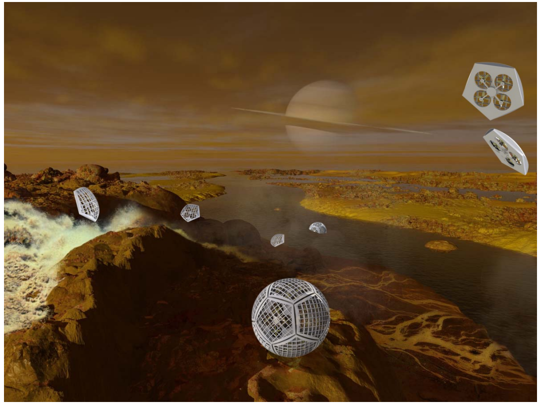

EXPLORING ICY WORLDS: ACCESSING THE SUBSURFACE VOIDS OF TITAN THROUGH AUTONOMOUS COLLABORATIVE HYBRID ROBOTS

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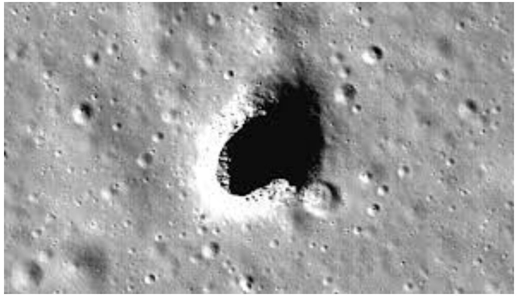
Exploration of Extreme Environments

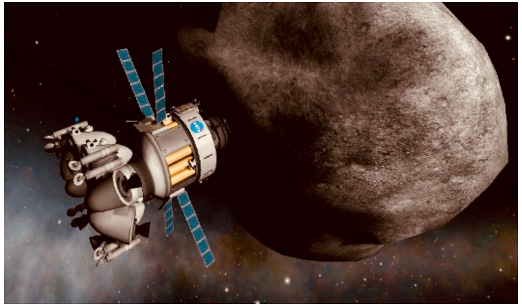
- More than **200 lunar and 2000 Martian cave-related features** have been identified.
- **Vents and fissures** associated with water ice plumes on Saturnian, Jovian, and Neptunian **moons** also represent possible cave systems (Wynne, et al., 2016 and ref therein).
- Lunar and Martian caves most commonly associated with **lava tubes**, although some have been proposed to be present in karstic sulfate terrain (Mars) and **cryovolcanic features** (outer planet moons).



Mare Tranquillitatis pit on the moon. Credits: NASA/JPL-Caltech

Verdes' cave in Spain is a lava tube analogous to extraterrestrial caves in the solar system. Credits: Wikipedia

Artist's impression of Titan's canyon and methane river. Credits: Ron Miller



Artist's impression of a spacecraft exploring a near-Earth asteroid. Credits: NASA/JPL-Caltech

Science Rationale

- Key questions to be addressed based on the planetary decadal survey (Vision and Voyages for Planetary Science in the Decade 2013-2022, The National Academies Press, 2011, p. 71):

Astrobiological Interest

1. What were the primordial sources of organic matter, and where does organic synthesis continue today?

2. Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?

3.How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?

Potential environment for future human exploration

1. Expected stable, UV-shielding environment and potential to act as volatile traps may make caves ideal habitats for future human exploration (e.g. Boston et al., 2007; Boston et al., 2010).

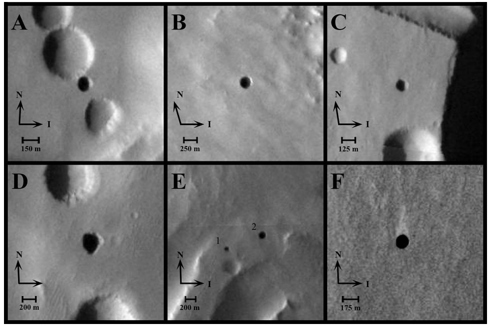


Image of probable cave entrances on Arsia Mons on Mars captured by THEMIS onboard Mars Odyssey Orbiter. Credits: NASA/JPL-Caltech/ASU/USGS

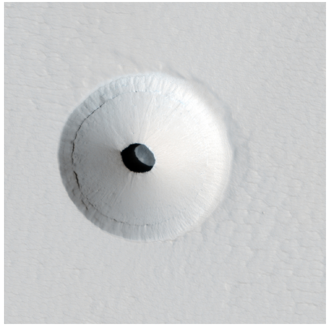


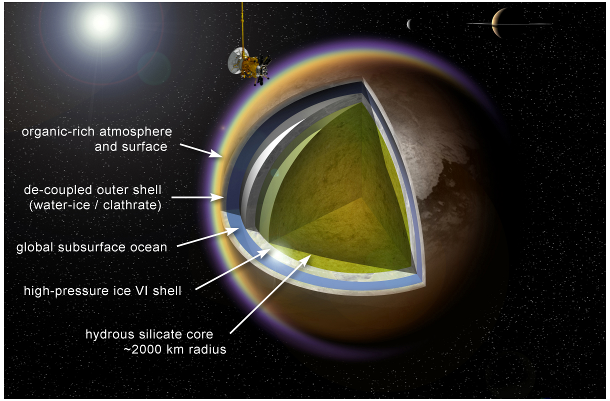
Image of a lava tube skylight entrance on the Martian volcano Pavonis Mons captured HiRISE onboard Mars Reconnaissance Orbiter. Credits: NASA/JPL-Caltech/University of Arizona

Why Explore Titan?

- Titan has the **most complex atmospheric chemistry** in the solar system. Titan is also the only moon with a dense atmosphere and part of a **methane hydrologic cycle** analogous to Earth's water cycle.

- A mission to Titan would be beneficial to understand the following:

1. Is Titan's liquid and solid surface environment capable of sustaining life?
2. What are the origins of cryovolcanoes such as Sotra Patera?
3. How does such similar geology to earth get formed?



Artist's concept shows a possible model of Titan's internal structure that incorporates data from NASA's Cassini spacecraft. Credits: A.D Fortes/UCL/STFC

Titan's surface from a distance of 85 cm from ESA's Huygens lander. It shows pebble-sized rocks or ice blocks. Credits: ESA/NASA/JPL-Caltech/University of Arizona

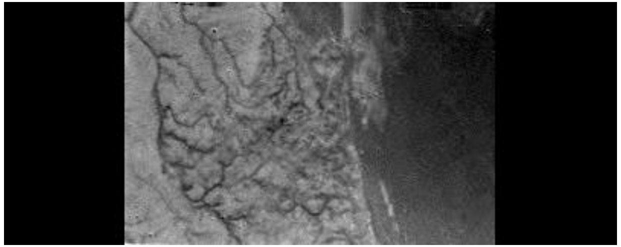
Challenges

- Scientifically enticing locations are **difficult to access due to challenging surface conditions** such as steep slopes, narrow passages, seafloors etc.

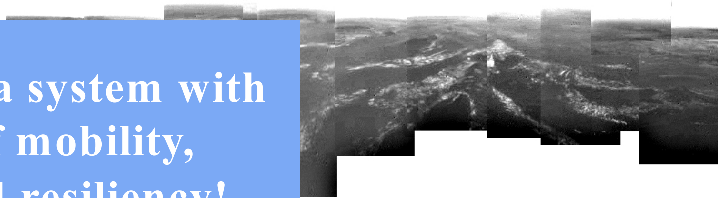
- A desire to explore all of Tit terrains, but **inability to tra distances** between them.

- Current autonomous mobility systems for planetary exploration are mechanically complex, and/or single purpose, **tailored to a specific terrain and domain, and/or not resilient and failure-tolerant**.

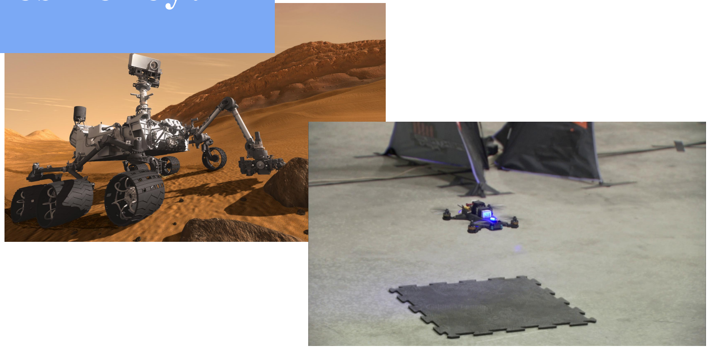
This calls for a system with high degree of mobility, autonomy and resiliency!



Raw images returned by the Huygens probe during its successful descent. It was taken from an altitude of 16.2 kilometers. It apparently shows short, stubby drainage channels leading to a shoreline. Credits: ESA/NASA/JPL-Caltech



Composite of Titan's surface seen during descent. It shows a full 360-degree view around Huygens at an altitude of 8 kilometers. Credits: ESA/NASA/JPL-Caltech

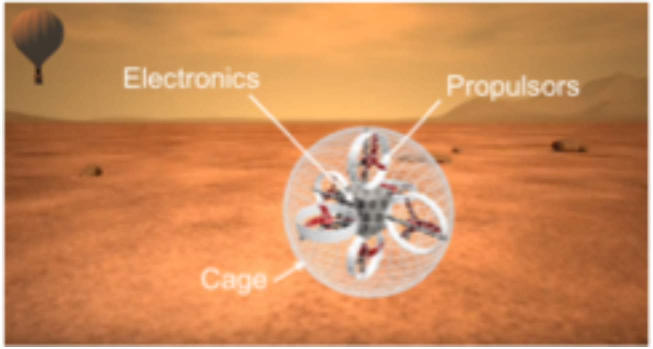


Current state-of-the-art mobility systems. Credits: NASA/JPL-Caltech

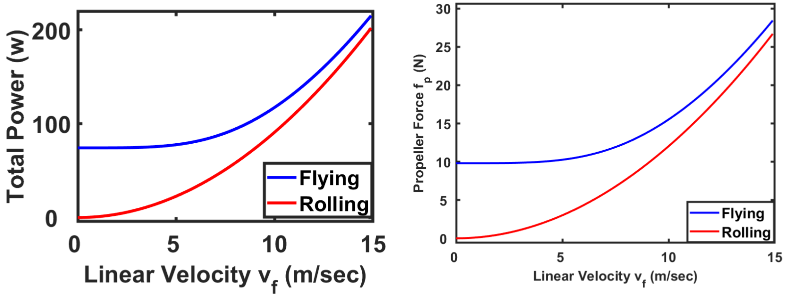
Recent Work: Hybrid Robot Concept

- **Rollocopter** concept is an **autonomous, collision-resilient, energy efficient** novel mobility robot design for exploring extreme environments such as subsurface voids on Titan, being developed at JPL.
- Rollocopter would **save up to an order of magnitude energy** when compared to flying-only vehicles.
- At higher speeds – Rolling and flying would consume almost the same amount of power

  At lower speeds – Rolling consumes much less power when compared to flying
- Titan's atmosphere is 4x denser than Earth and gravity is 1/7th that of Earth, which makes it **extremely favorable to systems that can switch between aerial and ground modes**.

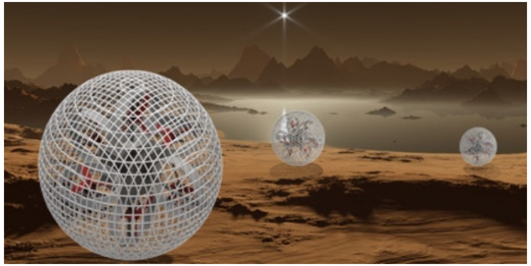


Artist's impression of Rollocopter Concept. It is capable of multiple locomotion modes: flying, rolling, hovering, and bouncing. Credits: NASA/JPL-Caltech



(a) Demonstrates power consumption of Rollocopter (for a given mass) at different linear velocities vf for rolling and flying. (b) Shows the propeller force fp required to roll and fly with linear velocity. Credits: NASA/JPL-Caltech

Mission Scenario



Artist's concept of hybrid robots operating on Titan. Credits: NASA/JPL-Caltech

- A **team of collaborative, resilient, autonomous, and long-endurance assets** (rollocopter) would be deployed by a lander to explore the Sotra Patera region.

- The objective would be **to confirm its cryovolcanic origin** and determine the extent to which lavas have interacted with organic surface materials.

- In order to fulfill the science objectives, the assets would be designed so as to complete the various tasks, including:

a) <u>Low/high resolution local mapping</u>: Builds maps of the region near their base.

b) <u>Stratigraphy:</u> explores cliffs to analyze their potential sedimentary nature.

c) <u>Deep excursion</u>: explores to its maximum range, making most efficient use of available energy by switching between ground and aerial modes.

d) <u>Cave exploration</u>: explores detected caves and cryolava tubes.

Multi-agent Autonomy

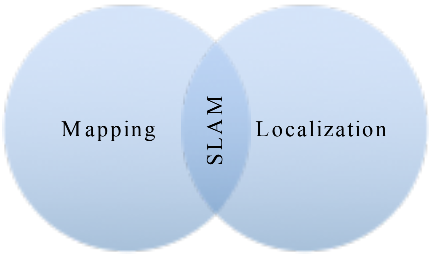
- In the proposed exploration scenario, rollocopters would be used as a **robotic network capable of collaborating with each other** for navigating autonomously across various domains.

- **Robust motion planning** methods would be incorporated into our autonomy framework based on **Simultaneous Localization and Mapping (SLAM)** algorithms.

- Navigation would be divided into two phases by the the autonomous mission planner:

a) <u>Scouting phase</u>: Scouting rollocopters will be dispatched to create an initial low resolution map of the environment.

b) <u>High-resolution science (HRS) mapping</u>: Mission planner deploys a set of rollocopters equipped with advanced sensory suite and science instruments to selected parts of the terrain.



Autonomous single hybrid system prototype.
Credits: NASA/JPL-Caltech

Persistent Situational Awareness

- To enable HRS-mapping over long distances, we adopt a **range-sweeping technique**:

At each episode, a rollocopter traverses the mapped area with high-speed (using trajectory following), reaches the frontier of the mapped area, and then explores the unmapped area via low-speed, higher-energy mapping behavior.

- While a preliminary set of target measurement regions may be part of the initial mission plan, **autonomy enables opportunistic science** and updates the mission plan based on observations made onboard.

- This behavior can be accomplished collectively by communicating any significant discoveries made by one rollocopter to other team members.

Energy-aware Task Allocation

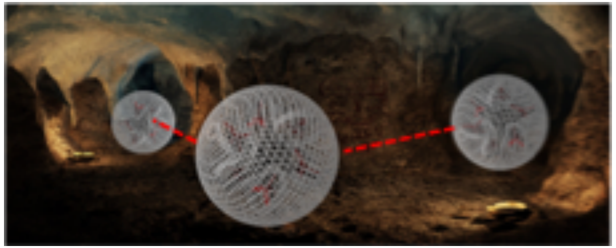
- Development of energy-efficient power sources and managing them to operate robotic assets on the surface is a challenge due to extremely cold temperatures on Titan.
- Autonomy framework allocates the tasks to the robots based on mission specifications, and the **vehicle energy level**.
- Due to the **energy-aware mode-switching ability**, rollocopters can traverse and map the area for long distances without the need for recharging.
- Mission planner schedules optimal visits to the recharging base station, when required.

Block diagram showing energy-aware task allocation by autonomous mission planner. Credits: NASA/JPL-Caltech

Communication Protocol

- We would rely on Disruption-tolerant Networking (DTN) protocol techniques that allow **autonomous management of communication links and data transmission**.
- DTN is a highly reliable and resilient scheme to enable a **communication network between a group of mobile nodes**.
- The acquired data would be relayed back to the lander, which will then be sent to Earth for further processing and analysis.
- DTN ensures **successful communication between all assets in the system** even if an end-to-end communication path does not always exist.

The Disruption Tolerant Network protocols will enable the Solar System Internet, allowing data to be stored in nodes until transmission is successful. Credits: NASA/JPL-Caltech



Artist's impression of hybrid robots following DTN protocol on extraterrestrial surfaces. Credits: NASA/JPL-Caltech

Conclusion

- Technology demonstration for **small autonomous rotorcrafts** has matured dramatically in the last decade. Mars helicopter and Dragonfly projects are receiving intensive study for a **potential technology demonstration** on **Mars** and **Titan** respectively.

- Team of **autonomous energy-efficient hybrid robots** would allow **high-redundancy** in the system, where not only specific targets on Titan could be closely observed, sampled and cached, but also high-risk, high payoff measurements could be taken (since the loss of one rollocopter would not spell the end of the mission).

- Incorporation of DTN and capability-aware mission planner **enables opportunistic science** in addition to providing a **resilient solution** that can adapt to a wide **range of contingencies** by altering the path to accomplish the mission objectives.

Thanks for your attention!

Any questions?

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Future Funding: One of the 6 selected teams by DARPA to participate in their upcoming Subterranean Challenge (award pending)

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