LEAP: Legged Exploration Across the Plume

novel mobile robots Lab

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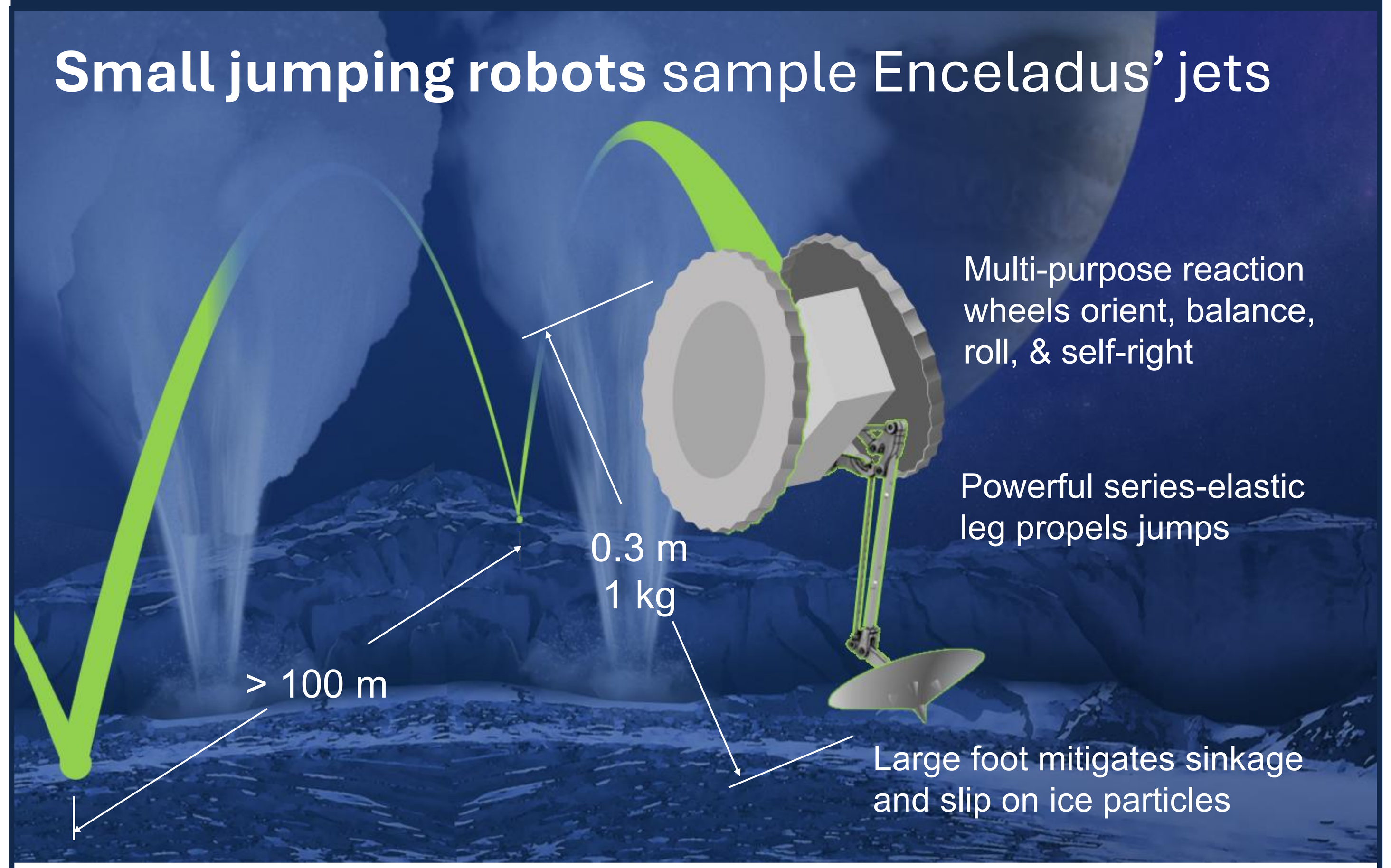
NIAC NASA Innovative Advanced Concepts

Mission concept

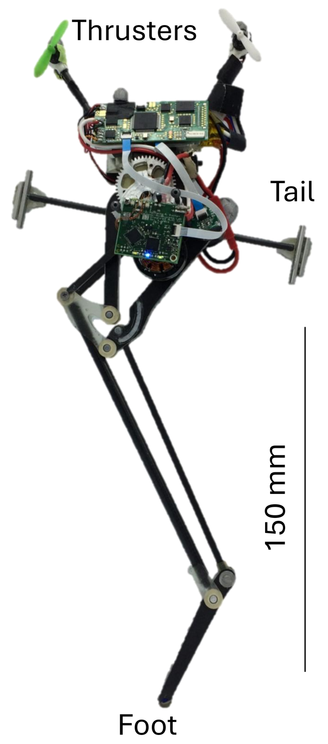
Small jumping robots sample Enceladus' jets



Enceladus' cold surface covered in ice particles and ridges is tough to traverse. Flight is impossible with no atmosphere and rockets could pollute samples, but small **jumpers** could travel far in gravity 80 times weaker than Earth's to reach the jets that release ocean material to Enceladus' plume. Multi-use reaction wheels could control orientation and serve as wheels to roll and self-right these jumping robots.

Inspiration: prior work

The **Salto-1P** robot's agile hops on Earth suggest amazing performance in Enceladus' low gravity



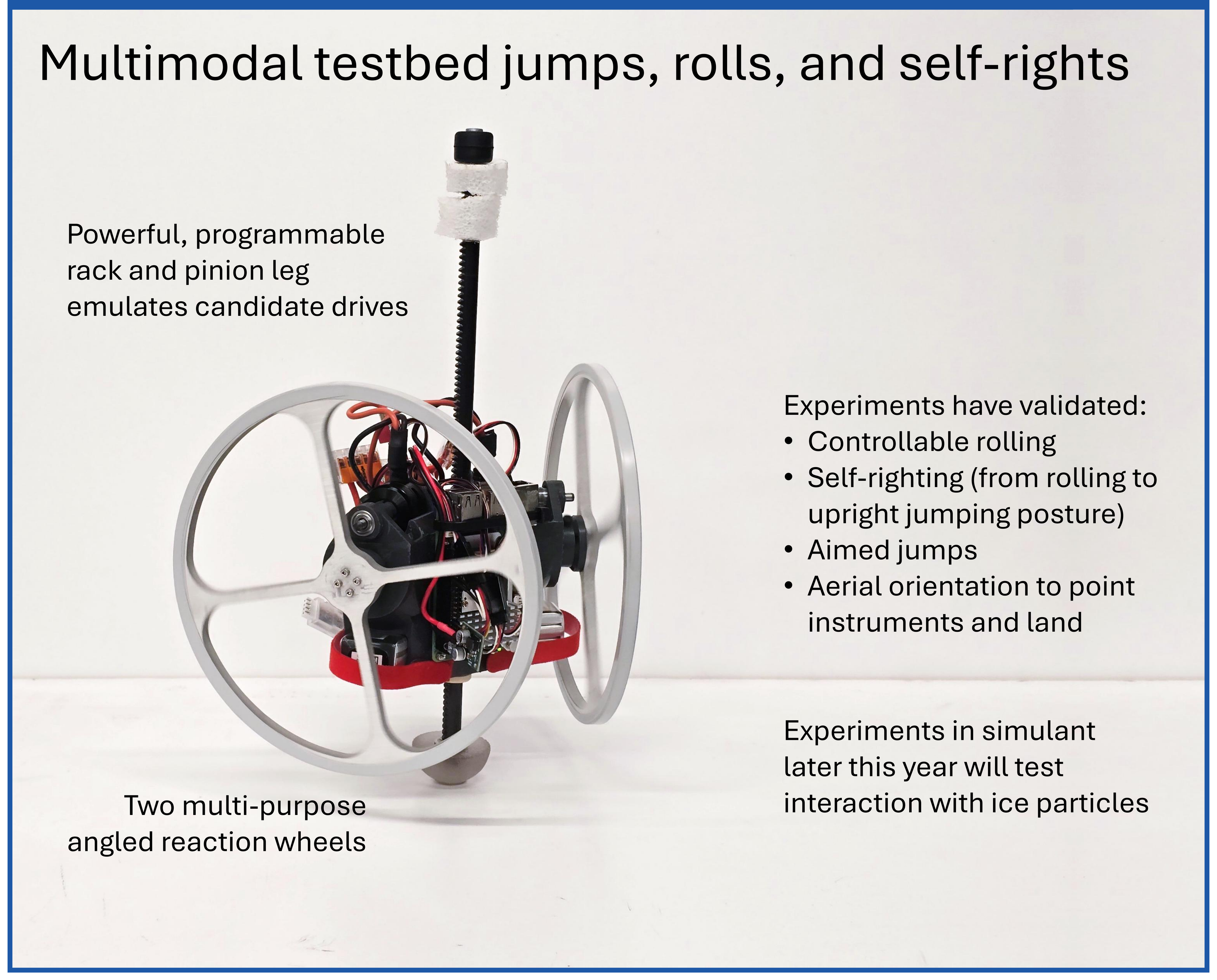
	Capability on Earth	Potential on Enceladus
Jump height	1.15 m	> 80 m
Long jump	2 m	> 100 m
Hop accuracy	9 cm radius	?
Leap accuracy	<2 cm radius	?
Battery life	~ 1 km (800+ hops, 600+s)	10 – 80 km

Watch the video!

www.youtube.com/watch?v=qFmeHPVtK0o

NIAC Phase I Progress

Multimodal testbed jumps, rolls, and self-rights



Science and Operation

Scientific impact: direct jet sampling

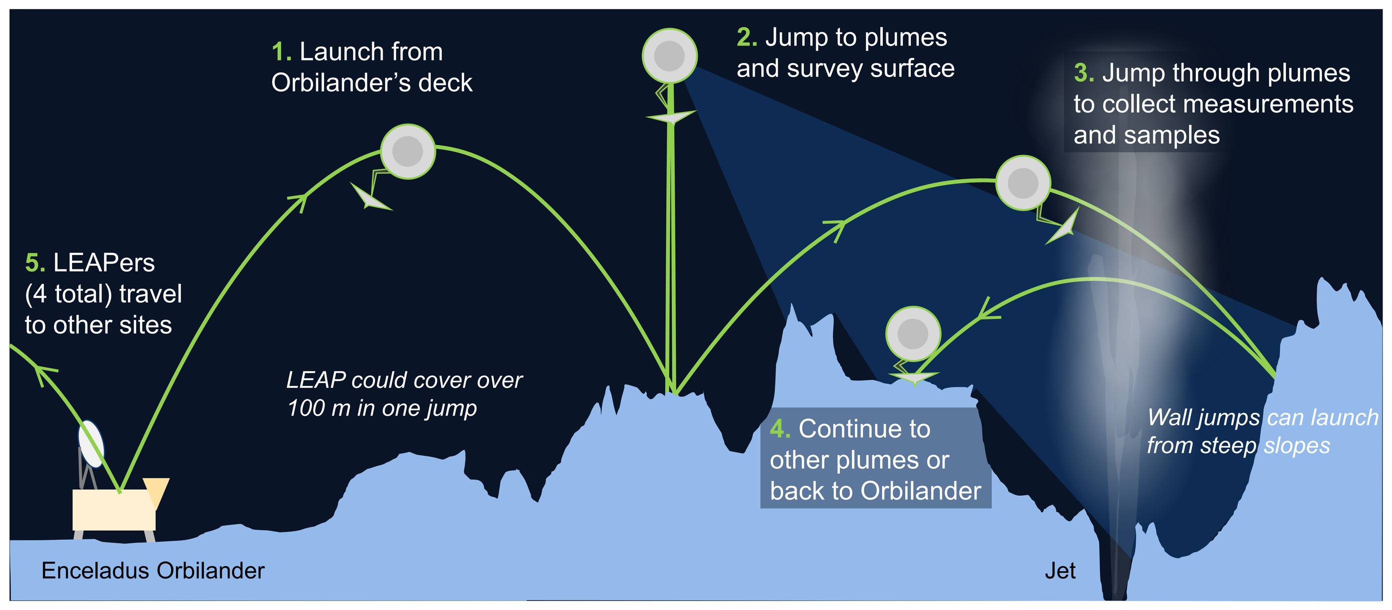
Enceladus is a leading candidate for life with a subsurface ocean, organic chemistry, and energy. Furthermore, the plume emanating from the south pole provides direct access to ocean-derived material. LEAP can augment a mission like the proposed Enceladus Orbilander to provide direct jet sampling capability for answering key questions:

OWLS Decadal Survey Goal (Q10.1)	EMF Science Objective (OWLS)		LEAP Science Objectives	Measurement Objectives	Measurement Requirements	Flux sensor	Optical Aerosol Counter	Mass Spectrometer	Pressure sensor	Temperature sensor
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's 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, particle size distribution, 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.					
				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.					
					1b2. Plume particle flux, particle size distribution 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, particle size distribution, 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.					
					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.					
					2a3. Temperature at or near the walls of the crevasse in close proximity to diffuse and jet emissions.					

Example candidate research-grade sensors:

- J. Renard "LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles" Atmospheric Measurement Techniques, 2016
- P. Szyszka "MEMS quadrupole mass spectrometer", Sensors and Actuators B: Chemical, 2024

Concept of operations



Future work:

Future development will advance more flight-like designs including scaled-up leg linkages and more detailed avionics. Actuator power profiles and avionics specifications will inform refined thermal models. Increased autonomy will include vision and navigation sensors (considering cameras, LIDAR, event cameras). We will explore flight infusion opportunities for other low-gravity environments.

Subcomponent analysis

In discussion with experts, we consider materials, avionics systems, and leg propulsion designs suited to the mission and environment.

Materials: Flight-qualified materials for cryogenic conditions can be used for LEAP's structures, leg spring, bearings, and avionics insulation

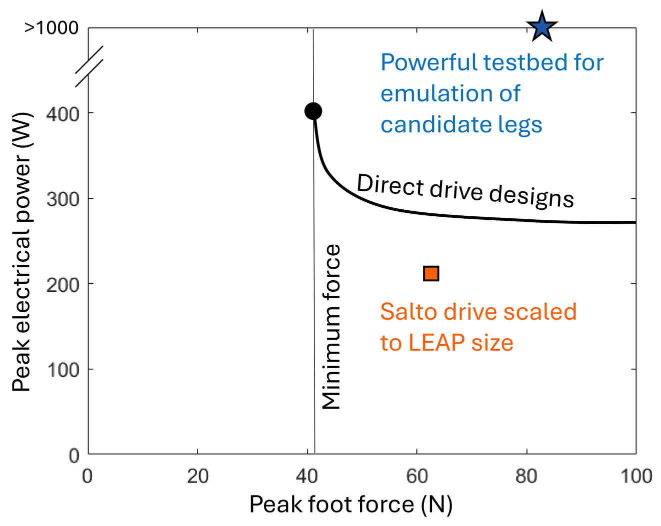
Component	Performance criteria	Potential materials
Structure (leg, foot, wheels)	Strength, ductility at cryogenic temperature	Al (Al 5083), Ti (Ti-6Al-4V ELI), Austenitic steels (e.g. 302, 304, 316)
Spring	Specific elastic energy and density, efficiency,	Steel (17-7 PH), Beryllium Copper, Elgiloy
Bearings	Strength, toughness, friction	Graphite-metal alloys
Avionics insulation	Insulation, weight, volume	G-10, MLI blankets, aerogel

Avionics: LEAP is at the same size, mass, and power scale as the Ingenuity Helicopter, enabling leverage of JPL flight-heritage avionics while also considering new components benefitting from continued technology maturation.

Component	Ingenuity	LEAP candidates
Processors	Snapdragon + MCU, FPGA	Snapdragon or VOXL2 + MCU, FPGA
Battery	Li-Ion, 40 Wh; 510 W peak, 350 W average; 273 grams	Li-Ion or Li/CFx, 40 Wh; 250 W peak, 300 grams
Localization	IMU, inclinometer, altimeter, camera	IMU, inclinometer, altimeter, camera
Vision	NAV and RTE cameras	Cameras, event cameras, LIDAR
Telecom	Zig-Bee, 1km +	Zig-Bee, 1km +

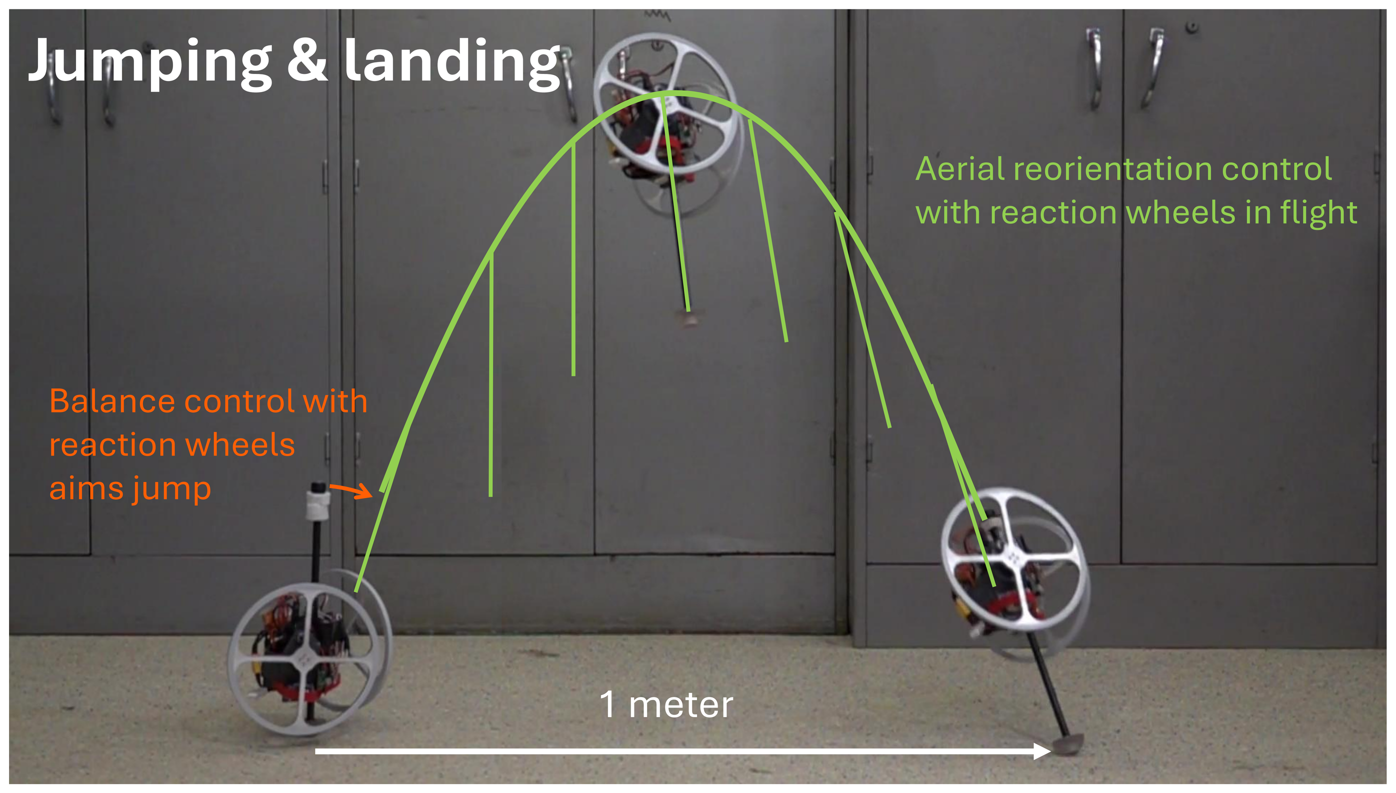
Propulsion: Compared to direct-drive leg propulsion, Salto's series-elastic leg mechanism reduces required motor power to propel large jumps, but it develops large internal forces requiring careful material selection and linkage design. Compared to parallel-elastic "wind-up" leg propulsion Salto's mechanism can control force profiles for improved efficiency on granular material.

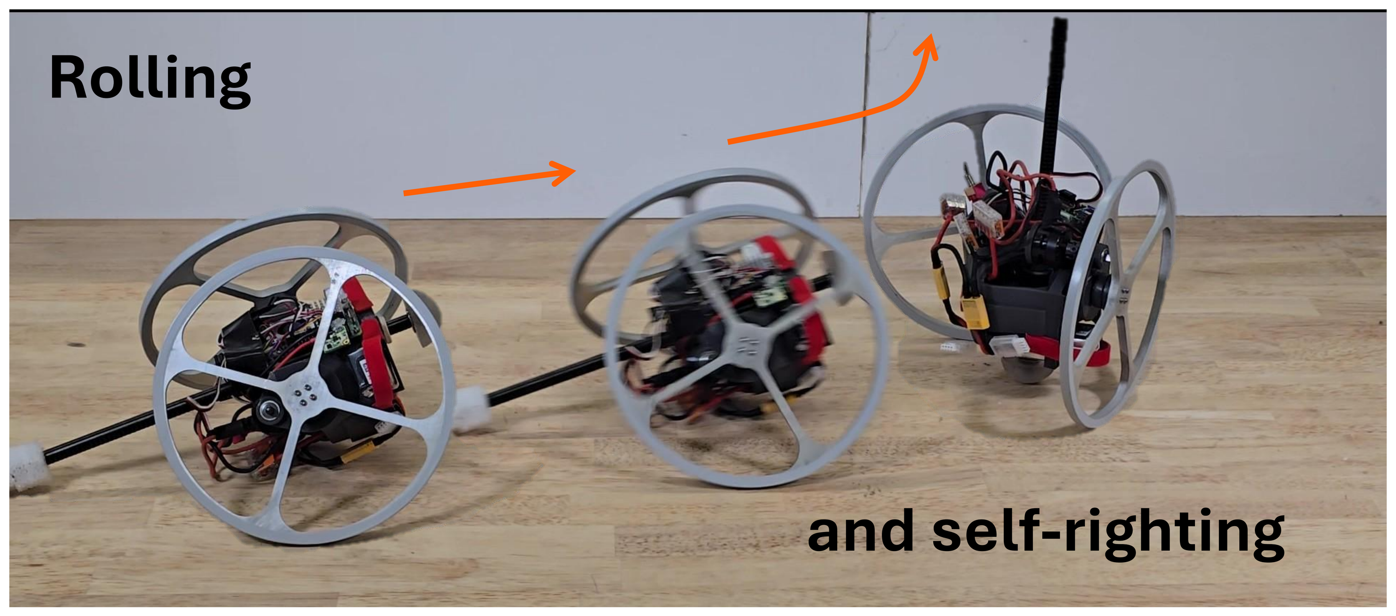
Power consumption vs. foot force for a 30 cm leg launching a 1 kg robot 5 m/s



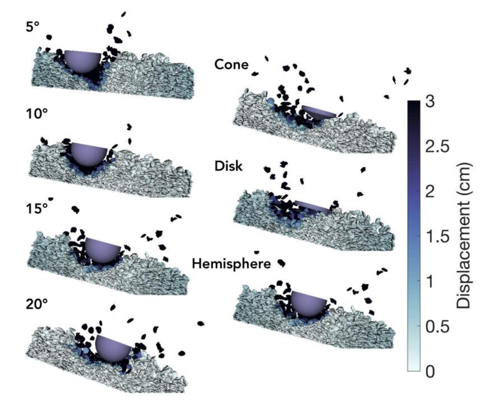
	Min force (const. force)	Variable direct drive	LEAP-scale Salto drive	Original Salto (15 cm, 120 g)
Accel. (G load) (m/s^2)	42	61	61	120
Peak foot force (N)	42	61	61	13
Peak linkage force (N)	42	61	750	150
Peak electric pwr. (W)	417	280	200	32

Testing



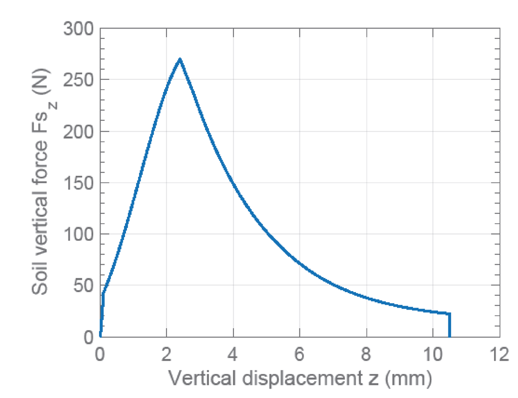


Granular material testing: Later this year we will test jumping, rolling, and landing at NASA Glenn SLOPE Lab in high-sinkage Fillite simulant to evaluate foot designs (to distribute force over the substrate), launch profiles (to improve efficiency), and jump accuracy (to reduce jump distance and angle variation).



Prior work has simulated landing on Enceladus' icy surface.

Figure from:
J. M. Harmon, M. L. Cable, S. J. Moreland, J. E. Andrade, "Predicting the Effect of Surface Properties on Enceladus for Landing" The Planetary Science Journal, 2023



We have run preliminary simulations based on landing models of a 1 kg robot landing at 1.4 m/s (in Fillite simulant).

However, we lack validated models at LEAP's jumping speed regime