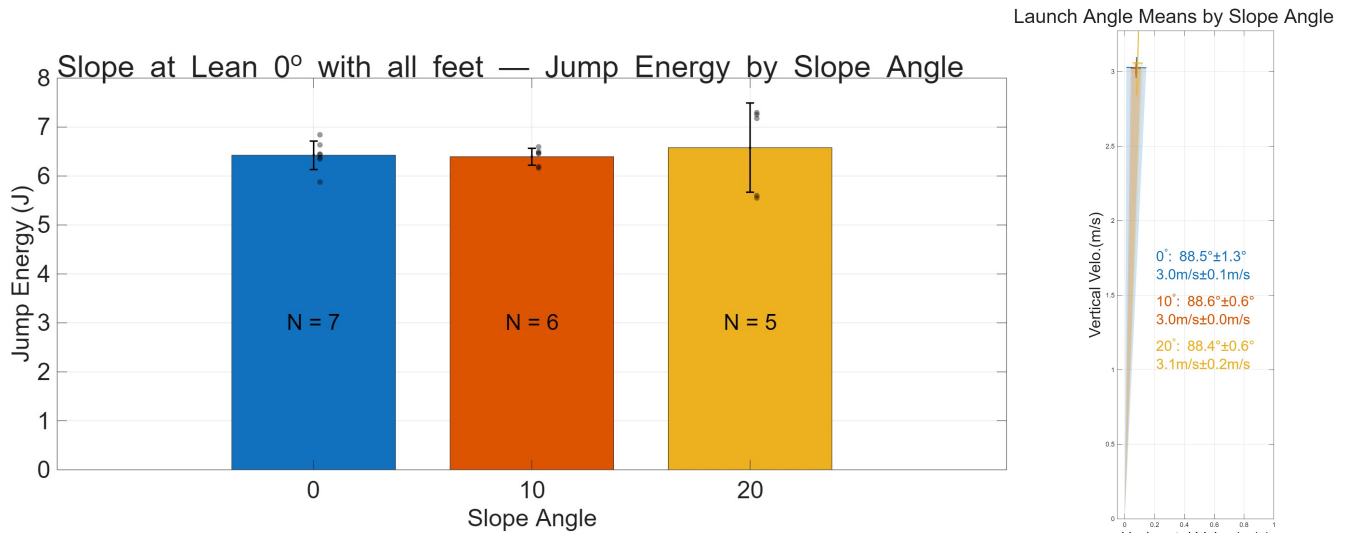


Figure 34. Jump energy on differing slope angles.

Figure 35. Launch Accuracy on different slope angles.

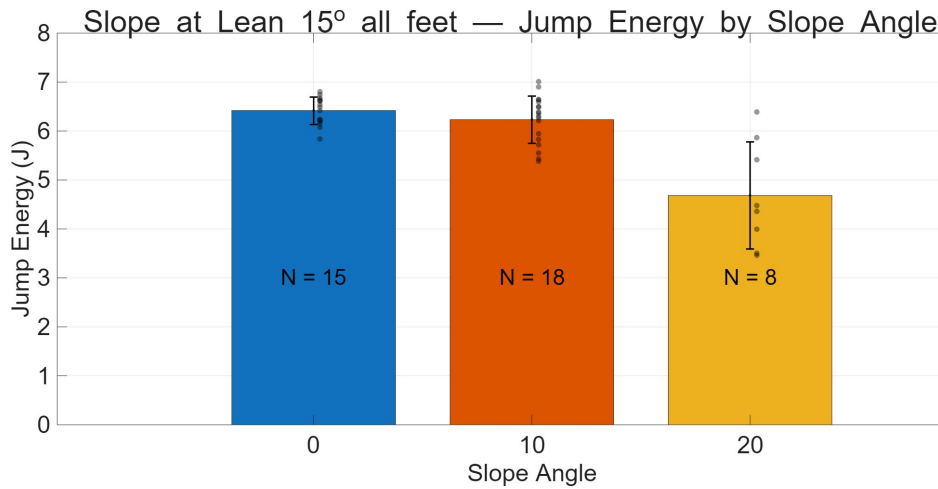


Figure 36. Jump energy of lean jumps at varying slope angles.

Launch Angle Means by Slope Angle

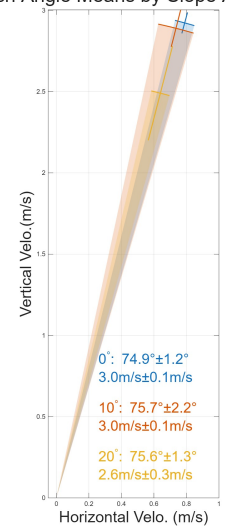


Figure 37. Launch accuracy for lean jumps at differing slope angles.

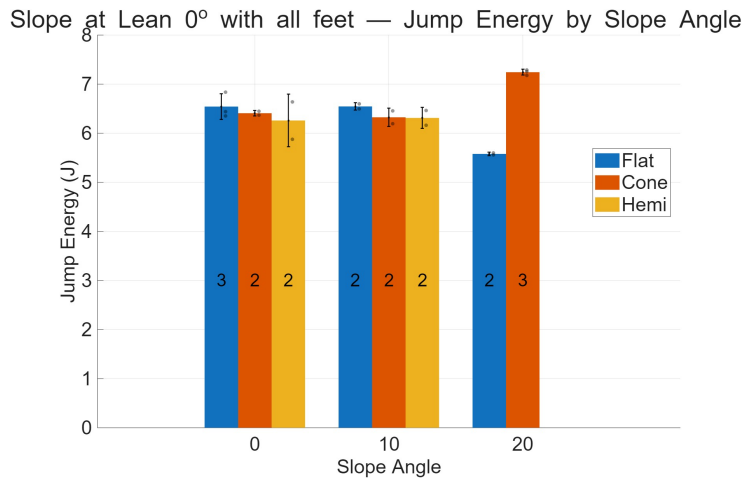


Figure 38. Jump energy of differing foot profiles on varying slope.

Launch Angle Means by Slope Angle

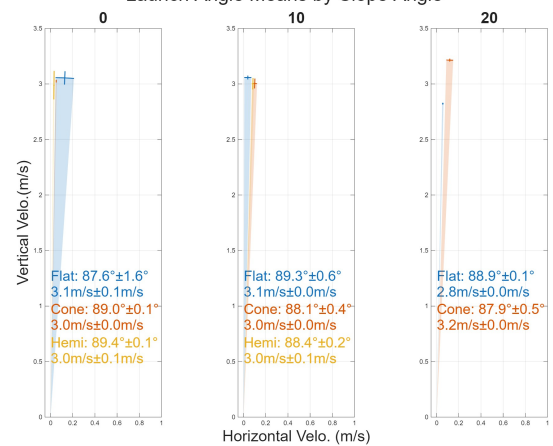


Figure 39. Accuracy of slope jumping with varying foot profiles.

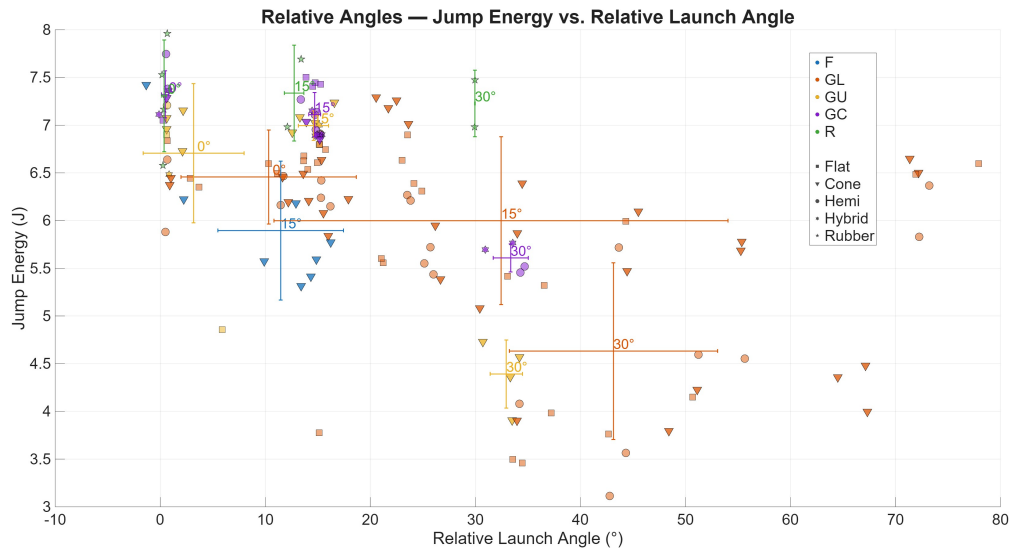


Figure 40. Scatter plot of Jump energy and launch angle. Data points are trials and error bars are drawn for the mean and standard deviation of jump energy and relative angle for each lean angle setting (lean angle is measured from vertical while relative angle is measured from surface normal).

For lean jumps on slopes, as the slope increases the jump energy decreases. When jumping on 20° slopes the jump energy falls drastically, shown in Fig. 36, indicating that the jumps start to experience the soil interactions described below. The high variation may also be attributed to difference in relative angle of the slope tests, whether the platform is jump up, down, or cross slope. The energy loss can be seen when comparing relative angles as displayed below. The accuracy of lean jumps on sloped terrain is also relatively unaffected and the launch velocity is comparable between 0° and 10°, but decreasing by 0.4m/s on the 20°, as shown in Fig. 37. The jump energy and accuracy on slope terrain between vertical and lean jumps is shown in Table 5.

3.5 Foot profile vs sloped terrain

As slope angle changes, the foot profile performance changes as well. Displayed by Fig. 38, the cone provides a consistent jumping platform, and even increasing in jump height as the slope increases. The hemisphere also provide a consistent platform but at lower jump energies. The flat profile can perform well, but as the slope angle increases, slipping can occur and result in a loss of jump energy.

Fig. 39 shows the cone profile to be the most consistent and has the best velocity out of the three profiles for the 20° slope. The flat profile also provides high launch velocities and best performance for both 0° and 10° slopes, however the low number of trials restricts consistent conclusions.

3.6 Energy and relative launch angle comparison

To determine the relationship between platform lean and jump energy we plot the relative launch angle, the angle between platform and ground normal, and the jump energy, as shown in Fig. 40. The error bars are at 0°, 15°, and 30° lean angles from vertical (not relative angle) for each simulant. As the lean angle increases we see a slight decrease in jump energy between 0° and 15°, but as we approach 30°, the points become far more spread out and are far lower in mean jump energy as well. This may be attributed to the increasing effect of jumping phenomena described in the next section. To reduce the potential of the effects occurring, keeping the relative angle under 30° is beneficial. This relationship holds for all simulants and all foot profiles indicating this limit is present regardless of material and foot design.

Table 3 shows the jump energy and accuracy mean and standard deviation relative to simulant over lean and slope angles. Here, Fillite has the lowest jump energy consistently over all operating conditions. The jump energy follows the same pattern of more cohesion between particles, more resultant jump energy. The accuracy of launch angle is lower for the highest compaction levels, and negligible difference between the three lower cohesion media.

3.7 Granular media jumping interactions

3.7.1 Foot shearing

While testing, several unique jumping behaviors occurred. The most common was the foot shearing the top surface and sliding sideways on horizontal jumps, particularly with the flat foot as shown in Fig. 41. If the jump angle was too far from vertical, it could leave the friction cone and begin to slide. The result of this behavior was two-fold, a drop in jump energy and a

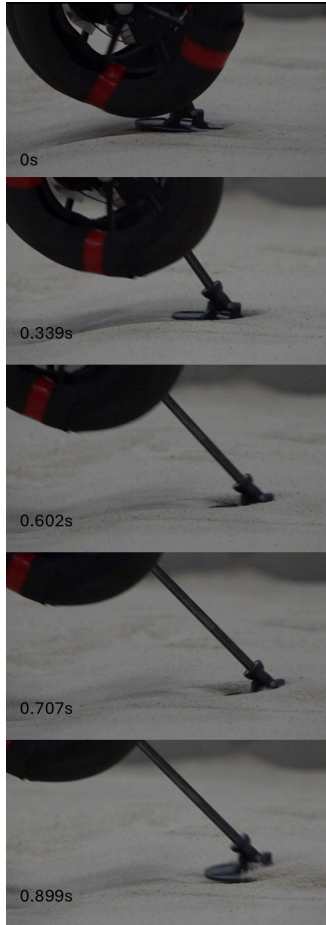


Figure 41. Video panel of shearing phenomenon for lean jump of 30° in loose GRC-1 with a flat foot profile.

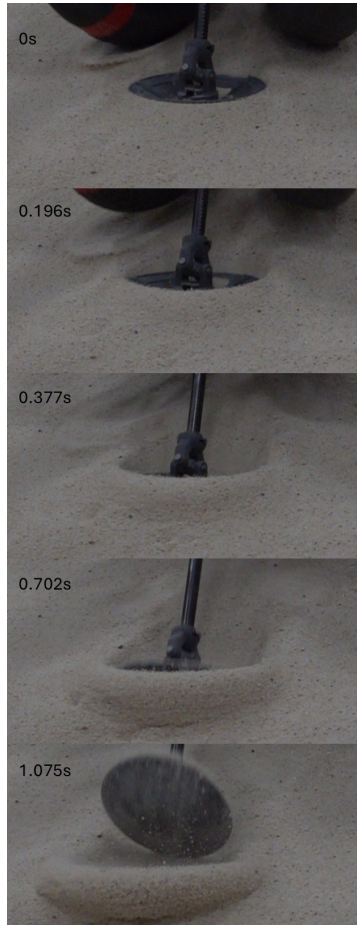


Figure 42. Video panel of shearing phenomenon during 30° lean jump uphill on a 10° slope in loose GRC-1.

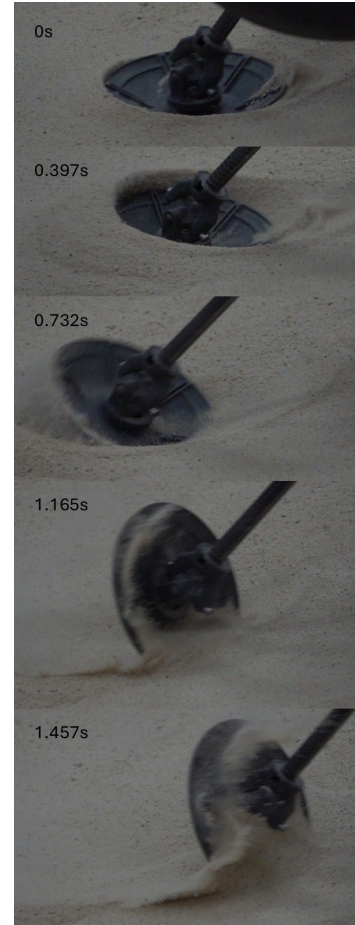


Figure 43. Video panel of digging during 30° lean jump crosswise on a 10° slope in loose GRC-1.

Granular Media	Energy (J) 0° lean	Energy (J) 15° lean	Accu. (°) 0° lean	Accu. (°) 15° lean
Fillite	6.3 ± 0.0	5.9 ± 0.7	87.8 ± 0.0	76.4 ± 2.2
GRC-1 Loose	6.4 ± 0.3	6.4 ± 0.3	88.5 ± 1.3	74.9 ± 1.2
GRC-1 Uncompacted	6.7 ± 0.7	7.0 ± 0.1	86.8 ± 4.8	75.4 ± 1.4
GRC-1 Compacted	7.3 ± 0.2	7.1 ± 0.2	89.5 ± 0.3	75.3 ± 0.6
Rigid	7.3 ± 0.6	7.3 ± 0.5	89.6 ± 0.2	77.2 ± 0.9

Table 3. Jump energy and accuracy for simulants with varying launch angle.

Foot profile	Energy (J) (0,0)	(15,0)	(0,10)	(15,10)	(0,20)	(15,20)
Flat	6.4 ± 0.7	7.0 ± 0.4	6.7 ± .01	6.6 ± 0.2	5.5 ± 0.2	5.1 ± 0.4
Cone	6.9 ± 0.4	6.8 ± 0.6	6.4 ± 0.2	6.3 ± 0.6	7.3 ± 0.1	5.4 ± 0.9
Hemisphere	7.1 ± 0.8	6.7 ± 0.5	6.4 ± 0.2	6.0 ± 0.4		
Hybrid	7.0 ± 0.4	6.9 ± 0.1				
Rubber	7.3 ± 0.4	7.3 ± 0.5				

Table 4. Jump energy for foot designs with varying launch and slope angle.

exaggerated lean due to the foot sliding out from under the platform. This effect was correlated to foot profile and substrate compaction. The hemisphere, cone, and hybrid designs were less impacted as they dug into the substrate unlike the flat profile. These non-flat profiles penetrate deeper into the surface, raising the force limit. The more compacted the substrate around the cone, the harder to move that material and therefore the less prone to slipping. During the trial shown in Fig. 41, the foot slid 56mm, reducing the effective leg length (full stroke length minus deflection lost to sliding) by about 33%, a major reduction.

On high degree slopes, the material around the foot profile is more prone to moving. This behavior is an effect of the substrate shearing outside the compaction cone of the material, where the force of the jump can move material downhill. This phenomenon decreases jump energy and lean accuracy as described above, and if the shearing is large enough, even provide little to no jump at all as the leg slips out from the media. An example of this is shown in Fig. 42. In this trial the foot displaced 34mm of material. This reduced the effective leg length by 20%. This behavior is more common the higher the relative angle, so jumping up slope will be less effective the higher the slope. Jumping down slope will lessen the effect of shearing on jumps.

3.7.2 Foot dragging

Lastly, the edge of the foot can drag across the surface of the substrate. Whilst lean jumping or hopping, when the leg is accelerated into the ground, the ground compresses, and the foot sinks below ground level. If the compression sinks below the height of the edge of the foot, the foot can grab material as it jumps and “trip”. The lifted material increases resistance as the leg moves through the material, rotating the platform on take-off as well as absorbing more of the jump energy. This effect can cause immediate failure of the jump or hop (both reducing jump distance and causing a tumble); however, this may be counteracted with different foot profiles, such as increasing height or surface area to limit compression or to construct the foot’s top as convex to let the material slide off. This behavior is shown in Fig. 43. The foot in this trial sank about 22mm into the ground, exceeding the height of the foot. This displacement normal to the media causes the digging behavior seen afterwards causing the platform to crash.

3.8 Conclusion

In these experiments we investigated the effect of different media with varying compaction levels on jumping locomotion. We also tested different foot profiles, lean angles, and slope angles to determine the characteristics of jumping on granular media and the associative design restrictions for jumpers. Overall, we found that with increasing levels of compaction, the amount of energy lost decreased compared to rigid surfaces. This finding held across varying foot parameters and lean angles, with the difference between the uncompactable Fillite media and rigid surfaces being 15.5% for vertical jumps and 22.3% for

Slope Angle (°)	Energy (J) 0° lean	Energy (J) 15° lean	Accu. (°) 0° lean	Accu. (°) 15° lean
0	6.4 ± 0.3	6.4 ± 0.3	88.5 ± 1.3	74.9 ± 1.2
10	6.4 ± 0.2	6.2 ± 0.5	88.6 ± 0.7	75.7 ± 2.2
20	6.6 ± 1.1	4.7 ± 1.1	88.4 ± 0.7	75.6 ± 1.3

Table 5. Jump energy and accuracy for slope angle with varying launch angle.

lean jumps of 15° . When analyzing the launch angle accuracy, the lower the compaction level, the lower the accuracy of the jump. The launch accuracy dropped between rigid and loose GRC-1 by over 6 times during straight jumps and 33% for lean jumps. For jumping on varying slope angle, we found that the higher the slope angle the more variability in the launch angle and jump energy. Using the covariance of the jump energy data and launch angle data set, we discovered that there was little to no relation between jump energy and lean angle variations for jumps at 0° and 15° lean angles. Overall, the decrease of a maximum 22.3% of the jump energy and accuracy variation of a max of 2° can be adjusted for in the platform's locomotion. This analysis shows that jumping locomotion is fully capable in environments with granular media, supporting the feasibility of jumping platforms on Enceladus.

For foot design, we found the best design for jumping at relative angles from surface normal, of 0 and 10° was the flat profile. On higher relative angles of 20° or more, the flat foot encountered slipping more often, and was unreliable. The cone profile handled the higher slope levels more consistently. To counteract the slipping behavior and retain the vertical jumping performance a combination of the two could be beneficial, such as a flat profile with a cone outer rim to provide resistance from slipping. We did not experiment with high traction foot profiles that may allow for higher relative angles without shearing or digging into the ground.

Lastly, we analyzed interactions between the foot and substrate. Two main behaviors of slipping or shearing and digging occurred. Slipping and shearing occurred when jumping force moved the top material across the surface and increased in likelihood with greater relative angle. Digging happened when compression or shearing of the media was so great that the edge of the foot sank below ground level and upon liftoff, the foot dragged the surrounding soils. This behavior occurred only with relative angles greater than 25° , so when jumping on different slopes, it is important to take the gradient into account to avoid jump failures.

In the future we plan to conduct tests on continuous jumping behavior in similar media, with different parameters such as new foot profiles, jump force profiles, and jumping redirection in a subsequent bounce after landing. We plan to analyze the efficiency of locomotion methods, like jumping and rolling, on these media and varied terrains to study path planning on various extraterrestrial environments. Finally we plan to simulate or test in low gravity to further analyze the conditions that this platform may encounter on Enceladus.

4 SPACECRAFT DESIGN FOR ENCELADUS

Adapting the versatile Salto robot [28, 29, 68, 71] to operate successfully on Enceladus requires a re-envisioning of all major subsystems (and the introduction of some new ones). Herein, we will cover three main aspects of the LEAP spacecraft design for Enceladus operations:

- Section 4.1: details the relevant materials and component selection for Enceladus conditions
- Section 4.2: power system design and implications for operations (battery technology, recharge vs. single-shot, duration of operation, range of exploration, and science return strategy)
- Section 4.3: thermal system modeling, including a series of parameter sweeps to encapsulate likely thermal design / operational parameters (heat-before-use, overheating vs. cooldown, and long-term survival)

4.1 Hardware Design for Enceladus

The Enceladus environment – vacuum, cryogenic temperatures, and icy terrain – creates unique demands on the LEAP robot hardware that are not experienced on Earth and can only be addressed through careful component material selection and surface treatments. Key hardware concerns include:

- **Hardware embrittlement** under cryogenic temperatures, leading to early failure under high impulse loads generated by the repeated, energetic jumping and landing motions (and potential collisions with terrain hazards)
- **Vacuum cold welding** of like materials under vacuum conditions, leading to permanent mechanism binding
- **Excessive thermal conductivity**, causing rapid heat loss to the environment, and requiring excessive, energy-intensive survival heating
- **Excessive thermal cycling**, causing internal stress build-up across components with a dissimilar Coefficient of Thermal Conductivity (CTE) that can lead to early circuit failures

Through conversations with Subject Matter Experts (SMEs) at JPL, we identified key performance criteria and potential materials for all relevant hardware components within the LEAP robot. The details are captured in Section 4.1, and additional details thereafter.

System	Component	Key Criteria	Salto Equivalent	Potential Materials	Comments
Structures	Chassis	Strength (impact) Ductility Machinability	Carbon Fiber + Epoxy	Aluminum (Al 5083) Titanium (Ti-6Al-4V ELI) Austenitic Steel (302, 304, 316)	Ductile metal alloys. Supports the avionics, power, instruments, insulation; must survive launch / landing / jumping / crash loads. Motors for wheels / legs mounted to chassis.
	Wheels	Strength (impact) Ductility Durability	Carbon Fiber + Steel (Tail) Plastic (Propellers)	Aluminum (Al 5083) Titanium (Ti-6Al-4V ELI) Austenitic Steel (302, 304, 316)	Ductile metal alloys. Tough rim with spring spokes. Connects directly to a driving motor; will rest in contact with the cryogenic ice / terrain and must survive / dissipate possible impact loads.
	Leg	Strength Ductility	Carbon Fiber + Epoxy	Titanium (Ti-6Al-4V ELI)	Very tough, lightweight, ductile metal alloy to handle high jumping forces. Multi-bar linkage vs. rack-and-pinion design.
	Foot	Strength Ductility	Epoxy	Aluminum (Al 5083) Titanium (Ti-6Al-4V ELI) Austenitic Steel (302, 304, 316)	Ductile metal alloys. Hemisphere or conical footpad shape; will rest in contact with the cryogenic ice / terrain. Optional G10 spacer added at ankle (between foot / leg) for insulation.
Motion	Leg Motor	High Torque Low Mass	Brushless DC Motor	Brushless DC Motor	High-torque brushless DC motors w/ cold encoders (no resolvers).
	Wheel Motors	High Torque Low Mass	Brushless DC Motor (Tail) Brushed Motor (Propellers)	Brushless DC Motors (1 per wheel)	High-torque brushless DC motors w/ cold encoders (no resolvers).
	Spring	Specific Elastic Energy Density Efficiency	Latex	Steel (17-7 PH) Beryllium Copper Elgiloy	Low mass, high elastic energy storage spring that operates at cryogenic temperatures.
	Bearings	Strength Toughness / Durability Friction	Bushings	Graphite-Metal Alloys	Low friction assemblies that operate without lubricant under significant side-loads and maintain tolerance / performance at cryogenic temperatures. Minimize debris ingress paths.
Thermal	Exterior Insulation	Emissivity (high) Mass / Volume	N/A	Spacerless MLI (SMLI) Modular MLI (MMLI)	Ultra low mass + emissivity; no structural strength.
	Component Insulation	Emissivity (high) Mass / Volume	N/A	Aerogel G10	Low mass + emissivity; no structural strength
	Heat Rejection	Emissivity (high) Mass / Volume	N/A	Radiator + Thermal Switch	Controllable heat rejection / emissivity, at the cost of added mass.

Table 6. Flight-qualified materials for use under LEAP operational loads and cryogenic conditions.

Chassis The LEAP robot chassis supports the avionics PCBs, battery modules, instruments, and provides mounting points for the wheel / leg motors and Multi-Layer Insulation (MLI). The chassis material requires high impact strength (to accommodate launch / landing loads), a measure of ductility at cryogenic temperatures (to avoid brittle failures), high strength-to-weight ratio, and machinability (to enable creation of complex, non-standard features for maximum weight-savings).

Multiple viable structural metals were identified as ideal candidates for the chassis material – Austenitic Steels (e.g. 302, 304, 316), Titanium (Ti-6Al-4V ELI), and Aluminum (Al 5083). Other considerations such as cost (Titanium is more expensive) and thermal conductivity (Aluminum is much more conductive) will further constrain the final material selection, but the identification of these metals is sufficient for Phase I proof-of-feasibility.

Wheels LEAP employs two reaction wheels, which serve four functions:

1. providing 3D vehicle attitude reorientation during the aerial phase
2. providing steerable surface mobility (i.e. driving on the surface)
3. providing impact protection and energy dissipation during accidental / uncontrolled hard landings (protecting the chassis, MLI, and instruments from damage by absorbing collision loads)
4. providing a stable, stationary resting state for the robot in contact with the cryogenic ice

Several wheel designs were considered, including:

1. a machined metal wheel with integrated rim and spokes (similar to the aluminum wheels on the CADRE rovers [7])
2. a solid metal rim with wire spokes (similar to the wheels on the Soviet Lunokhod rover [36])
3. a mesh spring wheel (similar to the wheels on the NASA Apollo Lunar Roving Vehicle [36])

In all cases, the wheels connect directly to a brushless motor (avoiding a gearbox) via a high-strength metal axle. To achieve these functions, the wheels require a balance of low mass, ductility, toughness, and impact resistance.

We identified three potential ductile metal alloys that can meet these combined functions – Aluminum (Al 5083), Titanium (Ti-6Al-4V ELI), or Austenitic Spring Steel (302, 304, 316). One item of note is that Aluminum has higher thermal conductivity than Titanium or Steel, which may necessitate a G-10 spacer at the wheel hub for insulation.

We considered superelastic metal alloys alternatives like Nitinol (NiTi), which NASA used to develop durable, high-performance spring wheels [36]. A key drawback of these alloys is that the alloy's superelastic characteristic is only maintained in the Austenite crystal phase; below the Austenite finish temperature (A_f) the material enters a deformable Martensite phase. Even special cryogenic Nitinol alloys (NiTiNbY) have an $A_f \sim -130^\circ\text{C}$ [25], compared to the expected Enceladus surface temperature of $\sim 50 - 100\text{ K}$ (-223 to -173°C).

Leg + Foot LEAP will likely employ a multi-bar linkage with pin + bushing joints, similar to the leg mechanism on Salto [54, 28, 29]. Due to the magnified loads generated within the linkage during jumps / landings, only a very tough, lightweight, and ductile metal alloy (e.g. Titanium Ti-6Al-4V ELI) is suitable.

An alternate rack and pinion leg mechanism is also being studied, and was used in the Phase I LEAP robot design shown in Fig. 4. This design is more robust than a multi-bar linkage and can electronically simulate a range of spring / damper behaviors through precise control of the driving motor, which is valuable for exploring various jump strategies in regolith testbeds. However, this mechanism is less compatible with a series-elastic energy storage / recovery element, and thus leads to overall lower jump efficiency. Additionally, it can be fouled more easily, and may require the entire leg mechanism be shrouded in a flexible bellows [9].

LEAP will employ a large-area hemisphere or conical foot, to provide a stable launch / landing pad for each jump. A universal joint ankle shown in Fig. 24 was tested which was highly effective in passively aligning the foot with non-flat terrain. The foot will sit in contact with the cryogenic ice / terrain while the robot is at rest, but the foot / leg can be retracted when necessary (e.g. to avoid dragging while driving). An optional G10 spacer could be added at ankle (between foot / leg) for insulation.

Motors LEAP will employ one high-power brushless motor for jumping, similar to Salto [27, 28, 29] and the custom rotor motors on Ingenuity [5, 4]. The leg motor will likely include a small gearbox to increase motor torque before the series elastic torsion spring (for energy storage), as seen in [28]. While current LEAP prototypes use an outrunner brushless motor for the leg motor, debris considerations will likely require the final flight-qualified motor to be fully encapsulated.

LEAP will also employ a pair of lower-power brushless motors for wheeled driving and aerial orientation control. These motors would require significantly lower torque, given the reduced gravity environment, and may be able to operate entirely without gearboxes (i.e. direct drive). On Ingenuity, a set of three brushed motors (Maxon DCX10 brushed DC motors) with

four-stage gearboxes were used to control each of the two rotor swashplates [5, 4]. Brushed motors offer advantages of lower cost and simpler motion control than brushless motors, but LEAP may still opt to use brushless motors for the wheels for the superior power-to-weight efficiency and reduced friction wear, particle contamination, and electrical noise.

Spring LEAP requires a spring that connects leg linkage to the driving motor and stores elastic energy for jumps / landings. Salto uses a latex series-elastic spring, which provides excellent specific elastic energy, but is brittle at cryogenic temperatures [54, 28]. Alternative cryogenic-compatible spring materials include high-performance metal alloys: Steel 17-7 PH, Beryllium Copper, and Elgiloy. The primary disadvantage of these metal springs is a higher mass than an equivalent latex spring.

Bushings / Bearings LEAP will aim to employ vacuum- and cryogenic-temperature-rated bushings within the multi-bar leg linkage, in line with the Salto leg design [28, 29]. Bushings offer superior durability to bearings under high loads (internal leg loads can be an order of magnitude greater than the foot reaction force) and better tolerance for shock / vibration on launch and landing. Bushings also offer superior debris tolerance but can still be susceptible to fouling, and may require felt seals / covers around each joint or else shrouding the entire leg mechanism in a flexible bellows [9].

A primary concern was in identifying suitable lubricant materials for the bushings (or lubricant-free bushings). Many space-rated lubricants have a minimum operating temperature above that of Enceladus, which would require energy-intensive heating of the full leg.

A promising candidate is the graphite-metal alloy bushing [14], which meets temperature requirements (33 to 1000K), is self-lubricating, operates dry without grease or oil, is dust-tolerant, and is non-galling (no vacuum welding).

Should future testing reveal that these bushings are not suitable for the LEAP leg demands, alternate bearing options include stainless steel or Silicon Nitride (Si_3N_4) ceramic balls, paired with dry film lubricant coatings such as Tungsten Disulphide (WS_2 , developed by NASA) and Molybdenum Disulphide (MoS_2) [6].

Insulation LEAP will employ one of two relatively novel forms of MLI – Spacerless Multi-Layer Insulation (SMLI) or Modular Multi-Layer Insulation (MMLI) [8] – for thermal insulation. MLI blankets are a ubiquitous thermal management technology on spacecraft, and consist of layers of metal-coated plastic film (usually Mylar or Kapton, coated with aluminum or gold) separated by low thermal conductivity mesh. It provides excellent insulation for radiative heat transfer, which is the primary heat transfer mechanism of LEAP, per preliminary modeling in Section 4.3.3. SMLI and MMLI remove the mesh spacers and instead hang a series of overlapping film sheets around the spacecraft avionics, connected to the structure only via low-conductivity threads (SMLI) or posts (MMLI). This provides greater design flexibility than conventional MLI blankets, maintains low mass, and provides low emissivity (ϵ^* of 0.005-0.015).

Other common space-rated insulation materials include G10 (fiberglass laminate) and Aerogel. Aerogels have high insulation and ultra-low mass, but are quite brittle and may not survive repeated shock loads. They also notably increase the spacecraft volume. G10 provides excellent insulation and is a tough material able to handle structural loads, has significantly higher density / mass. It is possible G10 spacers would be used in the MMLI system, or to reduce thermal conductivity paths from robot internals to the wheels or foot.

Heat Generation / Rejection LEAP will likely require no dedicated heat-rejection surfaces (i.e. radiators) or heat-generation surfaces (i.e. heaters or Radioisotope Heater Unit (RHU)), based on preliminary thermal analysis results in Section 4.3.3. The combination of appropriately-designed MLI, heat-generation by onboard avionics / motors, and a suitable operational cadence will ensure that the robots remain within operational Allowable Flight Temperature (AFT) at all times.

However, for applications on warmer worlds than Enceladus, it is possible that a dedicated radiator may be required to minimize overheating and accelerate cooling while idle. Under those situations, LEAP would include a solid-state mechanical thermal switch [8] that links warm internal structures to the radiator without power or coolant. Above a mechanically-defined temperature threshold, the switch is “ON” / “Closed” and creates a thermally conductive path between the chassis and radiator, through the MLI (enabling radiative cooling). Below this threshold, the switch is “OFF” / “Open” and eliminates this thermally conductive path, resulting in heat remaining trapped inside the MLI.

4.2 Avionics + Power System Design for Enceladus

LEAP performance is highly defined by the capabilities and limitations of its avionics and power systems. Herein we develop the preliminary

1. High-level avionics architecture, in Section [4.2.1](#)
2. Power budget and potential operating modes, in Section [4.2.2](#)
3. Battery architecture and power system trade, informed by potential operating modes, in Section [4.2.3](#)

4.2.1 Avionics Architecture

We developed a high-level LEAP avionics architecture, which leverages flight-heritage components from the Ingenuity Mars helicopter wherever possible [[5](#), [4](#), [11](#)]. In the future, lessons learned from hardware selections for the CADRE lunar rovers and MoonFall lunar drones will also be integrated into the LEAP avionics architecture. Details of the key avionics subsystems are provided in Table [7](#).

For now, the avionics design, focuses on key compute elements – the high-level navigation computer, the fault-tolerant flight control computer, the radiation-tolerant, high-speed central avionics system manager, and the telecommunications system. We also identify initial candidates for the primary wheel / leg actuators and battery assembly. We assume that the motor controllers are integrated into the flight control computer board, but it is possible that radiation-tolerant Commercial Off The Shelf (COTS) Electronic Speed Controller (ESC) will instead be used. Additionally, some navigation computers (e.g. Modal AI Voxl 2) integrate an Inertial Measurement Unit (IMU) and flight control computer within the navigation computer board, saving mass and volume.

Future work will focus on developing the jump autonomy capability for LEAP, at which point a detailed trade study and selection of the navigation computer, IMU, and optical sensors will be performed. In particular, the camera / optical sensor trade space has numerous potential options, including: a monocular camera + event camera, a binocular camera + event camera, a solid-state LIDAR system. It is also possible that LEAP will require a combination of these sensors, to provide overlapping functionality, or multiple copies of these sensors, to provide redundancy or broader field of view (e.g. a forward-looking camera while driving, and a downward-looking camera while jumping).

The LEAP robot is not yet mature enough to require a detailed design of the avionics system (e.g. limited component selection and trade studies, no PCB design), which is left for future work.

Avionics Element	Ingenuity Hardware (Model & Type)	LEAP Concept Hardware (Model & Type)	Mass (Approx.)	Power Specs	Primary Flight Role	Redundancy & Radiation Resilience
Navigation Computer (NC)	Qualcomm Snapdragon 801 (via Intrinsic Open-Q 8074 System-on-Module)	Qualcomm QRB5165 (via Modal AI Voxl 2)	Ingenuity: 10.0 g (50mm x 25mm) LEAP: 16.0 g (70mm x 36mm)	Ingenuity: 1.5 W – 5.0 W (Depending on active video tracking payload) LEAP: 2.5 W – 7.0 W	High-Level Brain: Runs Linux OS. Processes 30 Hz downward-facing camera images for real-time visual-inertial odometry.	None (COTS). Swaps data across duplicate memory buffers to flag radiation-induced bit flips.
Flight Control Computer (FC)	Texas Instruments Hercules TMS570LC4357 Microcontroller (×2 units)	<i>Use Ingenuity heritage</i>	~1.5 g	500 mW – 800 mW (Active deployment at 300 MHz)	Piloting System: Executes the primary real-time flight control laws and guidance loops to maintain stability.	Dual-Redundant. Two identical MCUs configured as a primary and an instant hot-spare, operating in lockstep.
Central Avionics System Manager	Microsemi (Microchip) ProASIC3L FPGA (A3PE3000L)	<i>Use Ingenuity heritage</i>	~2.0 g	2 mW (Static base) up to ~200 mW (Dynamic high-frequency routing)	Central Avionics Manager: Manages 25 distinct serial interfaces, data flows, synchronizes sensor clocks, and serves as the flight failure arbiter.	Highly Radiation-Tolerant. Fabricated flash-based logic structure running internal Triple Module Redundancy (TMR).
Telecom Subsystem	LS Research SiFlex 02 RF Transceiver Module (with Atmel AT86RF212B chip)	<i>Use Ingenuity heritage</i>	~5.0 g	940 mW (Peak transmit at 285 mA); 100 mW (Receive mode at 30 mA)	Communication Link: Operates a 914 MHz local radio cross-link to transmit telemetry at up to 250 kbps.	None (COTS). Transceiver modules operating on commercial IEEE 802.15.4 ZigBee protocols.
Motor Drive Actuators	Maxon DCX 10mm Brushed DC Servos (×6 units for blade pitch)	Custom Brushless DC (BLDC) Motors (×2 units) Custom motor controllers integrated in avionics PCB.	Ingenuity: ~11.0 g (per individual micro-servo assembly) LEAP: 20.0 g (per motor)	Ingenuity: 1.5 W – 4.0 W (per servo under aerodynamic torque) LEAP: 1.0 W (per motor while driving)	Ingenuity Swashplate Control: Physically adjust blade pitch angles at 500 Hz to execute directional maneuvers. LEAP Wheel Control: Physically rotate reaction wheels for attitude control and surface driving mobility.	None (modified COTS motors; no redundancy).
Primary Propulsion Motors	AeroVironment Custom Brushless DC Motors (×2 units) Custom motor controllers integrated in avionics PCB.	Custom Brushless DC (BLDC) Motor (×1 unit) Custom motor controller integrated in avionics PCB.	Ingenuity: ~150 g – 200 g est. (Custom lightweight design integrated into the rotor assembly) LEAP: 100 g (single motor)	Ingenuity: 350 W (Typical flight hover draw) up to 510 W (Peak mechanical output during aggressive maneuvers) LEAP: 200 W (peak draw)	Ingenuity Propulsion: Direct-drive actuation of counter-rotating carbon-fiber propeller blades at 2,400–2,800 RPM. LEAP Leg Control: Direct-drive actuation of leg, for jump launch and landing.	None (custom motors; no redundancy).
Main Battery Assembly	Sony Energy Devices SE US18650 VTC4 Lithium-Ion Cells (×6 cells)	Samsung 30Q (18650) Lithium-Ion Cells (×7 cells)	Ingenuity: 273 g total (45.5 g per cell) LEAP: 352 g total (48.0 g per cell)	Ingenuity: 36 Wh / 510 W peak (~21 Wh/sol for night heating; ~10 Wh per flight) LEAP: 75.6 Wh / 756 W peak	Energy Storage & Delivery: Powers entire spacecraft (computers, radios, motors). Recharge via the top-mounted solar array (Ingenuity), or by chargers on Orbilander spacecraft (LEAP).	Ingenuity: No cell redundancy, 6S config (15.0V – 25.2V). Dual internal Kapton film heaters to prevent freezing. LEAP: 7S config (25.2V), no heaters.

Table 7. Summary of key avionics components / subsystems, with direct heritage from Ingenuity helicopter where relevant [5, 4, 11].

4.2.2 Power Budget + Operating Modes

We derived a preliminary LEAP power budget (Table 8), based on a roll-up of the estimated per-subsystem power budgets within the avionics architecture (Table 7) (including rough estimates for instruments, cameras, and telecom.), combined with estimates of power consumed for jumping and orientation control extrapolated from Earth-based experimental data to the relevant Enceladus conditions and LEAP robot mass.

A key takeaway is that LEAP's maximum power consumption (200 W peak / 150 W average, on launch and landing, see Fig. 5b) is similar to the Ingenuity helicopter (350 W average, during flight), but for far shorter durations (0.21 sec vs. 169 sec) [42]. Therefore the flight-heritage avionics developed for Ingenuity can supply sufficient power for all LEAP actuators.

Four potential operational modes / scenarios were developed to bracket our power budget:

1. **Scenario 1:** Compute / planning constrained – spend 25% of the time moving / collecting + processing samples from the plume, and 75% of the time processing image / science data, building maps, planning next jumps. Consumes 13.8 W when on and 0.2 W in hibernation. See Table 9.
2. **Scenario 2:** Balanced exploration – spend 50% of the time moving / collecting + processing samples from the plume, and 50% of the time processing image / science data, building maps, planning next jumps. Consumes 19.7 W when on and 0.2 W in hibernation. See Table 10.
3. **Scenario 3:** High mobility / sampling – spend 75% of the time moving / collecting + processing samples from the plume, and 25% of the time processing image / science data, building maps, planning next jumps. Consumes 25.5 W when on and 0.2 W in hibernation. See Table 11.
4. **Scenario 4:** Balanced exploration + low power electronics – spend 50% of the time moving / collecting + processing samples from the plume, and 50% of the time processing image / science data, building maps, planning next jumps. Consumes 8.7 W when on and 0.2 W in hibernation. See Table 12.

LEAP's overall average power consumption is estimated at 8.7-25.5 W across the above operating scenarios, along with a low-power (0.2 W) hibernation mode. The thermally-constrained operational cadence is provided in Section 4.3.3 and Fig. 47, and indicates an average power of 3.0 W when combining operational and hibernation modes. This permits the LEAP robots to operate for 2 orders of magnitude longer periods of time between recharges than was possible on Ingenuity, using a similar battery capacity.

4.2.3 Battery Architecture

Two power / battery architectures were studied based on the expected avionics architecture, power budget, and operating modes. The first architecture uses a primary (non-rechargeable) battery, with ultra-low-discharge and higher energy density. The second architecture uses a secondary (rechargeable) battery, that is similar to the Ingenuity helicopter.

Table 13 compares candidate batteries for both architectures: a pair of non-rechargeable Li-CFx batteries (EaglePicher LCF-15004 [21], EaglePicher LCF-136HR [20]) and a pair of rechargeable Li-ion batteries (Sony / Murata US18650-VTC4 [18], Samsung 30Q 18650 [58]), with metrics sourced from online datasheets.

The Li-CFx battery and Li-CFx / MnO₂ hybrid battery have excellent shelf life with low discharge rates, and would not require maintenance charging during flight prior to use (simplifying interfaces to Orbilander). They have significantly higher energy density (2-2.5x) than rechargeable batteries, which provides a longer operational duration and greater exploration range than an equivalent Li-ion battery. The ultra-low power density of the Li-CFx battery necessitates additional energy storage components (e.g. supercapacitors) for the high-power, low-duration energetic jumps used by LEAP robots. The Li-CFx / MnO₂ hybrid battery offers improved power density over the Li-CFx battery (and 25-50% of equivalent Li-ion batteries), and is able to sustain current pulses up to 20 A for 20 seconds, thereby avoiding the need for large supplemental energy storage capacitors.

The Sony / Murata Li-ion battery was used on the Ingenuity Helicopter (6 cells, series configuration) [5], and provides extremely high power density and continuous power output (approx. 100 W per battery). In comparison, the Samsung Li-ion battery provides a improved energy density (1.33x), but lower power density (0.5x). Since both batteries can supply significantly higher current / power than demanded by the LEAP robot, the Samsung battery is preferable for its increased energy capacity.

In the context of the LEAP mission and robot, we defined five primary design constraints on the power system / battery architecture:

1. Power subsystem is allocated approximately 0.35 kg mass (35% of 1 kg robot total mass; no margin)
2. Jumps require 200 W (peak) / 150 W (average) power over approx. 0.21 second (31.5 J) on both launch and landing, plus up to 30 W additional power for instruments and avionics
3. Avionics require stable 5.0 V and 3.3 V power (avoid brownouts during peak battery load)

LEAP – Legged Exploration Across the Plume

System	Min Power (W)	Max Power (W)	Comments
Avionics + Compute	4.2	9.5	Max tested was 4.5 W / min tested was 0.5 W
Avionics	1.7	2.5	Power electronics, battery control board, and other miscellaneous avionics hardware.
VOXL 2	2.5	7.0	Tested at 4.5 W max / 0.5 W min; using product spec. values. For additional margin.
Cameras + Instruments	5.0	15.0	Instruments likely used at low duty cycle near the plume; cameras likely used at high duty cycle.
Cameras	0.6	1.0	Cameras are quite low power; considering stereo pairs and event cameras. LIDAR consumes more power.
Instruments	4.4	14	IMU is low power (0.1W). High uncertainty on instruments (mass spec., particle detector, etc.)
Telecom	1.0	14.0	Operate at 10% duty cycle (predominantly used close to the lander; bookkeeping high-power S-band if needed)
Total	9.3	25.9	15% margin up to 30 W max for instruments + compute (and includes 10% active comms.)

Table 8. Power budget estimate, by subsystem, across the avionics system.

Operating Mode	Leg Power	Wheel Power	Avionics + Instruments	Operating Time (%)	% Scaled Power (W)	Notes
Balancing	1.0 W	0.4 W = 2x 0.2 W (average) / 30.0 W (max, disturbance)	30 W = 15.0 W (avionics) + 15.0 W (instruments)	1%	0.31	Robot balances on its leg with the wheels acting as reaction wheels
Driving	0.0 W	2.0 W = 2x 1.0 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	5%	1.60	Robot uses the two wheels to drive around on the surface
Hopping (0.30 m Series-Elastic Leg)	1.0 W (continuous) = 2x 200 W (peak) / 150 W (avg) over 0.21 s (31.5 J) every 1 min (for launch + landing)	0.2 W = 2x 0.1 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	19%	5.93	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.
Thinking	0.0 W	0.0 W	5.0 – 11.0 W (avionics)	75%	6.00	No power required for motors; only avionics and / or instruments
Hibernate / Cooldown	0.0 W	0.0 W	0.2 W (avionics)	Non-Op / Cooldown	0.20	No power required for motors; only avionics and / or instruments

Operating Mode	Leg Power	Wheel Power	Avionics	Operating Time (%)	% Scaled Power (W)	Notes
Hopping (Direct-Drive Leg)	1.0 W (continuous) = 2x 280 W for 0.11 secs (~31 J) every 1 minute (for launch + landing)	0.2 W = 2x 0.1 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	19%	5.93	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.

Operating Mode	Net Power (W)	Notes
On	13.8	Use this power when robot is operational .
Hibernate / Cooldown	0.2	Use this power when robot needs to cool down .

Table 9. Operating Scenario 1: Compute / planning constrained scenario – spend 25% of the time moving / collecting + processing samples from the plume, and 75% of the time processing image / science data, building maps, planning next jumps.

Operating Mode	Leg Power	Wheel Power	Avionics + Instruments	Operating Time (%)	% Scaled Power (W)	Notes
Balancing	1.0 W	0.4 W = 2x 0.2 W (average) / 30.0 W (max, disturbance)	30 W = 15.0 W (avionics) + 15.0 W (instruments)	2%	0.63	Robot balances on its leg with the wheels acting as reaction wheels
Driving	0.0 W	2.0 W = 2x 1.0 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	10%	3.20	Robot uses the two wheels to drive around on the surface
Hopping (0.30 m Series-Elastic Leg)	1.0 W (continuous) = 2x 200 W (peak) / 150 W (avg) over 0.21 s (31.5 J) every 1 min (for launch + landing)	0.2 W = 2x 0.1 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	38%	11.86	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.
Thinking	0.0 W	0.0 W	5.0 – 11.0 W (avionics)	50%	4.00	No power required for motors; only avionics and / or instruments
Hibernate / Cooldown	0.0 W	0.0 W	0.2 W (avionics)	Non-Op / Cooldown	0.20	No power required for motors; only avionics and / or instruments

Operating Mode	Leg Power	Wheel Power	Avionics	Operating Time (%)	% Scaled Power (W)	Notes
Hopping (Direct-Drive Leg)	1.0 W (continuous) = 2x 280 W for 0.11 secs (~31 J) every 1 minute (for launch + landing)	0.2 W = 2x 0.1 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	38%	11.86	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.

Operating Mode	Net Power (W)	Notes
On	19.7	Use this power when robot is operational .
Hibernate / Cooldown	0.2	Use this power when robot needs to cool down .

Table 10. Operating Scenario 2: Balanced exploration scenario – spend 50% of the time moving / collecting + processing samples from the plume, and 50% of the time processing image / science data, building maps, planning next jumps.

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Operating Mode	Leg Power	Wheel Power	Avionics + Instruments	Operating Time (%)	% Scaled Power (W)	Notes
Balancing	1.0 W	0.4 W = 2x 0.2 W (average) / 30.0 W (max, disturbance)	30 W = 15.0 W (avionics) + 15.0 W (instruments)	3%	0.94	Robot balances on its leg with the wheels acting as reaction wheels
Driving	0.0 W	2.0 W = 2x 1.0 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	15%	4.80	Robot uses the two wheels to drive around on the surface
Hopping (0.30 m Series-Elastic Leg)	1.0 W (continuous) = 2x 200 W (peak) / 150 W (avg) over 0.21 s (31.5 J) every 1 min (for launch + landing)	0.2 W = 2x 0.1 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	57%	17.78	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.
Thinking	0.0 W	0.0 W	5.0 – 11.0 W (avionics)	74%	2.00	No power required for motors; only avionics and / or instruments
Hibernate / Cooldown	0.0 W	0.0 W	0.2 W (avionics)	Non-Op / Cooldown	0.20	No power required for motors; only avionics and / or instruments

Operating Mode	Leg Power	Wheel Power	Avionics	Operating Time (%)	% Scaled Power (W)	Notes
Hopping (Direct-Drive Leg)	1.0 W (continuous) = 2x 280 W for 0.11 secs (~31 J) every 1 minute (for launch + landing)	0.2 W = 2x 0.1 W	30 W = 15.0 W (avionics) + 15.0 W (instruments)	57%	17.78	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.

Operating Mode	Net Power (W)	Notes
On	25.5	Use this power when robot is operational.
Hibernate / Cooldown	0.2	Use this power when robot needs to cool down.

Table 11. Operating Scenario 3: High mobility / sampling scenario – spend 75% of the time moving / collecting + processing samples from the plume, and 25% of the time processing image / science data, building maps, planning next jumps.

Operating Mode	Leg Power	Wheel Power	Avionics + Instruments	Operating Time (%)	% Scaled Power (W)	Notes
Balancing	1.0 W	0.4 W = 2x 0.2 W (average) / 30.0 W (max, disturbance)	10 W = 5.0 W (avionics) + 5.0 W (instruments)	2%	0.23	Robot balances on its leg with the wheels acting as reaction wheels
Driving	0.0 W	2.0 W = 2x 1.0 W	10 W = 5.0 W (avionics) + 5.0 W (instruments)	10%	1.20	Robot uses the two wheels to drive around on the surface
Hopping (0.30 m Series-Elastic Leg)	1.0 W (continuous) = 2x 200 W (peak) / 150 W (avg) over 0.21 s (31.5 J) every 1 min (for launch + landing)	0.2 W = 2x 0.1 W	10 W = 5.0 W (avionics) + 5.0 W (instruments)	38%	4.26	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.
Thinking	0.0 W	0.0 W	6.0 W (avionics)	50%	3.00	No power required for motors; only avionics and / or instruments
Hibernate / Cooldown	0.0 W	0.0 W	0.2 W (avionics)	Non-Op / Cooldown	0.20	No power required for motors; only avionics and / or instruments

Operating Mode	Leg Power	Wheel Power	Avionics	Operating Time (%)	% Scaled Power (W)	Notes
Hopping (Direct-Drive Leg)	1.0 W (continuous) = 2x 280 W for 0.11 secs (~31 J) every 1 minute (for launch + landing)	0.2 W = 2x 0.1 W	10 W = 5.0 W (avionics) + 5.0 W (instruments)	38%	4.26	Robot uses leg to propel itself into the air; during jump, reaction wheels reorient robot in the air.

Operating Mode	Net Power (W)	Notes
On	8.7	Use this power when robot is operational.
Hibernate / Cooldown	0.2	Use this power when robot needs to cool down.

Table 12. Operating Scenario 4: Balanced scenario + low power electronics – spend 50% of the time moving / collecting + processing samples from the plume, and 50% of the time processing image / science data, building maps, planning next jumps.

4. Sufficient energy to reach 5.0 km from the lander (assume jumps cover 85 m, half of max 170 meter lateral jump)
5. Minimum state of charge of 30% is maintained for robot safety

Two power system architectures were developed that meet this set of constraints (Table 14). Robot endurance and range are determined by battery energy capacity versus the four operating modes highlighted in Section 4.2.2, and by the “ON” / “OFF” cadence defined in Section 4.3.3.

The “Endurance Mission” relies on 7x Li-ion batteries (Samsung 30Q 18650) in a series configuration, using 0.352 kg (with 5% mass margin for securing the 18650 cylindrical cells). This design exceeds the peak jump power requirement with 64% margin (at the nominal battery discharge voltage / current) and 230% (at peak battery discharge). This power pack provides sufficient energy for 3.0 hrs (Scenario 3) to 8.7 hrs (Scenario 4) of operational “On” time during the single 26.3 hrs sortie. The corresponding exploration range is estimated at 3.5-11.1 km (one-way) or 2.3-7.4 km (with return to Orbilander, for guaranteed data download).

The “Single-Shot Mission” relies on 10x Li-CFx / MnO₂ batteries (EaglePicher LCF-136HR) in a series configuration, using 0.339 kg (with 15% mass margin for reinforcing the pouch cells). This design exceeds the peak jump power requirement with 130% margin (using the 20 A / 20 second max pulse battery discharge rating), but is unable to power jumps using nominal battery current alone. This power pack provides sufficient energy for 4.3 hrs (Scenario 3) to 12.5 hrs (Scenario 4) of operational “On” time during the single 37.8 hrs sortie. The corresponding exploration range is estimated at 5.0-16.0 km (one-way) or 3.4-10.7 km (with return to Orbilander, for guaranteed data download). The battery total energy was depreciated by 6.8% to account for the 0.7%/year self-discharge rate over an assumed 10 year interval from pre-launch integration on the spacecraft until use on Enceladus.

Both options provide a reasonable path to accessing targets / regions of interest within 5 km of the Orbilander in 2+ different directions, using a variety of conservative estimates on exploration cadence and power usage.

In general, LEAP will maximize exploration range through a combination of maximally power efficient avionics / instrument (to reduce average operational power draw) combined with high jump cadence (Scenario 3, jumping 75% of the time). The ranges above assume a LEAPfrog exploration strategy (see Section 5.2.6) on the outward journey to a new target / region of interest, and retracing steps along the mapped path on the return journey (for 2x faster traversal speed by skipping the vertical mapping jumps). It is therefore possible to extend the round-trip range estimates above, by repeatedly traversing a previously-mapped corridor towards a distant target of interest and marginally extending the distant edge of the map on each sortie with the energy saved from reduced vertical mapping jumps.

The “Endurance Mission” power system architecture has several key advantages over the “Single-Shot Mission” architecture. The “Endurance Mission” is a flight-proven architecture (Ingenuity helicopter) with reduced electronics complexity (no need for energy storage capacitors). The recharge ability at Orbilander allowed unlimited sorties until hardware failure, which allows for more methodical exploration, terrain mapping, and periodic data return to the Orbilander.

Our strong preference going forward is to baseline the rechargeable “Endurance Mission” power system architecture for LEAP. This is contrary to our initial focus on a non-rechargeable “Single-Shot Mission” architecture, which has simplified interface requirements to Orbilander, but would likely yield inferior science return due to the single sortie constraint.

Performance Metric	EaglePicher LCF-15004	EaglePicher LCF-136HR	Sony / Murata US18650VTC4	Samsung 30Q 18650
Primary/Secondary	Non-Rechargeable (Primary)	Non-Rechargeable (Primary)	Rechargeable (Secondary)	Rechargeable (Secondary)
Chemistry	Li-CFx	Hybrid (Li-CFx / MnO ₂)	Li-ion (NMC/NCA)	Li-ion (LiNiMnCoO ₂)
Cell Size	D-Cell (33×61 mm)	Pouch (50×48×6.5 mm)	18650 (18×65 mm)	18650 (18×65 mm)
Cell Weight (g)	97.0 g	29.5 g	45.3 g	48.0 g
Operating Temp (°C)	-40 to +60°C	-40 to +60°C	-20 to +60°C	-20 to +75°C
Nominal Voltage (V)	2.6 V	2.65 V	3.6 V	3.6 V
Voltage Range (V)	2.0–3.3 V (Flat at 2.6 V)	1.5–3.3 V (Flat at 2.65 V)	2.5–4.2 V	2.5–4.2 V
Nominal Capacity (Ah)	16.0 Ah (16,000 mAh)	4.8 Ah (4800 mAh)	2.1 Ah (2100 mAh)	3.0 Ah (3000 mAh)
Total Energy (Wh)	41.6 Wh	11.7 Wh	7.6 Wh	10.8 Wh
Energy Density (Wh/kg)*	429 Wh/kg	396 Wh/kg	168 Wh/kg	225 Wh/kg
Power Density (W/kg)*	80 W/kg	630 W/kg	2400 W/kg	1125 W/kg
Max Cont. Current (A)	3.0 A	6.0 - 8.0 A (varies w/ temp)	30.0 A	15.0 A
Max Cont. Current (C)*	0.2C	1.5 C	15C	5C
Pulse Capability (A)	6.0 A	20.0 A (20 seconds)	>35 A	30 A
Max Cont. Power (W)	7.8 W	7.2 W	108.0 W	54.0 W
Pulse Power (W)	15.6 W	53 W	126.0 W	108.0 W
Self-Discharge	<0.5% per year	≈0.7% per year	≈2–5% per month	≈2–5% per month
Shelf Life	15–20 Years	15–20 Years	Maintenance charging	Maintenance charging

* Approximate values computed from supplied data, and rounded

Table 13. Battery architecture trade, between Li-CFx batteries, Li-CFx / MnO₂ hybrid batteries, and conventional lithium-ion (Li-ion) batteries.

Metric	Design A: Endurance Mission	Design B: Single-Shot Mission
Architecture	Li-ion Battery Pack (7S1P)	Li-CFx / MnO ₂ Battery Pack (10S1P)
Core Components	7x Samsung 30Q (18650)	10x EaglePicher LCF-136HR (Pouch)
Total Power System Mass	352 g (5% packaging margin on battery mass)	339 g (15% packaging margin due to pouch cells)
Total Energy	75.6 Wh	109.1 Wh (derated for 10 years flight)
Nominal Voltage	25.2 V	26.5 V
Peak Current Draw (for Jump)	9.1 A (direct from battery)	8.7 A (direct from battery)
Pulse Handling	Excellent (Battery has 15 A continuous rating)	Acceptable (Battery rated for 20 A / 20 sec pulses)
Sortie Duration (Avg)	5.8 hrs (On) / 26.3 hrs (Sortie)	8.4 (On) / 37.8 hrs (Sortie)
Scenario 1 (13.8 W / 0.2 W)	5.5 hrs (On) / 26.3 hrs (Sortie)	7.9 hrs (On) / 37.9 hrs (Sortie)
Scenario 2 (19.7 W / 0.2 W)	3.8 hrs (On) / 26.5 hrs (Sortie)	5.5 hrs (On) / 38.2 hrs (Sortie)
Scenario 3 (25.5 W / 0.2 W)	3.0 hrs (On) / 26.1 hrs (Sortie)	4.3 hrs (On) / 37.7 hrs (Sortie)
Scenario 4 (8.7 W / 0.2 W)	8.7 hrs (On) / 26.2 hrs (Sortie)	12.5 hrs (On) / 37.8 hrs (Sortie)
Range (km) *	3.5-11.1 km	5.0-16.0 km
Range w/ Return (km) *	2.3-7.4 km	3.4-10.7 km
Rechargeable?	Yes (Unlimited Sorties)	No (Single Use / One-Way)
Thermal Strategy	Insulation + Electronics self-heating	Insulation + Electronics self-heating
Complexity	High (interfaces for charging in cruise / on surface)	Low (no-touch after battery integration)

* Range assumes LEAPfrog exploration, with 85 meter lateral progress every other jump and jump frequency based on operating scenario. Range w/ Return via previously-mapped terrain has 2x exploration rate (skips vertical jumps).

Table 14. Power system architecture trade. Design A (“Endurance Mission”) provides approx. 70% range of Design B (“Single-Shot Mission”), but enables a rechargeable battery architecture for multiple sorties. To maximize exploration range, LEAP requires maximally power efficient avionics / instrument combined with high jump cadence (Scenario 3).

4.3 Thermal System Design for Enceladus

A major open question for LEAP (and all spacecraft) is what design accommodations must be made to ensure that the robot can successfully operate in the unique and challenging Enceladus thermal environment. Herein, we will briefly define this Enceladus environment. Then we introduce a simplified thermal nodal model that captures the relevant hardware components, material properties, system inputs, and boundary conditions. Finally, we perform parameter sweeps that vary these baseline properties to test a range of potential operating conditions, and aggregate these results relative to the baseline performance.

This work clearly demonstrates the **viability of the LEAP robot to operate without dedicated heaters** (or a RHU) under a range of relevant environmental conditions and design parameter variations.

4.3.1 Enceladus Environment

Enceladus presents a unique and challenging thermal environment for a robotic spacecraft to survive and operate. Relevant environmental conditions include the following:

- **Ground Temperature:** $\sim 50\text{-}150$ K (cryogenic ice)
- **Sky Temperature:** ~ 3 K
- **Pressure:** Vacuum
- **Solar:** $0\text{-}15$ W/m² (across a 33 hour day / night cycle)

These conditions imply that the LEAP robot must maintain sufficient minimum internal temperature to operate its batteries, avionics, and motors (including lubricants), while at the same time not overheat due to excessive heat generation (from high-power actuators, processors, and instruments) coupled with limited methods for heat dissipation (minimal heat conduction into the ice surface and heat radiation into deep space).

4.3.2 Thermal Model

We developed a nodal model (nodal mathematical model) to analyze the thermal behavior of the LEAP robot operating in the Enceladus environment.

This nodal model simplifies the (complex) heat transfer between the numerous robot subsystems and the environment into a network of nodes (representing isothermal mass / volumes, and heat sources or sinks) and edges (representing conductive heat paths between nodes). We then solve for temperatures at each node using energy balance equations.

The nodal model is depicted in Fig. 44.

Modeled Components Key components of the thermal nodal analysis model and their abbreviations are defined in Fig. 44.

The rover internals (INTLS, including avionics / motors) were treated as a single dissipative node that generates heat according to the robot operational power (OPS). This OPS power and “On” / “Off” duty cycling is based the potential vehicle operating modes defined in Section 4.2.2 and Tables 9 to 12. These internals are linked to the environment (ENV) via multiple hardware paths.

Two reaction wheels (RW) are modeled as arithmetic nodes, with heat transfer along the shaft from motor to wheel hub (RWSHFT). A combined leg (LG) and foot (FT) is also modeled as an arithmetic node. The temperatures of the reaction wheel (RW) and foot + leg (FT+LG) arithmetic nodes are based on conductive heat flow from the central robot internals (INTLS) diffusion node, through physical hardware connections modeled as cylindrical shafts of a specified material.

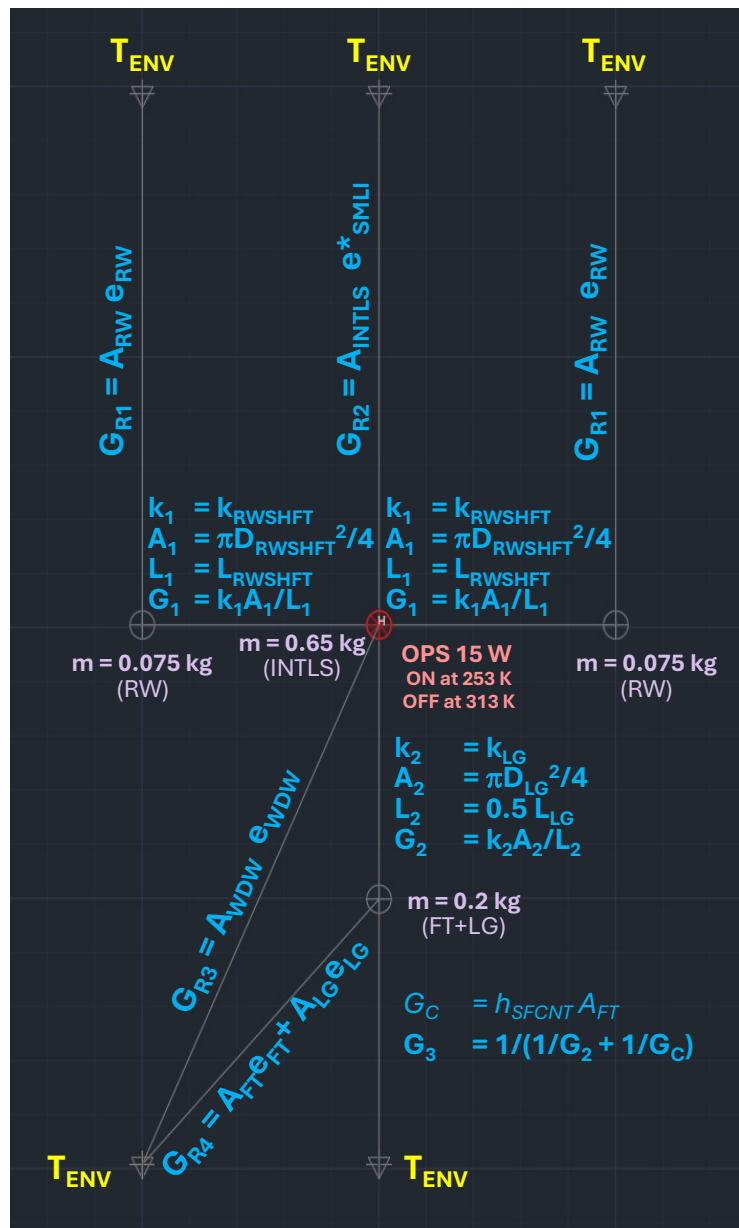
The specific dimensional or thermal property values associated with each component are also provided in Fig. 44.

Boundary Conditions Six boundary nodes / conditions to the environment (ENV) are tracked in this nodal model – five are radiative and one is conductive, and all are linked to the cryogenic ice surface at a fixed temperature (T_{ENV}).

The two primary radiative paths from the rover internals are through a high-surface-area, low-emissivity MLI shroud (G_{R2}) and an alternate low-surface-area, high-emissivity path through a window (WDW) cut in the MLI for cameras and instruments to be exposed to the environment (G_{R3}). Additional radiative paths are provided for each of the two reaction wheels (G_{R1}), and for the combined leg / foot (G_{R4}).

The primary conductive path is through the robot leg and foot, via surface contact (G_C).

There are three limitations of the current model’s boundary conditions. First, conductive heat transfer from the reaction wheels into the cryogenic ice surface (when the robot is resting on the surface) is not modeled, although this contribution is expected to be somewhat limited due to wheel contact area. Second, conductive heat transfer through the foot due to surface contact should be eliminated during the aerial phase of operation (which can be a significant portion of robot operation time under the “Balanced” (Scenario 2) and “High Mobility” (Scenario 3) exploration scenarios in Section 4.2.2. Third, no incoming solar radiation ($0\text{-}15$ W/m²) or outgoing radiation to deep space is currently modeled.



Name	Result	Expression	Comment
A_ft	0.00785398	$3.1415926 * D_{ft}^2/4$	m ²
A_intls	0.0967744	$(D_{intls})^2/4$	m ²
A_lg	0.012161	$3.1415926 * D_{lg}^2/4$	m ²
A_rw	0.0235619	$3.1415926 * D_{rw}^2/4$	m ²
A_sfcnt	0.00392699	$A_{ft}/2$	m ²
A_wdw	0.005	$50e-4$	m ²
Cp_ft	900	900	J/kg-K
Cp_intls	900	900	J/kg-K
Cp_lg	900	900	J/kg-K
Cp_rw	900	900	J/kg-K
D_ft	0.1	0.1	m
D_intls	0.127	$5/39.37$	m
D_lg	0.0127	$0.5/39.37$	m
D_rw	0.25	0.25	m
D_rwshft	0.0065	0.0065	m
estar_sml	0.005	0.005	
e_ft	0.1	0.1	
e_lg	0.1	0.1	
e_rw	0.1	0.1	
e_wdw	1	1	
G1	0.000873239	$k_{rwshft} * (3.1415926 * D_{rwshft}^2/4) / L_{rwshft}$	W/K
G2	0.00623411	$k_{lg} * (3.1415926 * D_{lg}^2/4) / (L_{lg}/2)$	W/K
G3	0.00538003	$1/(1/G_2 + 1/G_C)$	W/K
G_C	0.0392699	$h_{sfcnt} * A_{sfcnt}$	W/K
GR1	1.178097225000e-03	$A_{rw} * e_{rw}$	m ²
GR2	0.000435485	$A_{intls} * e_{star_sml}$	m ²
GR3	0.005	$A_{wdw} * e_{wdw}$	m ²
GR4	0.0020015	$A_{lg} * e_{lg} + A_{ft} * e_{ft}$	m ²
h_sfcnt	10	10	W/m ² -K
k_lg	7.5	7.5	W/m-K
k_rw	7.5	7.5	W/m-K
k_rwshft	7.5	7.5	W/m-K
L_lg	0.304801	$12/39.37$	m
L_rwshft	0.285	0.285	m
m_ft	0.1	0.1	kg
m_intls	0.65	0.65	kg
m_lg	0.1	0.1	kg
m_rw	0.075	0.075	kg
Q_op	15	15	W
T_env	50	50	K
T_init	253	253	K
t_rw_rim	0.005	0.005	m
w_rw	0.02	0.02	m

LEGEND

ENV	= Environment
INTLS	= Internals
FT	= Foot
LG	= Leg
OPS	= Operational Power
RW	= Reaction Wheel
RWSHFT	= RW Shaft
SFCNT	= Surface Contact
SMLI	= Spacerless MLI
WDW	= Window

Figure 44. Nodal model diagram for the LEAP robot, including the robot internals (INTLS), reaction wheels (RW), foot / leg (FT+LG), and conduction (surface) / radiation (sky) interactions with the environment.

4.3.3 Thermal Case Study + Results

We conducted a set of **32 test cases** simulating a range of potential hardware designs, thermal insulation, material selection, and operating conditions. Details of these parameter configurations are provided in Fig. 45. Aggregated results of these 32 simulation runs are provided in Fig. 47.

In each scenario, the robot was assumed to be pre-heated by the Orbilander to a minimum operational AFT before deploying onto the Enceladus surface and beginning nominal operations. In this simulation, would then operate in an “ON” state that generated net positive heat. When the internal temperature reached the spacecraft maximum operational AFT, it would then enter a hibernation “OFF” state to cool off until the minimum operational AFT was reached. This would be considered one cycle within a larger operational deployment lasting until onboard power was depleted (or the vehicle recharges).

Parameter Configurations Significant attention was given to explore the impacts to robot operational cadence / endurance under a range of potential hardware parameters. Parameters studied at this stage include: emissivity of MLI and robot hardware (e^* , $e_{FT,RW,LG}$), size of the instrument windows in the MLI (A_{WDW}), surface temperature (T_{ENV}), robot structural material, surface contact conduction (h_{SFCNT}), internal heat generation (Q), minimum AFT (T_{ON}), and maximum AFT (T_{OFF}).

Parameter	Values (Baseline Values in Bold)	Units	Additional Runs	Run Numbering
e^*_{SMLI}	0.002, 0.005 , 0.009, 0.015	-	4	R01,R02,R03,R04
e_{FT}	0.05, 0.1 , 0.3, 0.5, 0.9		4	R05,R06,R07,R08
e_{RW}	0.05, 0.1 , 0.3, 0.5, 0.9		0	
e_{LG}	0.05, 0.1 , 0.3, 0.5, 0.9		0	
e_{WDW}	1.0 (not varied)		0	
A_{WDW}	5, 50 , 500	cm ²	2	R09,R10
T_{ENV}	20, 50 , 100, 150	K	3	R11,R12,R13
Material	Ti64 , 5083 Al, 304 SS		2	R14,R15
k	7.5 , 115, 15	W/m-K (R14,R15)	0	
C_p	528 , 900, 500	J/kg-K (R14,R15)	0	
ρ	4430 , 2710, 7930	kg/m ³ (not used)	0	
h_{SFCNT}	1, 10 , 100, 1000	W/m ² -K	3	R16,R17,R18
Q	5, 15 , 25, S1, S2, S3, S4*	W	6	R19,R20,R21,R22,R23,R24
T_{ON}	223, 233, 243, 253 , 263	K	4	R25,R26,R27,R28
T_{OFF}	313 , 323, 333, 343, 353	K	4	R29,R30,R31,R32
Total Runs			32	

Figure 45. Configuration of the nodal model analysis parameter sweeps. Q is the internal heat generation of the central diffusion node, with S1-S4 based on scenarios specified in Tables 9 to 12.

Simulation Results Numerous insights were developed from the results of the 32 test cases (Fig. 47), with strong implications for the design of the LEAP robot. Useful metrics are provided in Fig. 47, including:

- Number of cycles simulated (N_{cycles}) – in this case cycles were limited by the simulation duration (**100 hours / 360,000 seconds**) and not limited by an assumed onboard power budget
- Time for a complete “ON” / “OFF” operating cycle (t_{cycle})
- Average power draw (Q_{AVG}) – time between recharges can be estimated relative to an assumed battery capacity of 75.6 Wh from Section 4.2.2
- “ON%” / “OFF%” percentages – with implications for the cadence of exploration vs. hibernation activities during surface operations

In all but one test case, the robot had sufficient insulation and heat generation that it would overheat / reach the maximum AFT and require hibernation cool-down periods.

Run 1 is the baseline test case, with an average power draw (Q_{AVG}) of 2.9 W and a 20% “ON” / 80% “OFF” operating cadence. Parameters were varied individually relative to this baseline in the subsequent **Run 2-32** test cases. The output of **Run 1** is shown in Fig. 46.

Results of those parameter variations are discussed below, with a focus on impact to average operating power (Q_{AVG}), since this has a direct impact on total endurance of the robot (before requiring a recharge). Other outliers or interesting behaviors are flagged where appropriate.

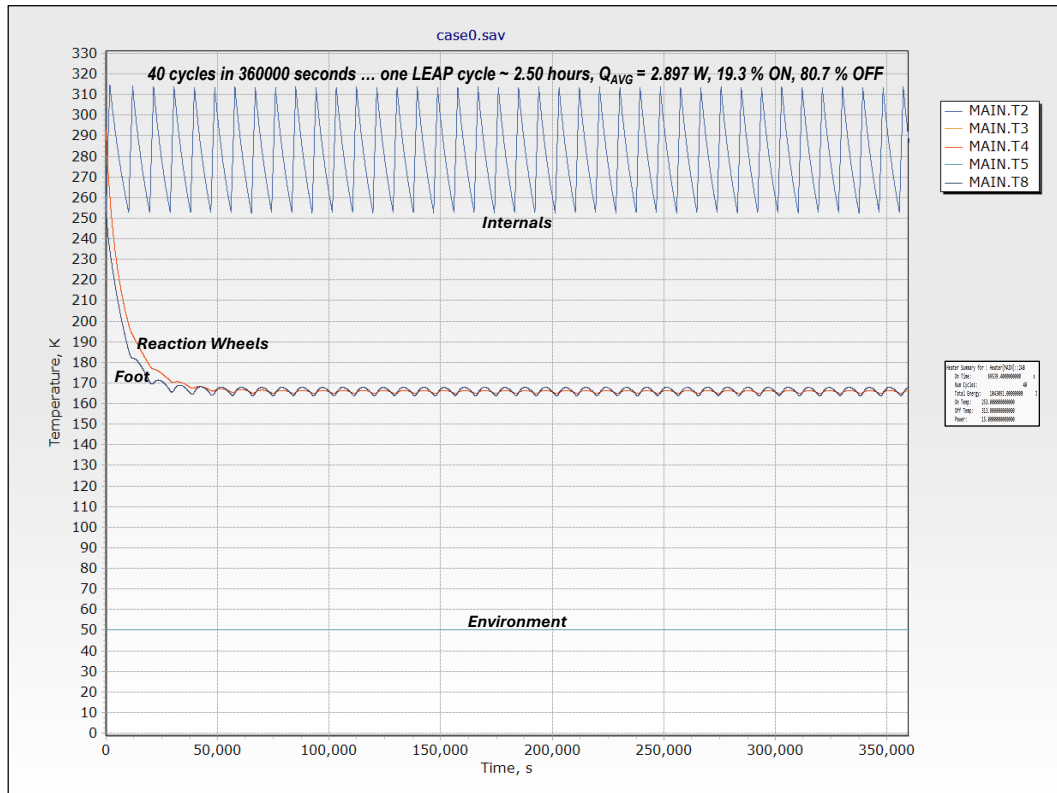


Figure 46. Results of the nodal model analysis parameter sweeps – **Run 1 / Baseline**. Temperatures of various components are labeled, along with relevant summary statistics.

1. **Runs 2-4:** Varying MLI emissivity (e^*) from 0.002 to 0.015 (baseline 0.005) results in a **15% variation** in power draw (QAVG).
 - **Conclusion:** MLI emissivity (e^*) should generally be as low as possible (by adding more layers and minimizing conductive paths through the MLI), but limited gains are observed within a single order-of-magnitude change in a reasonably-effective MLI.
2. **Runs 5-8:** Varying hardware emissivity ($e_{FT,RW,LG}$) from 0.05 to 0.9 (baseline 0.1) results in a **12% variation** in power draw (QAVG).
 - **Conclusion:** Emissivity of external surfaces should be as low as possible (through surface treatments, minimizing surface area, and material selection where possible)
3. **Runs 9-10:** Varying window area (A_{WDW}) from 5 to 500 cm^2 (baseline 50 cm^2) results in a **475% variation** in power draw (QAVG).
 - **Conclusion:** Areas of any windows in the MLI should be as small as possible, and the lack of sufficient MLI (500 cm^2 window area) was the only test case observed where the robot reached a steady-state temperature while remaining 100% “ON”. In other words, heat radiation was sufficiently high that the robot would freeze if it ever lost power. See Figs. 48 and 49.
4. **Runs 11-13:** Varying environmental temperatures (T_{ENV}) from 20 to 150 K (baseline 50 K) results in a **18% variation** in power draw (QAVG).
 - **Conclusion:** Temperature of the environment has a limited impact on operations. Higher temperatures yield fewer, longer operating cycles.
5. **Runs 14-15:** Varying materials from 5083 Al to 304 Stainless Steel (baseline Ti64) results in a **190% variation** in power draw (QAVG).

- **Conclusion:** Selecting low k materials is critical to minimize conductive heat transfer out of the robot internals and into non-insulated hardware (Ti or SS are greatly preferable to Al). This will significantly reduce power draw on the hardware required to maintain internal temperature above AFT (and also reduce “ON%”). See Figs. 50 and 51.
6. **Runs 16-18:** Varying surface contact (h_{SFCNT}) from 1 to 1000 W/m^2K (baseline 10 W/m^2K) results in a **9% variation** in power draw (QAVG).
- **Conclusion:** Contact with the surface of Enceladus has only a minor effect on heat transfer.
7. **Runs 19-24:** Varying internal heat generation (Q) from 5 to 25 W (baseline 15 W), and according to the 4 operating scenarios from Section 4.2.2, results in a **6% variation** in power draw (QAVG). Notably, significant variation in “ON%” is also observed across the different operating scenarios, ranging from a 20% baseline to 61% (5 W), 33% (Scenario 4), and 12% (Scenario 3).
- **Conclusion:** Variation in actual onboard power level results in relatively minor variation in average power draw (QAVG), due to hibernation cycles, but plays a significant factor in the “ON%” duration. Effectively, we can operate for longer wake cycles if we use less power, but the time between recharges will be about the same across all operating modes.
 - Leaving power “ON” at 0.2 W during cooldown lengthens the cooldown time and reduces the number of power cycles slightly for a given time period.
8. **Runs 25-28:** Varying minimum AFT (T_{ON}) from 223 to 263 K (baseline 253 K) results in a **26% variation** in power draw (QAVG).
- **Conclusion:** Reducing turn-“ON” temperature lengthens cycle time (fewer cycles), provides a 5% point increase in “ON%”, and also reduces average heat leak. See Fig. 52.
9. **Runs 29-32:** Varying maximum AFT (T_{OFF}) from 323 to 353 K (baseline 313 K) results in a **22% variation** in power draw (QAVG).
- **Conclusion:** Increasing turn-“OFF” temperature lengthens cycle time (fewer cycles), provides a 4% point increase in “ON%”, but also increases average heat leak. See Fig. 53.

Run	Parameter	Value	Baseline	Units	Ncycles	tcycle (hours)	QAVG (W)	ON%	OFF%	Comments
1	Baseline	see parameter	see parameter	see parameter	40	2.50	2.897	19.3	80.7	See comments for each parameter
2	e* _{MLI}	0.002	0.005	none	39	2.56	2.807	18.7	81.3	MLI e* should be as low as possible
3	e* _{MLI}	0.009	0.005	none	41	2.44	3.052	20.3	79.7	
4	e* _{MLI}	0.015	0.005	none	43	2.33	3.220	21.5	78.5	
5	e _{FT,RW,LG}	0.05	0.1	none	39	2.56	2.825	18.8	81.2	Emissivity of external surfaces should be as low as possible
6	e _{FT,RW,LG}	0.3	0.1	none	41	2.44	3.025	20.2	79.8	
7	e _{FT,RW,LG}	0.5	0.1	none	42	2.38	3.082	20.5	79.5	
8	e _{FT,RW,LG}	0.9	0.1	none	43	2.33	3.175	21.2	78.8	
9	A _{WDW}	5	50	cm2	20	5.00	1.295	8.8	91.2	Area of windows should be as small as possible
10	A _{WDW}	500	50	cm2	1	steady-state	15.000	100.0	0.0	
11	T _{ENV}	20	50	K	41	2.44	2.970	19.8	80.2	Temperature of the environment has only a minor impact
12	T _{ENV}	100	50	K	38	2.63	2.752	18.3	81.7	
13	T _{ENV}	150	50	K	35	2.86	2.447	16.3	83.7	
14	Material	5083 Al	Ti64	Cp, k varied	33	3.03	8.357	55.7	44.3	Use low k materials if possible (Ti, SS greatly preferable to Al)
15	Material	304 SS	Ti64	Cp, k varied	49	2.04	3.652	24.3	75.7	
16	h _{SFCNT}	1	10	W/m2-K	37	2.70	2.677	17.8	82.2	Contact with the surface of Enceladus has only a minor effect
17	h _{SFCNT}	100	10	W/m2-K	40	2.50	2.897	19.3	80.7	
18	h _{SFCNT}	1000	10	W/m2-K	41	2.44	2.930	19.5	80.5	
19	Q	5	15	W	20	5.00	3.047	60.9	39.1	Leaving power ON at 0.2 W during cooldown lengthens cooldown time and reduces number of cycles slightly
20	Q	25	15	W	43	2.33	2.867	11.5	88.5	
21	Q	S1: 13.8, 0.2	15	W	37	2.70	2.879	20.9	79.1	
22	Q	S2: 19.7, 0.2	15	W	39	2.56	2.858	14.5	85.5	
23	Q	S3: 25.5, 0.2	15	W	40	2.50	2.894	11.3	88.7	
24	Q	S4: 8.7, 0.2	15	W	31	3.23	2.887	33.2	66.8	
25	T _{ON}	223	253	K	22	4.55	2.310	15.4	84.6	Reducing turn-ON temperature lengthens cycle time (fewer cycles) and also reduces average heat leak
26	T _{ON}	233	253	K	27	3.70	2.540	16.9	83.1	
27	T _{ON}	243	253	K	32	3.13	2.710	18.1	81.9	
28	T _{ON}	263	253	K	49	2.04	3.068	20.5	79.5	
29	T _{OFF}	323	313	K	35	2.86	3.050	20.3	79.7	Increasing turn-OFF temperature lengthens cycle time (fewer cycles) and also increases average heat leak
30	T _{OFF}	333	313	K	32	3.13	3.195	21.3	78.7	
31	T _{OFF}	343	313	K	30	3.33	3.355	22.4	77.6	
32	T _{OFF}	353	313	K	27	3.70	3.525	23.5	76.5	

Figure 47. Results of the nodal model analysis parameter sweeps.

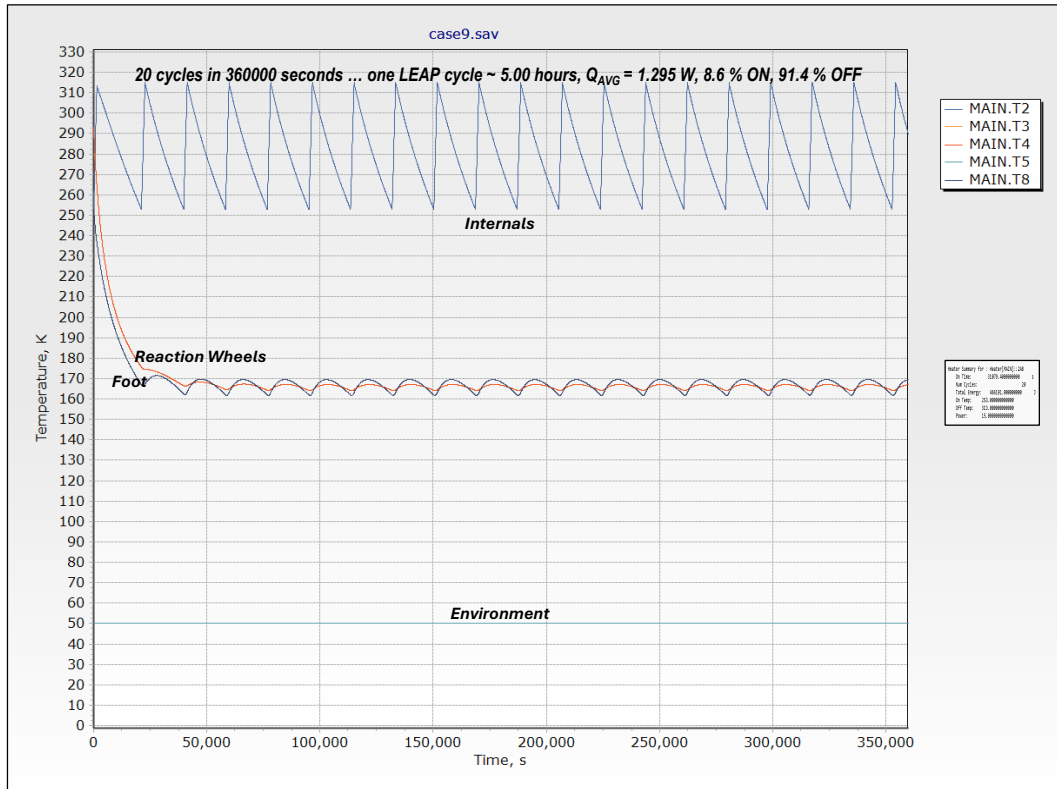


Figure 48. Results of the nodal model analysis parameter sweeps – **Run 9** ($A_{WDW} = 5 \text{ cm}^2$).

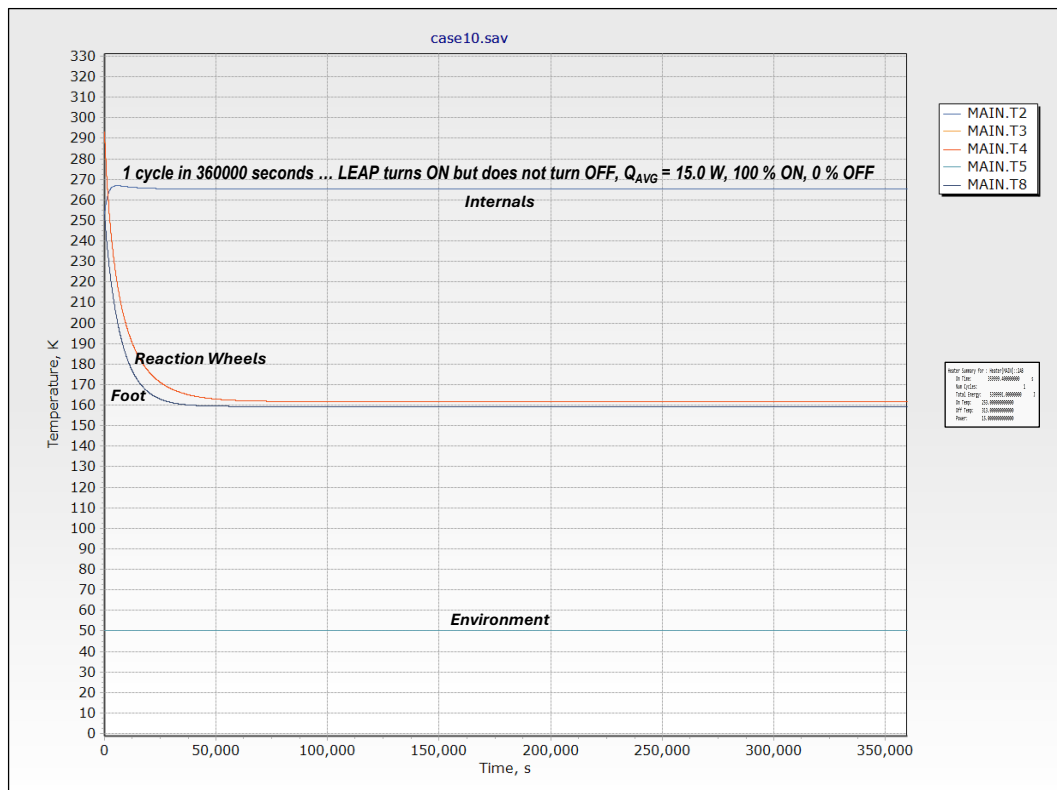


Figure 49. Results of the nodal model analysis parameter sweeps – **Run 10** ($A_{WDW} = 500 \text{ cm}^2$).

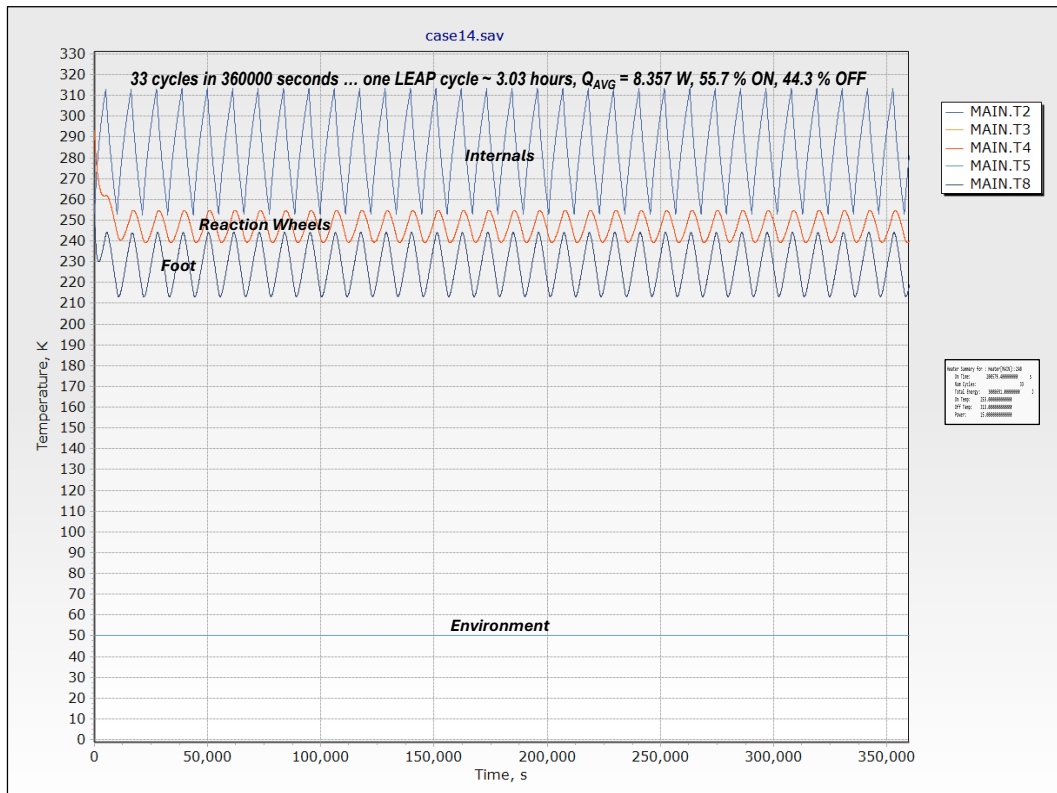


Figure 50. Results of the nodal model analysis parameter sweeps – **Run 14** (Material = 5083 Al).

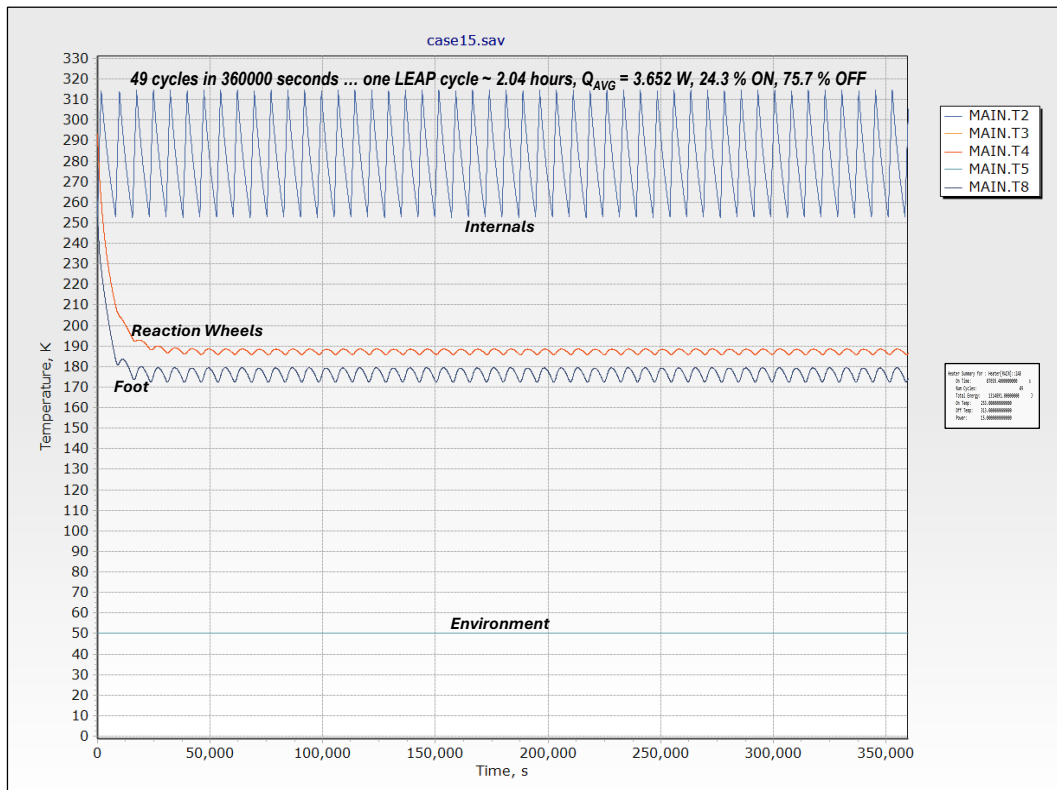


Figure 51. Results of the nodal model analysis parameter sweeps – **Run 15** (Material = 304 SS).

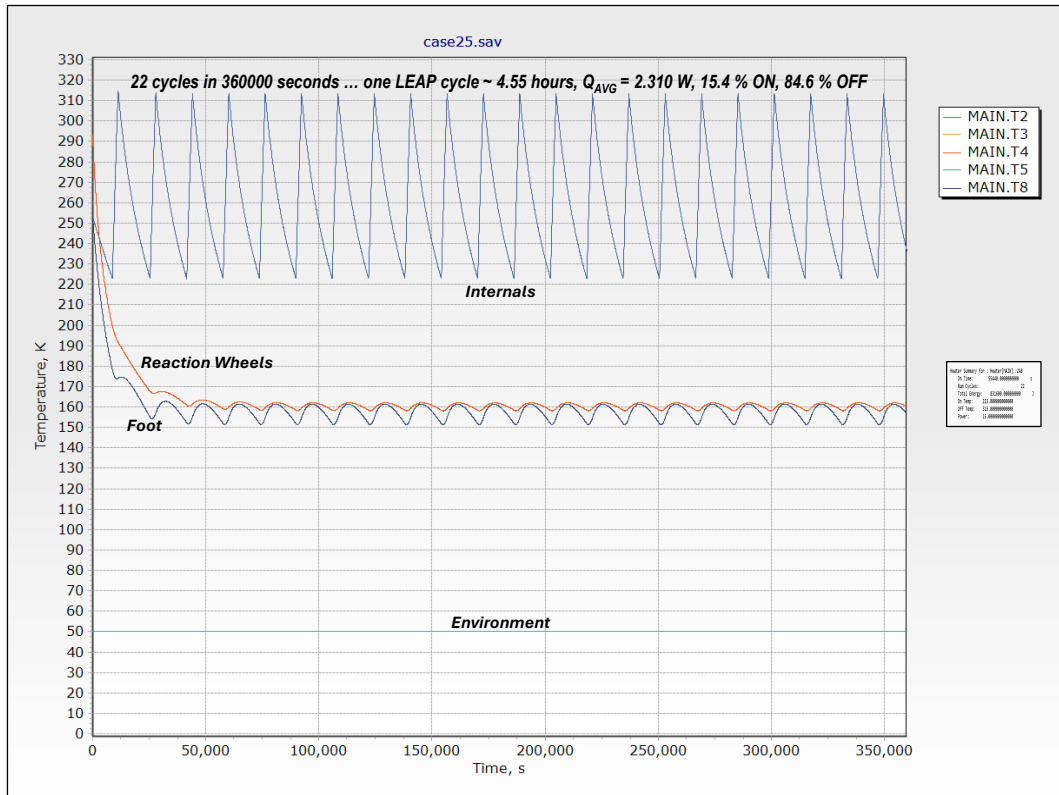


Figure 52. Results of the nodal model analysis parameter sweeps – **Run 25** ($T_{ON} = 223$ K).

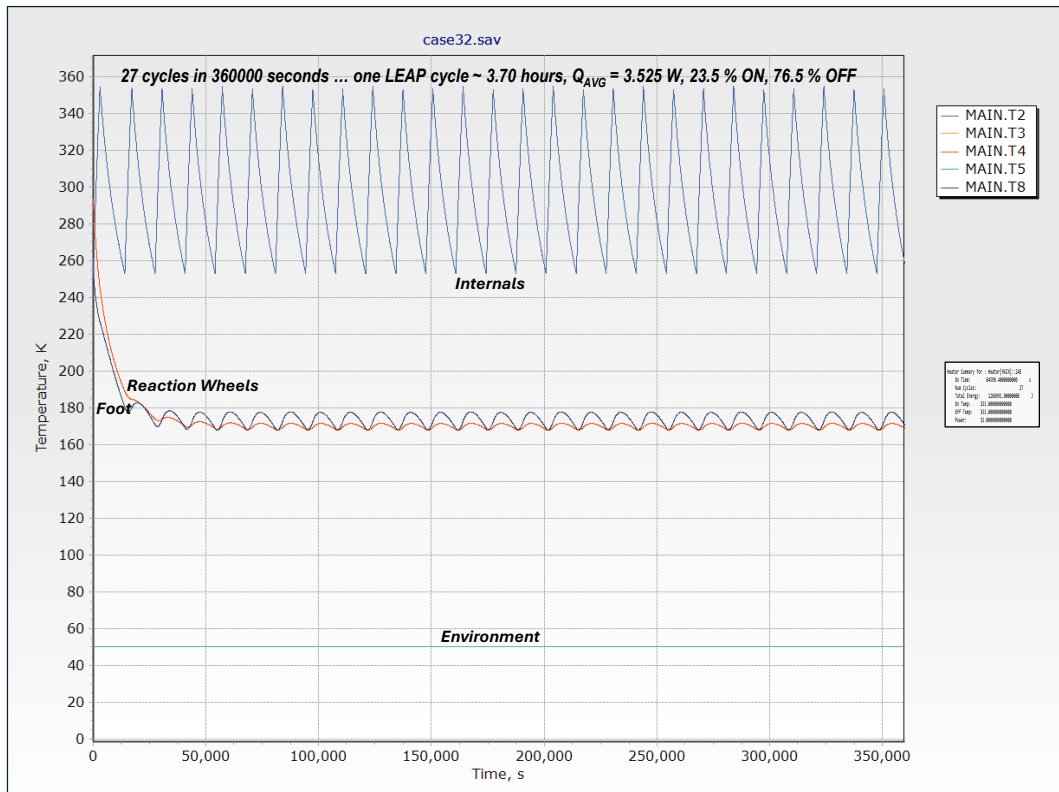


Figure 53. Results of the nodal model analysis parameter sweeps – **Run 32** ($T_{OFF} = 353$ K).

5 CONCEPT OF OPERATIONS

The LEAP mission is a fast-paced, moderate-range exploration mission that is enabled by miniature scientific instruments and a highly-capable mobility system, paired with significant onboard autonomy (including anomaly detection, recovery, and long-term mitigation). LEAP further requires multi-faceted interfaces and interactions with Orbilander across the integration, cruise, landing, commissioning, and operational phases of the Enceladus mission.

Herein, we will cover four main aspects of the LEAP mission Concept of Operations (ConOps):

- Section 5.1: details on the science-derived mission requirements for operations
- Section 5.2: step-by-step concept of operations for the LEAP mission
- Section 5.3: power implications for operations (recharge vs. single-shot, duration of operation, range of exploration, and science return strategy)
- Section 5.4: thermal implications for operations (heat-before-use, overheat vs. cooldown, and long-term survival)

It is important to note that a mission like Orbilander + LEAP requires a significantly different approach to operational cadence and commanding than is used on the Perseverance / Curiosity rovers and the Ingenuity helicopter on Mars – even as we are inspired by and heavily leverage the robotic autonomy capabilities demonstrated on these missions.

Data bandwidth between Orbilander (on Enceladus in Saturn orbit) and Earth is extremely limited and one-way communication times are approx. 1.5 hours (versus 8-30 minutes for Earth-Mars communication). As a result, we must rely almost entirely on onboard autonomy for spacecraft operations, science activities, robotic exploration, and anomaly recovery.

We will leverage existing cutting-edge NASA / JPL capabilities developed for three generations of Mars rovers (Spirit, Opportunity, Curiosity and Perseverance), including Autonomous Navigation (AutoNav) / Enhanced AutoNav (ENav) [44, 51, 63, 62, 61] for autonomous wheeled mobility planning / execution and Onboard Global Localization [64] for robot self-localization on orbital-derived maps using rover-derived context images of the local terrain. Additional groundbreaking work on multi-agent autonomy for space robotics has been pioneered for the lunar CADRE rovers for collaborative exploration / mapping of a region of interest and collecting coordinated scientific measurements across multiple robots [16].

We will simultaneously need to pioneer new capabilities, like autonomous jump planning / execution (which differs greatly from conventional path planners for wheeled robots) and end-to-end onboard anomaly detection / root-cause diagnosis / recovery, which have been prototyped on Earth but have little to no flight heritage. It is reasonable to expect that only a high-level mission plan and set of geo-referenced science targets is supplied by human operators for the LEAP mission, and all onboard activities / operations are planned, executed, and overseen by an onboard agentic AI. Opportunistic science on novel, in-situ targets discovered by LEAP robots during the course of their primary exploration / investigation mission is also encouraged.

5.1 Science-Derived Mission Requirements

The LEAP mission is designed around achieving the following high-level capabilities and requirements, which are derived from the scientific investigations identified in Section 1:

1. Land within 1-2 km of a Tiger Stripe, between two active jets (each within 3 km of the landing site).
2. Deploy 4 count of LEAP robots, with 2 robots sent to each of the two active collimated jet targets (i.e. robots dispatched in pairs to target jets).
3. Perform ≥ 5 jumps at different points in Enceladus' orbit period (i.e. over 32.9 hours) in diffuse plume emission.
4. Perform ≥ 3 jumps through the diffuse plume emission at 3 m/s horizontal velocity and TBD m altitude, at a distance of ≥ 250 m apart along the Tiger Stripe.
5. Perform ≥ 2 jumps through two different collimated jet emissions at 3 m/s horizontal velocity and TBD m altitude.
6. Perform targeted science activities before, during, and after jumping through the diffuse plume / collimated jet emissions.

Furthermore, the targeted science activities during each jump through the plume will include the following operations (depending on final science payloads):

- **Flux Sensor:** Operate while in plume during jumps.
- **Nephelometer:** Operate while in plume during jumps.
- **Pressure Sensor:** Operate while in plume during jumps and at crevasse edge prior to jumps.
- **Temperature Sensor:** Operate while in plume during jumps and at crevasse edge prior to jumps.
- **Mass Spectrometer:** Capture particles while in plume during jumps; process samples during aerial phase or post-landing.

5.2 LEAP Concept of Operation

Based on these science-derived capabilities / operations, as well as considerations from the power and thermal modeling efforts, the following detailed ConOps was developed.

At a high level, we assume that LEAP is operating as a payload on the Orbilander spacecraft, and therefore Orbilander takes precedence for all science, engineering, and maintenance activities. Once Orbilander is in a stable operational state on the Enceladus surface, deployment and operation of LEAP robots can commence. Orbilander provides all data relay services between Earth and LEAP, as well as recharge capability for the individual LEAP robots. High level autonomous decision making may be delegated to Orbilander, which can then provide instructions / updated goals to individual LEAP robots.

5.2.1 Cruise, Orbit, & Pre-Landing Phases

1. Orbilander provides survival heat and battery maintenance power to LEAP robots during all pre-deployment phases (cruise, orbit, landing) – this sets minimum thermal / power interface requirements between Orbilander and LEAP robots (i.e. coolant loop or heaters + thermisters, battery management + power wires)
2. Orbilander enters stable orbit around Enceladus
3. Orbilander maps Enceladus South Pole for active plumes / jets and suitable landing sites
4. Orbilander returns science data to Earth (potentially performing first-pass analysis and feature extraction from raw data onboard the spacecraft)
5. Science team identifies final Orbilander landing site, as well as key plume targets for LEAP and potential routes to / from the landing site
6. LEAP Operations team plans / uplinks plume targets and high-level routes to Orbilander
7. Orbilander Operations team plans / uplinks the deorbit and landing commanding to Orbilander

5.2.2 Orbilander Landing Phase

1. Orbilander executes deorbit burn, and approaches surface
2. Orbilander maps landing site in detail using optical cameras and / or lidar during pre-landing hover and approach
3. Orbilander executes successful soft landing on Enceladus surface

5.2.3 Orbilander Commissioning Phase

1. Orbilander transitions to surface Flight Software (FSW), commissions science and engineering systems (including cover deployments, instruments / mechanism checkouts, etc.) and relays data to Earth
2. Orbilander performs additional context imaging / mapping of landing site and surrounding environment and relays data to Earth
3. Orbilander localizes spacecraft on orbital map, and localize pre- / post-landing higher-resolution terrain maps to orbital map
4. Operations team identifies suitable initial deployment locations for all 4 LEAP robots (i.e. safe surface locations for individual LEAP robots to jump to from Orbilander) – ideally 3-5 meters from the lander³

5.2.4 LEAP Onboard Commissioning Phase

1. Operations team reviews / confirms primary spacecraft health based on commissioning data, then uploads LEAP plume targets and potential routes from / to Orbilander
2. Orbilander performs final LEAP onboard charging
3. Orbilander performs final LEAP onboard heat-to-use
4. Orbilander actuates protective cover(s) over LEAP robots⁴

³After initial LEAP deployment, a jumping Keep Out Zone (KOZ) of 3-5 meters will be enforced around the Orbilander, either (a) permanently, or (b) until LEAP robots are able to self-calibrate jump accuracy to a specified threshold on the surface of Enceladus surrounding the Orbilander. LEAP robots will be required to approach Orbilander within this KOZ using wheeled mobility only, to ensure primary spacecraft safety.

⁴This creates a potential design optimization, whereby the protective covers contain inductive charging surfaces that can be used for LEAP battery charging during both flight and surface operations. The covers would need to actuate open by pivoting outward from the top of Orbilander (closed / stowed state during cruise) to rest on the sides of Orbilander (deployed state ahead of LEAP surface operations).

5. Orbilander sequentially wakes up all four LEAP robots, establishes communications link with individual robots, and oversees initial systems checks:
 - (a) LEAP robots deploy camera / instrument covers
 - (b) LEAP robots perform instrument calibration tests
 - (c) LEAP robots perform actuator tests (limited range of motion within launch restraints)
 - (d) LEAP robots relay system health checks / telemetry to Orbilander
 - (e) Orbilander performs first GO / NO-GO assessment for each LEAP robot, and adjusts high-level LEAP exploration / mission plans if any robots show degraded performance
6. Orbilander uploads high-level exploration / mission plans to all LEAP robots
7. Orbilander commands / oversees the sequential deployment of each LEAP robot to the Enceladus surface (includes launch-lock, heater, power, and data cable separations, followed by initial powered jump from the Orbilander top deck to the Enceladus surface at the per-robot targeted landing location)⁵

5.2.5 LEAP Surface Commissioning Phase (time-sensitive)

1. Full system commissioning of each LEAP robot
2. Calibration of jumping performance / accuracy on surface
3. Validation of mapping capability / accuracy / onboard IMU + camera recalibration activities
4. Relay results to Orbilander
5. Orbilander performs second GO / NO-GO assessment for each LEAP robot, and adjusts high-level LEAP exploration / mission plans if any robots show degraded performance
6. Orbilander uploads revised high-level exploration / mission plans to all LEAP robots, then initiates active exploration / surface operations

5.2.6 LEAP Surface Operations Phase (time-sensitive)

The high-level goal of surface operations is to navigate to science target locations of interest on the global map, collect scientific data, and relay high-priority data back to Orbilander. Opportunistic discovery of novel high-value science targets by the LEAP robots using their onboard cameras / instruments (i.e. targets not identified in advance from Orbilander orbital / landing imagery) should also be supported. The baseline exploration strategy is defined as follows:

1. LEAP robots operate in pairs (2), navigating towards a common set of scientific coordinates / points of interest. Robots share mapping / localization data and coordinate jumps / path planning.
2. For exploration of new, unmapped areas, robots employ a “**LEAPfrog**” exploration strategy. The “LEAPfrog” strategy is designed to maximize exploration rate while ensuring all jumps land on imaged terrain that meets resolution threshold criteria (e.g. 1 cm/pixel, to ensure hazard avoidance):
 - (a) Robot 1 jumps vertically, collects images for a new map wedge / panorama, and lands in place. The new map wedge is localized on the existing map and shared with Robot 2. The updated map has a radius (R_{valid}) around Robot 1 that meets the map resolution threshold criteria (typically camera- or terrain-limited).
 - (b) Robot 2 plans and performs a parabolic lateral jump to a safe location on the updated map, followed by a second vertical jump for mapping. The new map wedge is localized and shared with Robot 1.
 - (c) Robot 1 leapfrogs Robot 2 to a new, safe location on the updated map using a parabolic lateral jump, and the process repeats until the robots arrive at a region of interest along the Tiger Stripe.
 - (d) **Advantages:**

⁵From this point forward, all LEAP activities are time-sensitive and consume onboard battery power.

- i. Allows longer jumps for each robot on higher resolution maps – instead of jumping to the resolution-limited mesh of onboard cameras (R_{valid}), each robot can jump $2R_{valid}$ with the leapfrog approach (leveraging the 2nd robot's map). This is especially valuable when the imaging- / lighting- / resolution-limited R_{valid} is much smaller than the max jump distance of the LEAP robots (estimated at up to 170m). Note that in areas with hazards or obstructed field of view (e.g. hills / cliffs), jump distance may be reduced.
- ii. Robots can always plan jumps / landing targets on sufficient-quality maps, and do not need to perform mapping updates while in mid-air on parabolic jumps.
- iii. In scenarios where one robot is incapacitated (e.g. taking damage after a jump onto an unexpected hazard on the other side of a fissure / plume), the second robot is able to retreat along the prior mapped path back to Orbilander, ensuring recovery of valuable scientific data.
- iv. Pairs of robots can perform certain joint science measurements that a single robot is incapable of [16], such as particle image velocimetry of the plume (using a laser-line illuminator on one robot jumping through the plume, and imaging the plume from a stationary second robot with a telescopic camera).

(e) **Disadvantages:**

- i. Each robot expends approximately 50% of its jumps (and thus processing time and energy) on vertical jumps, reducing total exploration range.
 - ii. Paired robots are able to explore less terrain together, than if they explore individually.
3. For locomotion across previously mapped regions, robots are able to employ continuous lateral jumps, with mid-flight imaging of the terrain for localization to onboard maps. Multi-jump planning can be performed, with updated planning after each localization. This strategy saves considerable energy, by avoiding the vertical mapping jumps, and allows both robots to move at a relatively constant and continuous pace. Robots would maintain small keep-out zones around their current positions and planned trajectories to avoid collisions.
 4. **Science Operations at a Tiger Stripe:** LEAP robots will perform measurements at two distinct regions of the plume along a given Tiger Stripe: **collimated jets** (expected to be spaced approx. every 5km) and the **diffuse emissions** (expected to be everywhere along the Tiger Stripe fissure / crevasse). Depending on the Orbilander landing site, the collimated jets could be 3-5 km away (within range of both LEAP battery architectures, Section 4.2.3). Tiger Stripes are spaced 30 km apart so it is unlikely that LEAP will be able to explore multiple Tiger Stripes.
 - (a) The STM requires LEAP robots to directly measure **2 collimated jets** and **3 locations of diffuse emission** along a Tiger Stripe, and to perform a minimum of 1 measurement per site (with more jumps providing improved science return). Spacing of sampling sites for diffuse emissions will be at least 250 m apart (preferably 500 m).
 - (b) Direct measurements / sampling is performed by jumping through the plume with instruments active and oriented towards the plume ejecta. The mass spectrometer will assess the volatile composition (H_2O , CO_2 , CH_4 , NH_3 and H_2), while other sensors will measure particle flux, pressure, and temperature of the jet / emission as we jump through.
 - (c) Initial jumps through the plume will target diffuse areas of emission where the LEAP robots stand the highest chance of imaging the far side of the fissure / crevasse before the jump, to minimize chance of a crash landing. The plume is a fine mist (at its densest) and robots should be able to take visible imagery through the plume without obscuring the view / mapping ability. Successful jumps through the diffuse plume will then provide confidence for subsequent jumps through collimated jets.
 5. Robots periodically downlink their status / high-priority data (e.g. coordinates for targets of interest, summarized science data) to Orbilander if the terrain provides line-of-sight communication opportunities (as performed between Ingenuity helicopter and Perseverance rover over >1000m).
 6. Robots coordinate hibernation periods when operating temperatures approach the max AFT on either robot.
 7. Robots commence return to lander after dropping to 67% state of charge. Robots retrace their path along previously-mapped terrain to minimize return risk (and reduce energy devoted to mapping), and maintain final state of charge above a 30% deep-dip threshold.
 8. Robots respect a “no-fly” zone around Orbilander and perform final approach to Orbilander using wheeled locomotion only, and park at recharge devices.

9. Robots recharge, downlink all data, and uplink new instructions / maps generated by other robots. The majority of data is communicated over a short-range wireless radio (e.g. Zigbee radio) during recharges, when the robots are sitting directly next to Orbilander.

There are several potential strategies for the deployment of the 4 LEAP robots during the Surface Operations Phase, even as they all follow the above baseline exploration strategy. Three are outlined here in order of science reward vs. mission risk:

1. Unconstrained Operations to Maximize Exploration + Science

- (a) Orbilander carries sufficient recharging stations for all 4 LEAP robots and sufficient surface comms. bandwidth / power to handle simultaneous uplink / downlink from all 4 LEAP robots to the Orbilander at any given time
- (b) **Advantages:**
 - i. Unconstrained operations and recharge cadence (no risk of occupied charging stations)
 - ii. Opportunity to pivot from 2 robot exploration to 3+ robot team exploration
 - iii. Back-up robots on hand if a single active robot is lost
- (c) **Disadvantages:**
 - i. Increased mass / power / bandwidth / processing budget requirements imposed on Orbilander

2. Hardware-Constrained Operations

- (a) Orbilander carries only 2 recharging stations that must be shared among the 4 LEAP robots, and / or has potentially limited comms. bandwidth / power to connect with only 1 LEAP robot at a time
- (b) ConOps pivots to having 2 active robots exploring Enceladus and 2 passive robots recharging / downlinking data at any given time; active / passive robot pairs swap when active robots return to the lander with valuable data or low state of charge
- (c) Note: this requires that 2 robots remain charging / survival-heating adjacent the lander after LEAP Surface Commissioning Phase
- (d) **Advantages:**
 - i. Reduced payload mass (fewer chargers on spacecraft)
 - ii. Increased longevity of mission through reduced hardware usage
 - iii. Efficient re-tasking of robots (each "expedition" can reuse maps from previous expeditions to avoid hazards, avoid science-poor locations, or return to science-rich locations to continue performing science investigations / interrogating targets of interest)
 - iv. back-up robots on hand if a single active robot is lost
- (e) **Disadvantages:**
 - i. Reduced exploration cadence

3. Risk-Averse Operations

- (a) Maintain all limitations, advantages, and disadvantages of the Hardware-Constrained Operations, with the additional restriction that LEAP robots only navigate to / from pre-identified science targets and have increased safety margins on hazard detection / avoidance until the end of the primary mission (i.e. once all primary science investigations are complete and data is successfully downlinked to Orbilander)
- (b) Increased requirements for terrain map resolution (limiting jump) and increased margins on hazards (slope limits, KOZ around , etc)would be imposed
- (c) **Advantages:**
 - i. Minimizes risk of robot damage / loss during exploration
- (d) **Disadvantages:**
 - i. Reduced exploration area, including access to potential science targets
 - ii. Reduced exploration cadence

5.3 Power Implications for Operations

Section 4.2 provides strong evidence that a LEAP mission architecture that supports individual robot recharge capability is the preferred choice. The rechargeable (secondary) battery architecture would parallel the Ingenuity helicopter avionics / power system, but replace a solar panel with inductive charging coils.

The operational duration for a single-shot mission is 37.8 hours. With no time allocated for a return to the Orbilander mothercraft, this operating mode would provide increased exploration range – allowing individual LEAP robots to travel an estimated 5.0-16.0 km from the Orbilander on a single charge compared with 2.3-7.4 km to support recharge. Furthermore, a single-shot mission would minimize interactions and interfaces with Orbilander – once deployed, the LEAP robots only require that Orbilander operate a communications link, avoiding recharging interfaces and the hazards associated of LEAP robots operating in close proximity to the primary spacecraft. There are two main limitations on this strategy, however.

The single-shot mission concept is contingent on the LEAP communication antenna having sufficient range and line-of-sight to permit reasonable data downlink from the LEAP robots to Orbilander. Ingenuity helicopter demonstrated downlink to the Perseverance rover at distances over approx. 1 km, albeit with significant dependence on terrain obstructions. Since Orbilander is a stationary spacecraft, any range or terrain limitations must be overcome by the LEAP robots, which reduces effective exploration / science mission life. Alternately, pivoting to a Direct To Orbit (DTO) antenna to enable LEAP to communicate directly with an orbiting spacecraft (avoiding line-of-sight terrain obstructions) would incur significantly higher antenna mass / power demands on LEAP and require an orbiting spacecraft that not included in the baseline Orbilander mission.

Employing a recharge architecture for LEAP simplifies or avoids many of these problems. LEAP data downlink can be performed exclusively during recharge periods where LEAP is directly adjacent to Orbilander, providing higher downlink rates with a low mass / power antenna, and with no need to factor in terrain obstructions between Orbilander and science targets. LEAP exploration endurance of 2.3-7.4 km would still provide sufficient range to reach multiple science targets. By incrementally building up improved terrain maps over multiple sorties (identifying safe, hazard-free routes), rechargeable LEAP robots may also be able to extend their effective exploration range up to 3.5-11.1 km from the Orbilander. Increasing battery energy (by more batteries, or batteries with higher energy density), decreasing avionics / instrument power consumption, and increasing jump frequency (above the 75% in Scenario 3) would further extend this range estimate.

The LEAP recharge architecture is a natural complement to a sample return capability whereby LEAP delivers high-quality plume ejecta samples directly to Orbilander. While sample return is not baselined into the LEAP ConOps at this time, it could be supported in the future if there is a notable enhancement to science return.

Section 4.3 provides guidelines on total mission duration, based on power usage and hibernation periods under multiple operating modes.

5.4 Thermal Implications for Operations

Thermal implications for operations are fairly straightforward, given the significant work presented in Section 4.3.3. The LEAP robots require survival heating while encapsulated on Orbilander, from launch until deployment. Immediately prior to deployment, the robots require heat-to-use from Orbilander, to reach their AFT. During nominal operation, the robots will regulate onboard temperature through avionics / motor self-heating and modulation of their operational cadence – thermostating between operational and cooldown periods.

To conserve mass and energy, no onboard RHUs or electric heaters are baselined, and insufficient solar insolation at Saturn precludes solar-powered recharging. As a result, long-term survival of the LEAP robots is not guaranteed. If a robot experiences a critical hardware or software anomaly, the onboard autonomy must be sufficient to recover from the anomaly and return to the Orbilander for recharging prior to battery exhaustion. There will be no time to plan and uplink a manual recovery from Earth.

5.5 Future Work

We have developed a fairly comprehensive high-level ConOps for the LEAP Mission, but expect that key details will continue to evolve as the concept matures.

The biggest areas of uncertainty surround the capability and energy efficiency of onboard compute / autonomy, which has showed tremendous improvements in recent years and will continue to advance prior to the LEAP mission. The automotive industry (electric and self-driving cars) is driving significant advances in solid-state batteries and solid-state LIDAR. Mature solid-state batteries will yield significant improvements in energy density (i.e. more robot endurance) and temperature tolerance over conventional lithium polymer batteries with liquid electrolytes. Similarly, reliable, energy efficient solid-state LIDAR will provide a new, valuable mapping technology that can operate independent of local illumination.

To further refine the above ConOps, we also need to develop estimates of mapping capability – map resolution vs. range, as a function of camera or LIDAR resolution / optics, scene illumination, terrain or hazard feature size, and terrain complexity – and what constitutes a terrain hazard to the robot (e.g. size of rocks or holes that can damage the robot). Since we should only jump onto visibly-safe terrain mesh (i.e. that meets the resolution threshold criteria and shows no positive or negative feature hazards), this mapping capability will define / inform the maximum jump distance requirement, and therefore the hardware

capability of the LEAP robot leg / motor assembly. It will also inform our risk posture for performing alternating vertical / lateral jumps vs. continuous lateral jumps.

The current exploration strategy assumes we only jump where we can see and plan a safe jump. If we need to jump into unexplored terrain, additional questions about jump accuracy and hazard avoidance / mitigation behaviors of the robot need to be addressed: how far can we jump and be confident we won't break ourselves, can we react if we're about to land on a hazard to absorb impact force, and do we have confidence that our foot + leg or wheels can handle the shock loads?

Finally, this high-level ConOps highlights numerous interfaces with Orbilander (vibration, power, mass, location, thermal-regulation, cable-cutters, recharging ports, communication) that we have not attempted to address, and would be the subject of significant negotiations between the Orbilander and LEAP teams.

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