Venture Deep, the Path of Least Resistance: Crevasse-Based Ocean Access Without the Need to Dig or Drill

A Mission Concept White Paper for the Planetary Science Decadal Survey

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Summary

The Cassini Mission unveiled Enceladus as a key target for astrobiology exploration in the coming decade (Schenk et al., 2018, and references therein). The Enceladus plume provides a unique pathway to sample from, and potentially travel to, an alien ocean. This ocean is global and habitable, containing all ingredients for life as we know it - “extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy source(s) to sustain metabolism” (Des Marais et al., 2008). A future mission to Enceladus, built with today’s technology, could address a pivotal question that reaches civilization-level science: Are we alone?

However, Enceladus presents many mobility challenges. The majority of grains emitted from the plume fall back onto the surface of this moon (Porco et al., 2017). At 1% Earth’s gravity, this unconsolidated plume ejecta likely fluidizes when disturbed, making traditional wheeled mobility untenable. Sintering of the ice grains might also need to be accounted for. Various models of how the plume is driven provide a wide range of environments to be traversed, not only on the surface but within the vent itself, which may be circuitous or constricted. The vent interior dimensions could also vary over the orbital period of Enceladus. With a ~2.5 hour round trip communications time and the dynamic environment of the plume and ocean, any mission looking to access the ocean through the vent system must be fully autonomous. **An adaptable, autonomous robotic architecture is capable of navigating Enceladus’ surface and reaching the subsurface ocean in the coming decade.**

Introduction

Following the discovery of an active plume sourced from the ocean, Enceladus has seen increased interest from the scientific community. Evidence of silica grains, as well as the detection of methane and molecular hydrogen by the Cassini Mission, suggest hydrothermal reactions (>90 °C) and serpentinization at the seafloor (Hsu et al., 2015; Waite et al. 2017). A possible organic-rich film located at the top of the water table offers a target for instruments looking to find signs of life (Postberg et al., 2018). At least one species of Earth methanogen still produced CH_4 in an analog Enceladus environment and withstood up to 50 bar of pressure (Taubner et al., 2018). Combined, this evidence makes Enceladus a potential sanctuary for extraterrestrial microbial life. If discovered, this breakthrough has implications for both terrestrial and astrobiological sciences.

Enceladus plume vents are an optimal pathway for robotic access to ocean water. To obtain a sample that will conclusively detect potential microbial life, the robot must be able to sample the surface of Enceladus, navigate Enceladus’s icy terrain towards a vent opening while sampling the materials that falls out of the plume in concentric rings based off of mass, and attempt to sample directly from the plume itself. If none of these yield conclusive results or as an extended mission, the robot could attempt to navigate down through the vent conduits in the ice shell of Enceladus to explore the ice-water interface.

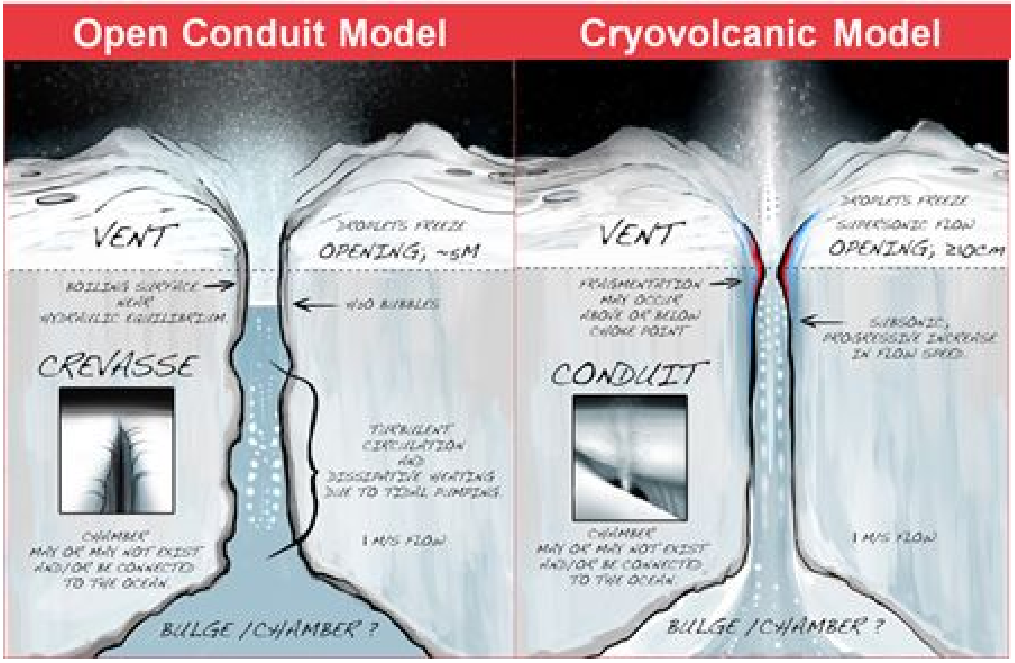

Figure 1: Two different models are consistent with Cassini observations of the Enceladus plume. **Left:** The open conduit model posits that the erupting fissures are underlain by slots that connect the surface to the ocean (Kite and Rubin, 2016). **Right:** The cryovolcanic model is more consistent with explosive volcanic eruptions on Earth, and has ocean water filling a chamber and exiting at a choke point (>10 cm).

Reports of Enceladus' ice shell thickness vary, but there is growing consensus that it might be closer to 20 km (Thomas et al., 2016; Čadek et al., 2016). The ice shell appears to be thinner at the thermally-active south pole, indicated by a topographic depression (Thomas et al., 2007), one of the early indications of a localized subsurface liquid reservoir (Collins and Goodman, 2007). Recent studies imply <5 km thickness in the south polar region (Čadek et al., 2016). The high tide point is estimated to be 10's of meters to one kilometer from the surface.

Multiple models have been suggested for the ascent and eruption of ocean water feeding the Enceladus plume. Kite and Rubin (2016) suggest large crevasses that open and close with tidal flexing in the **open conduit model**, with hydraulically-supported liquid water pumped up and down turbulently, and the water-surface exposed directly to near-vacuum causing boiling which supplies a gas-dominated plume with liquid droplets (see Fig. 1, left panel). Alternatively, Ingersoll and Nakajima (2016) evoke a controlled boiling model that results in much narrower fractures. However, neither of these take into account the role of dissolved volatiles, which appear to be present (e.g., Waite et al., 2017), and may cause activity to be more akin to terrestrial fire fountaining volcanism (we refer to this scenario as the **cryovolcanic model**, per Lopes et al., 2010). In this case, ascent is fueled by exsolution and expansion of volatiles from the liquid water during decompressional ascent (see Fig. 1, right panel) within a relatively narrow conduit, passing through a nozzle and liquid water flashing to solid and vapor when pressure drops below the triple point (Mitchell et al., 2017 and in prep.). All of these cases likely have some evolution of the conduit through redeposition, abrasion and sublimation on/of the surrounding ice, which may lead to circularization of the vents and conduit structure from an initial fissure/fracture. It is anticipated that the vent connects to the subsurface ocean in all cases, but the extent to which the plume samples the ocean materials differs greatly.

The differences between these models impact the requirements on any robotic explorer. In the open conduit model, the opening may be a few meters wide, with water being pumped up and down within the vent and a boiling water surface at a depth controlled by hydraulic equilibrium. Dynamic pressures would be very weak (Mitchell et al., 2017). In other models, the throat may be considerably smaller, of order ~10 cm, as a fissure (Ingersoll and Nakajima, 2016) or as circular vents in the cryovolcanic model (Mitchell et al., 2020, in prep.). Supersonic flow within the conduit is possible, and dynamic pressures may be considerable, potentially a daunting 10^7 Pascals (Mitchell et al., 2017). This relationship informs an architecture that may fall or repel down a wide crevasse, reacting to increasingly large forces down to the centimeter range. For the open crevasse model gravity likely dominates and rappelling is possible. For the evolved vent model a 10 cm throat would take ~60 kg earth weight equivalent to plug. Local gravity is ~1% that of Earth, and easily overcome by most of the range of potential plume forces.

The greatest possible plume forces bring more scientifically relevant samples to the surface so a mission may achieve its sampling goals regardless. As the dynamic pressure goes up, so does the static pressure, which means that the ice is heated and pressurized by the flow to be above the triple point. The force from gravity on Earth acting on a robot is in line with the forces the plume will impart on a robot descending a vent. These cases make it possible to test solutions on Earth as a relevant environment. **This enables development and demonstration of a full autonomous system here on Earth going up against gravity in ice crevasses, ice bore holes and moulins to validate and verify the capability.**

Traversing the Surface

Recent experimental work (Choukroun et al., 2020) indicates that, for regions of Enceladus' surface that are <70 K, it would take a very long time (Gyr) for plume deposit materials to sinter substantially. Right next to the Tiger Stripes, which are warmer, there are two possible scenarios:

1. If the plume deposit does not receive fresh plume material on top, it will sinter and strengthen quickly (on the order of years).
2. Conversely, if the plume deposit is in a region where fresh materials are constantly being newly deposited, then these materials would be loose (and

presumably cold) so would not have time to sinter, building a possibly substantial layer of unconsolidated media.

There are several limitations to distinguishing between the two scenarios. Because the Tiger Stripes are not in thermal equilibrium, there presumably exist pretty large lateral temperature gradients with distance on the surface. The temperature of the plume materials as they fall onto the surface is also not well constrained, nor is how these equilibrate together to possibly reach a thermal steady-state. Further, the texture of the plume deposit is poorly constrained, which could impact thermal conductivity by 1-2 orders of magnitude. Despite these limitations, it is likely that areas with lots of fresh deposits (which would be the primary target of an astrobiology-focused mission), even quite close to the Tiger Stripes, would still be mostly expected to consist of loose materials. **We recommend continued modeling efforts supported by experimental validation (including test beds and field work) to assess how consolidated the surface of Enceladus may be near the TIger Stripes. However the technologies to traverse these environs exist today.**

Autonomy

Subsurface missions on Ocean worlds impose the most demanding technology advancements in Autonomy. Unlike Mars Missions, these missions do not allow human-in-the-loop operations due to presence of large latency and blackout in communication which are upto two weeks long during the solar conjunction.

Autonomous navigation consists of three phases: surface traversal, sub-surface traversal and transition. Each phase challenges autonomy in unique ways. During surface navigation, the system must traverse through challenging terrain such as unconsolidated medium, as described in the previous section. It should also be able to detect and navigate to the crevasse without any orbital maps. Subsurface traversal in the crevasse requires the system to maintain stability in presence of disturbance forces from the plume by establishing robust contacts on walls with irregular geometries and unknown time-varying terra-mechanical properties. Finally, the system must be capable of making a safe transition from the surface phase into the subsurface phase where it faces all these challenges together.

Achieving fully autonomous navigation in these uncertain dynamic environments requires the following fundamental changes in paradigm compared to Mars Mission Operations:

1. *Adaptive* rather than robust*:* Presence of large uncertainty will likely prohibit fixed design of autonomous behaviors that robustly work for any imaginable situations; instead, the system must adapt its behaviors by continuously learning about the new environment.
2. *Redundant and Resilient* rather than protective*:* One of the main challenges for sub-surface navigation is to ensure that the system does not get pulled up by the plume. In the event of a failure, either in hardware

or environment (e.g. contact loss) the system cannot enter a safe state by switching off control. To ensure safety, the system must generate sufficiently large normal reaction forces by pushing into the wall which can be achieved by redundancy in hardware along with resilient autonomy which is capable of continuing operations under partial failures.

3. *Reactive* rather than deliberative: Unlike Mars rovers, we are in a dynamic environment with short-range visibility and no orbital maps. Therefore, it has to quickly react to observed situations instead of making a long-range plan deliberatively.

Recommendations for autonomy development:

1. **Develop autonomy algorithms and software to meet the capabilities described above**
2. **Build an ocean worlds simulation model and software for unit, sub-system and full integration testing of autonomy software against different types of environments through Monte-Carlo simulations**
3. **Build and test autonomy capabilities on hardware at earth-analog environments**

Crevasse Access Vertical Mobility Architectures

Getting to and down a crevasse requires next generation mobility. Many solutions of varying development exist in this space as shown in Figure 2. Many of these have been field tested and demonstrated in relevant environments. Current efforts will yield autonomous demonstrations by 2023.

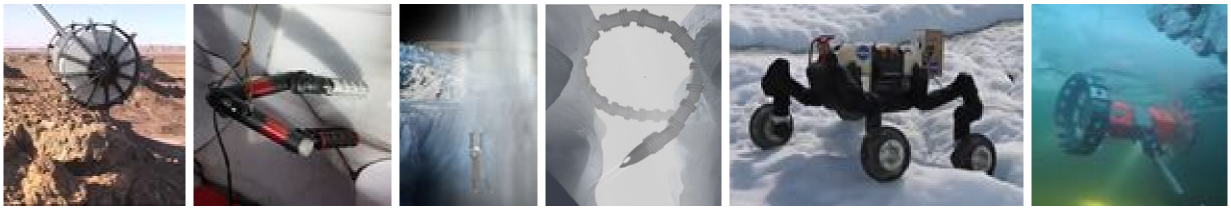

Figure 2. Examples of various robotic concepts capable of part or all of the challenges in crevasse ocean access. **Left to right:** Axel, a repelling robot with over a decade of development; Ice Worm, a field tested ice climbing robot; Enceladus Vent Explorer (EVE); the Exobiology Extant Life Surveyor (EELS) concept uses counter-rotating Archimedes screw propulsion units to move around obstacles and through unconsolidated media such as plume deposits (Carpenter et al., 2019); RoboSimian uses a wheel-on-limb platform with active suspension to navigate Europa analog terrain at Matanuska Glacier, Alaska (Reid et al. 2019); the Buoyant Rover Under Ice Explorer (BRUIE) can navigate the under-ice environment**.**

Adaptable architectures to traverse ocean world inspired terrain, fluidized media, enclosed labyrinthian environments and liquids may take many forms. A robot or nested doll group of robots must be able to get to a vent exit, follow the streamline to its source and proceed into the open water. The mobility solution must traverse consolidated cryo ice, unconsolidated plume ejected, down slopes of up 30 degrees, manage undulating terrain, boulder fields, cracks, steps, one sided cliffs, creavsses, conduits, throats (Smallest cross section conduit) and underwater mobility. Of importance is the ability to transition between these terrain types.

Recommendation: Various robotic architectures exist focused on vertical mobility and ocean access, and accelerated development of the necessary technologies in the beginning of the decadal period will lead to mature capabilities in time for a 2031 launch.

Power and Communications

Currently, JPL is developing next-generation, end-to-end power delivery architectures that support efficient (>90 %) power transmission over kilometer-scale distances to serve remote exploring rovers and/or probes. Three key elements comprise this power system architecture:

1. Robust electromechanical tethers that support climbing/descending robots and provide power/communication (JPL in collaboration with commercial partners has been active in developing planetary tether designs capable of surviving extreme conditions)
2. A high voltage conversion system comprised of GaN-Based Modular Multilevel Converters (MMCs), and
3. A long-distance communication system comprised of fiber optics that allow high-speed data transmission upto 1 Gbps at multi-kilometer scales.

The complete system provides power transmission capabilities for critical operations through all phases of the journey to reach liquid water on the Solar System's Ocean Worlds.

We recommend the continued development of high voltage tethers and tether management technologies for power and communication.

Conclusion

This paper is meant as a primer to crevasse-based ocean access and associated technology developments necessary to achieve it. The current development level of these technologies is not covered here. Many of the component technologies are funded to reach TRL 6 within the next three years. Furthermore, funded efforts demonstrating or that will demonstrate system level crevasse access capabilities in the field are ongoing. Relevant crevasses in glacial ice can be easily found on Earth; validation and verification of these access concepts does not require exotic facilities and can be readily demonstrated in the near term.

Key recommendations to enable robotic ocean access in the next decade include:

- Continued modeling efforts supported by experimental validation (including test beds and field work) to assess how consolidated the surface of Enceladus may be near the TIger Stripes.
- Build an ocean worlds software system simulation environment, high-fidelity models, and hardware testbeds to fullytest autonomy subsystems and components.
- Construct a community V&V certification framework that will assess proposed autonomy systems against the quantified metrics.
- Continued development of high voltage tethers and tether management technologies for power and communication.

Accelerated development of these technologies in the beginning of the decadal period will lead to mature crevasse exploration capabilities in time for a 2031 launch.

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