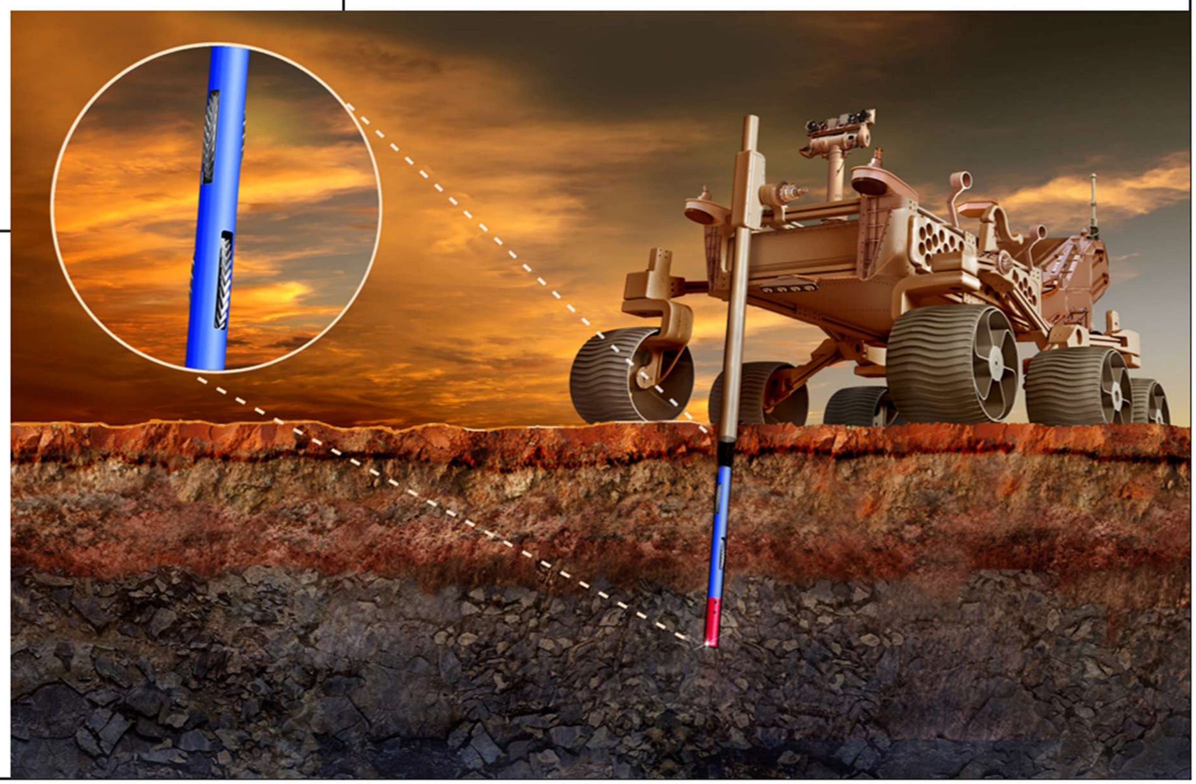
Autonomous Robotic Demonstrator for Deep Drilling (ARD3)

Innovation

- Drill and recover core samples from Mars South Polar Layered Deposits
- Roughly 1m long drilling robots drive up and down the borehole
  - Self propelled
  - No tether
- Autonomous deep drilling has never been performed anywhere but Earth
- Mars 2020/MSL type mission in the 2023-2032 decade to the Mars South Polar Layered Deposits
- 20-50m depth target with extended mission goal of 1.5km

Technical Approach

- Evaluate concept feasibility
- Determine the range of possible borehole travel speeds
- Evaluate power consumption and power sources
- Evaluate strategies to preserve sample integrity
- Assess science instrumentation relevant to ice core analysis
- Bring concept to TRL 2, outline a path to TRL 3 if plausible



Potential & Benefits

- Proposing 10-fold increase over state of the art, which is:
  - 2m (Rosalind Franklin Rover)
  - 5m (Insight Lander HP3)
- Provides a concept for expanding drilling capability, with specific advantages that multiply as depth increases and gravitational field strength decreases
- Performing the study now allows a pathway for the Technology Readiness Level to mature in time to support next-decade missions

Background and Problem Statement

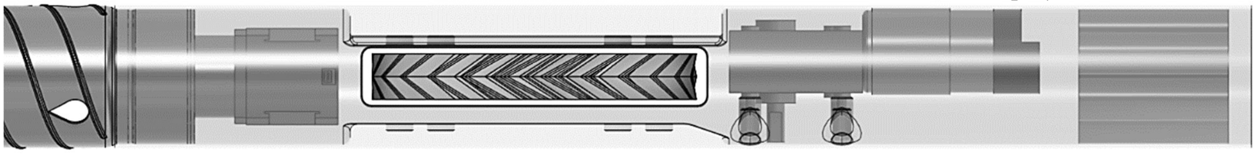
It is now believed that subglacial liquid water exists on Mars, at a depth of 1.5 km in the South Polar Layered Deposits (SPLD). This evidence was published by Orosei et al. in 2018, and immediately sent reverberations through the aerospace community. Chris McKay, Senior Scientist for the NASA Ames Research Center was heard on the Planetary Radio podcast saying: “If we’re going to do astrobiology, we need to not just see it, we need to get a piece of it, we need to get a sample of it. So I think this becomes a very strong argument for deep drilling” (Kaplan, 2018). The chances that this formation and subglacial lake may harbor life are greatly increased if the liquid phase is made possible due to heat produced by volcanic activity under the crust, which was indicated in a follow-up report by Sori & Bramson in 2019. Prior to these discoveries, the SPLD was already one of the most scientifically significant formations on Mars, having witnessed atmospheric and climactic changes dating back to 4 billion years (Bar-Cohen, 2009, p. 352). There is currently no deep drilling system ready to take on this task, with the technology leader (the InSight HP^3 “mole” probe) stuck just centimeters under the ground. Furthermore, there are no autonomous deep drills currently above TRL 4 in the NASA technology pipeline (Zacny, 2018).

Discussion

We propose an autonomous drilling system that would utilize a Perseverance-type rover as a drill rig. The rover would be outfitted with minimal but appropriate science instruments, and a drilling strategy that has a high level of redundancy. The drilling strategy does not rely on cables; instead, self-contained robots drive up and down the borehole autonomously. These robots are nicknamed “borebots” and are on the order of 1 m long.

The borebots are deployed from a tube moved into place by simple linear actuators on the rover deck and can begin drilling while driving into the borehole. Locomotion is achieved using a rubber tank track system that presses against the sides of the borehole. The borebot will drill approximately 150 mm during each trip, and then the ice core is parted off and carried to the surface by driving up the borehole. A robotic arm is used to remove the borebot from the borehole and move it into one of the service bays in the side of the rover for core sample removal and automated servicing. Once out of the way, the next borebot can go down the hole and start drilling. Around a dozen borebots could be housed in honeycomb-esque service bays, while shorter bays near the rear of the rover can house extra coring bits and other spare parts.

Borebot (colored red) in deployment tube.



The main body of the borebot is shown here with 50% opacity. The fluted coring module extends 150 mm to the left. From left to right, inside the body: the drill motor, the tank-tread drive system, drive motor, room for electronics, and a 7-cell battery pack. The main body is 500 mm long, while the whole borebot is around 0.75 m to 1 m long.

When an ice core is removed from a borebot in one of the service bays, the rover will prepare the core for *in-situ* analysis and caching with internal processing equipment. It is likely that core samples will either be dedicated to *in-situ* analysis or cached for later retrieval. However, it may be possible for cores to be both analyzed and cached. Preserving the integrity of the ice cores must be a top priority. Thus, the processing systems will be studied carefully.

The proposed mission is to drill 20 m to 50 m deep in the SPLD using a nuclear-powered Perseverance-type rover and the borebot drilling architecture. If $20\ \mathrm{m}$ to $50\ \mathrm{m}$ depth is achieved within a 90-day mission, an extended mission could aspire for the goal of 1.5 km. The system does not grow in complexity as depth increases, and consumable use scales linearly. The extended mission could take around four years and collect thousands of core samples. The samples would be analyzed, and the data returned to Earth. Dozens of samples could be cached during this time.

The energy required to raise a 10 kg payload (such as a borebot and ice core) a distance of 1.5 km on Mars, using a gravitational field strength of $3.71\ \mathrm{m/s^2}$:

$$\Delta\mathrm{PE} = \mathrm{PE_f} - \mathrm{PE_i} \quad \rightarrow \quad \Delta\mathrm{PE} = \mathrm{mgh}$$

$$\Delta\mathrm{PE} = (10\ \mathrm{kg})(3.71\ \mathrm{m/s^2})(1.5\ \mathrm{km}) = \boxed{\mathbf{55.6\ kJ}}$$

Consumer-grade remote-control toys that feature a rubber-tank-track-type motion system provide an estimate of how much energy a small, tracked system consumes. One of these toys features a rechargeable $9.6\ \mathrm{V},\ 700\ \mathrm{mAh}$ battery pack (RC Toy Memories, 2014). That translates to around $6.7\ \mathrm{Wh}$. Using a $20\ \mathrm{km/h}$ average speed and 10 minutes of run time per charge:

$$6.7\ \mathrm{Wh} \cdot (3600\ \mathrm{s}/1\ \mathrm{hr}) = 24{,}120\ (\mathrm{J/s}) \cdot \mathrm{s} = \boxed{\mathbf{24.12\ kJ}}$$

$$20\ \mathrm{km/h} \cdot 10\ \mathrm{min} = \boxed{\mathbf{3.33\ km}}$$

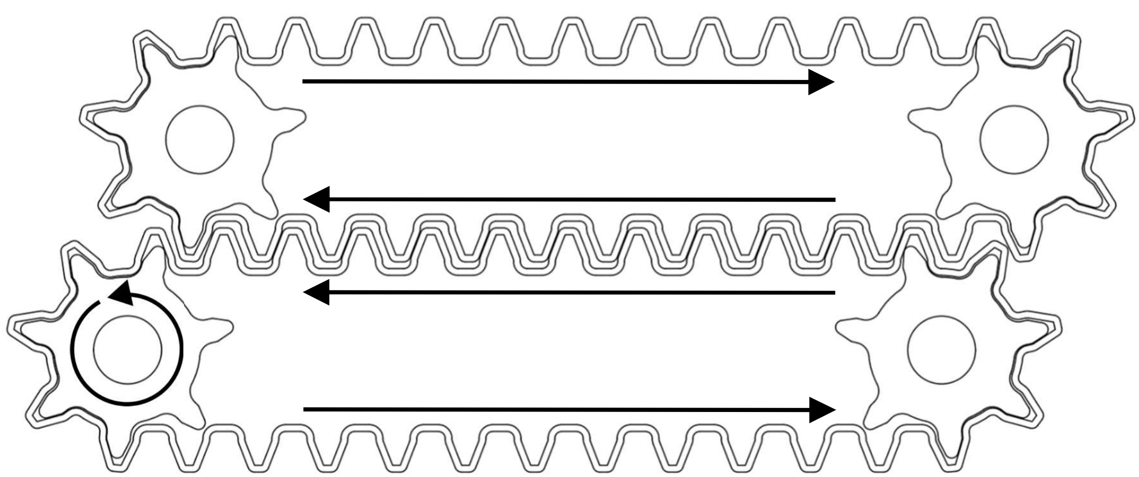
That is an estimated $24.12\ \mathrm{kJ}$ to go about 3.3 km on the flat-and-level. If we add these two estimates, the 3 km round-trip distance down and back up a 1.5 km borehole could consume as little as 80 kJ of energy. Note: Drivetrain energy use is examined again in the "Challenges" section. During initial testing, the ExoMars Drill had a power draw of $14.5\ \mathrm{W}$ when drilling into gas concrete, with a penetration rate of $240\ \mathrm{mm/h}$ (Magnani et al., 2004). Using these figures as an estimate, a 150 mm core could require roughly $40\ \mathrm{kJ}$ of energy, bringing the total energy consumed to $120\ \mathrm{kJ}$. To support this energy requirement, four 18650 Li-Ion cells would be required. The inner diameter of the borebot can fit battery packs containing seven 18650 cells each.

This concept has the potential to change the way we think about deep drilling, as illustrated by these calculations. All competing automated deep drilling technologies rely heavily on direct links to the surface (Bar-Cohen, 2009). Because of this tethered approach, every drilling system on the books lacks the redundancy and resiliency to sustain operations for years while unattended. The most exciting thing about the borebot approach is the strategy and logistics of having a dozen robots taking turns performing the work autonomously. This approach has applications beyond Mars, and closer to home, too: such a resilient and automated system would be able to drill in the Arctic and Antarctic ice, as well as ice on the Moon, Europa, and other icy worlds in our solar system. This concept could potentially be lighter, more efficient, and better suited to frequent trips to the surface (core-carrying) than other systems. On worlds with less gravity, these advantages become greater as the potential energy calculation is more forgiving.

The borebot drive system has been prototyped using flexible parts printed on a workshop 3D printer. The system is a flexible-gear-drive, where the teeth of the ring gears act as power transmission belts as well as traction belts at the borehole interface. This allows for a compact package. Floating idler gears are added to provide more consistent and intense pressure along the belt and may fare better at passing small pebbles than a fixed guide. The flexibility of components can be adjusted and optimized to minimize mechanical resistance and maximize durability.

It may be advantageous to "decouple" the treads from one another, by reducing the size of the gears and adding a separate drive motor for the track on the other side. This would complicate the design and increase cost, but can potentially provide some element of steering. If it is shown necessary, a second set of drive tracks can be added to enhance this steering effect and provide additional traction. The second set of tracks would be rotated 90 degrees with respect to the first set of tracks about the borebot axis. This may provide sufficient steering force to enable accurate directional drilling, providing a strategy for keeping the borehole straight (Bar-Cohen, 2009, p. 183). The attitude of the borebot could be

Above: Drive system mockup with floating idler gears to intensify pressure at borehole interface.
*Below: **True size** schematic of the drive system, with gears shown doubling as "tank tracks." Idlers omitted.*



detected using onboard accelerometers and could be maintained with this steering effect. The second set of tracks may also reduce wear and tear on the borehole wall. According to Bar-Cohen and Zacny, "the only straight and vertical borehole is in a textbook" (Bar-Cohen, 2009, p. 183). This issue is discussed again in the challenges section.

To calculate the travel speed necessary to accomplish the primary mission goal of 20 m to 50 m depth in a 90-day mission, the 50 m depth figure is used. For this calculation it is assumed that time not spent drilling will be used driving up and down the borehole, with no downtime. A core length of 150 mm is used, and the time allowed to drill each core is assumed to be one hour. The number of trips and cores, n, required: $50\ \mathrm{m}/150\ \mathrm{mm} = 334$ trips and cores.

$$\sum_{n=1}^{n=334} 150\ \mathrm{mm} \cdot 2n = 16{,}783{,}500\ \mathrm{mm} = 16{,}784\ \mathrm{m}$$

$$16{,}784\ \mathrm{m}/(90\ \text{days} - 334\ \text{hours drilling time}) = 2.55\ \mathrm{mm/s}\ \text{ or } \boxed{\mathbf{154\ mm/min}}$$

A travel speed of $154\ \mathrm{mm/min}$ can safely be used as the back-of-the-envelope calculation for the bottom end of the borehole travel speed range. It is unlikely that a speed this slow will be used, but the mission could still be successful in this case. For the top end of the speed range, it is helpful to imagine boring the extended mission goal of 1.5 km in a timespan of four years. The number of trips and cores, n, required: $1500\ \mathrm{m}/150\ \mathrm{mm} = 10{,}000$ trips and cores.

$$\sum_{n=1}^{n=10{,}000} 150\ \mathrm{mm} \cdot 2n = 15{,}001{,}500{,}000\ \mathrm{mm} = 15{,}002\ \mathrm{km}$$

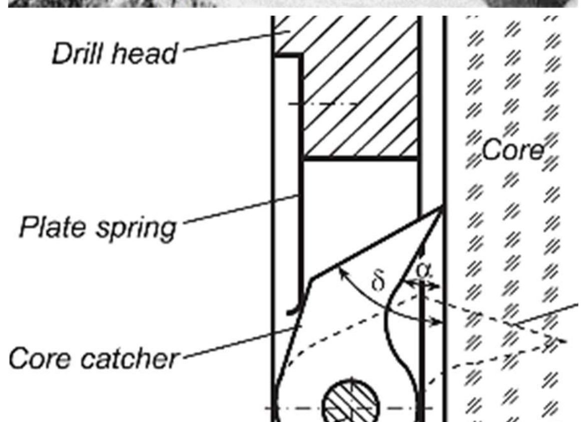
$$15{,}002\ \mathrm{km}/(4\ \text{years} - 10{,}000\ \text{hours drilling time}) = 166.4\ \mathrm{mm/s}\ \text{ or } \boxed{\mathbf{10\ m/min}}$$

A travel speed of $10\ \mathrm{m/min}$ is required in order to accomplish a 4-year nominal mission. This seems like a reasonable expectation for the borehole travel speed range and is a good starting point for an investigation. This broad range can help set the requirements for an investigation of motors and other drivetrain components. Faster speeds may increase heat output and energy use, as well as increased stress on the borehole wall and drivetrain. The travel speed will be evaluated, and these estimates revised if necessary.

A wide variety of instruments exist for *in-situ* analysis of Martian materials, including the 40 kg Sample Analysis at Mars (SAM) instrument suite used in the Curiosity rover, the 11.5 kg Mars Organic Molecule Analyzer (MOMA) instrument used in the Rosalind Franklin rover, and the never-flown 4.4 kg Urey instrument (NASA Mars, n.d.; Goesmann, 2017; Aubrey, 2008). An appropriate *in-situ* analysis suite could likely be developed by merging philosophies from all three of these instruments into a lightweight package capable of analyzing hundreds of core samples. Appropriate scientific instruments for *in-situ* analysis will be evaluated in detail. However, the existing legacy hardware shows that small and lightweight sample analysis packages have been created before, and it is reasonable to believe that an instrument package could be successfully integrated into a large rover without creating a burden to drilling activities or storage volume.

One of the largest challenges facing exploration of the SPLD is the characteristics of the substrate. It is believed that the SPLD has a varying density and composition (Li, 2012). The substrate properties play a critical role in the integrity of the borehole. Increasing the borehole surface area can potentially reduce the wear and tear caused by the drive system, so the diameter needs to be considered. Several deep drilling systems developed by NASA and ESA have used a diameter of 45 mm or less. This is believed to be too small for practical deep drilling operations because it requires tighter tolerances on mechanical components, and a very thin annular kerf in order to obtain usable cores (Bar-Cohen, 2009, pp. 482-483). Newer drilling systems have started using larger diameters, with 64 mm currently being a popular size (Planetary Society, 2016). This increase in size provides an over 40% increase in diameter and effectively doubles the cross-sectional area of the borehole compared to 45 mm. For these reasons, this study uses 64 mm as a starting point. To mitigate the impact of the variable composition on drilling, different drilling heads could be used for rocks/cobbles, water ice, and crumbly mixtures.

The "coring module," or more simply, the drill bit, is a plastic or metal fluted tube attached to an annular drilling head, which is very similar to the handheld Livingston Island Mini Drill (LIMD) shown on the right (Talalay, 2016). Some type of core-carrying feature must be added to the borebot coring module in order to work with the varying composition of SPLD cores. A sheetmetal-basket-style core catcher could be effective, while the crumbliest of materials may require a spherical iris-type aperture to contain the core materials (see the photo on the following page). To close the iris, the coring module could counter-rotate while the cored material provides some mechanical resistance. However, a basket-style catcher relies on spring tension to dig in when upward movement occurs. Traditional Earth-based ice drilling systems often use "core dogs," metal teeth that dig in when the drill is pulled up (or rotated backwards), causing the solid ice to fracture. This option is the easiest to integrate into a drill head but may offer little effectiveness considering the layered stratigraphy of the SPLD.



Top: Livingston Island Mini Drill, (Talalay, 2016).
Above: Core dog cutaway view, (Talalay, 2014).
Below: Coring module mockup, with drill motor.
Core-carrying devices omitted.

Sudden and rapidly-expanding bursts of sublimated water vapor help to clear debris from the cutter head and motivate them up the flutes when drilling into ice-bearing materials on Mars. (Zacny and Cooper, 2007). This important effect allows for dry drilling on Mars, which aids in extracting a pure sample (Bar-Cohen, 2009, p. 488). However, the substrate properties must be properly accounted for in order to avoid clogged or jammed drills. Excessive sublimation would have a high energy cost during drilling operations and would require measures to prevent re-deposition further up the borehole.

The current state-of-the-art for Mars deep drilling is represented by the HP^3 mole, which has had a challenging life so far, unable to reach $1/10^{th}$ of its target depth of 5 m. Because of this, the ExoMars Drill (ESA rock coring drill, 2 m depth) appears to be the current technology leader. Both are at TRL 8.

3D printed spherical iris, actuated by twisting. A metal iris of similar design could be fitted inside the coring module to retain ice cores. An Emmett Lalish design (Lalish, 2016).

A Second Path

The borebot concept is not exclusive to a large, expensive rover. The most important traits of the rover are: it is a box full of borebots and parts, it has a one-meter-long tube on it, it has one or more robot arms for moving borebots from one place to another, and it can analyze samples. Taken in this context, the rover can be dissected into its constituent pieces and a second path to a mission architecture emerges. A box full of parts and processing equipment could be sent to Mars along with two small rovers that each have a robot arm. A bolt-in-place, one-meter-long tube could be sent with the rovers, which can be erected on site for semi-permanent use. This architecture also provides an additional advantage – scalability. The initial cost could be that of a single, small, solar-powered rover. This pioneer could set up the tube, and perhaps only carry two borebots that would operate at a slower cadence due to the lower energy availability. Later, a large crate can be landed nearby with a nuclear battery, 12 more borebots, and a sample handling system – now the little rover can be working overtime with access to a large battery charger and more supplies. The following season a second rover can join the first. This could allow for a best-in-show science return with a series of sub-$200-million missions. The funding flexibility could leave room for expanding the sample return architecture, and the supply crate could include a small ascent vehicle, eliminating the need for a separate sample-fetch rover and the associated expense.

Challenges

There are monumental challenges to deep drilling on Mars. The biggest challenge is facing the fact that we know so little about the SPLD. It may be extremely difficult to bore a long, straight, and stable hole in such a stratified and varied substrate. Rocks and cobbles may be present (and are unlikely to be located from orbital remote sensing), so ways to deal with such obstructions will be evaluated. Mitigation strategies to keep the borehole straight and stable will be evaluated, as well as ways to maintain the borehole as time goes on. Careful use of accelerometers and drive system "steering" may help bore a straight-and-true hole in the first place, but maintenance may be necessary (like honing the hole every few trips) and will be considered. Many of these topics will need to be addressed more thoroughly in a future study, and drilling properties analyzed experimentally. This is outside of the scope of this proposal and may not be possible today given our current understanding of SPLD processes and stratigraphy.

Table 1 - Other Potential Challenges		
CO_2 ice buildup	Borehole collapse	Cores fall to pieces/dust
Borebot malfunction in bore	Unexpected ice composition	Robot arm fails
Borebot communications lost	Drilling too slow or jams	Motors (rover/borebot) freeze

With regards to energy usage, a three kilometer down-and-back round trip at 1500 mm/min would take about 34 hours. If the borebot motors consumed more energy than expected during this timeframe, the battery capacity could easily be exceeded. A modest drivetrain power draw of 0.5 A at 12 V could use 735 kJ during this period, which would require more than 16 Li-Ion 18650 cells. This would warrant the use of three battery packs of seven cells each (to use space most effectively), bringing the total battery mass to around 1 kg. This demonstrates how important the motor selection and drivetrain design will be. Any inefficiencies present must be recognized and accounted for, so a suitable battery pack can be worked into the design. A large battery pack, heavy geared motors, and a steel drill head; combined with aluminum casing for the fluted core drill and borebot body, could result in a mass of 10 kg for each unit (measuring up to 1 m long). Twelve borebots would weigh approximately 120 kg and take up a considerable volume in the rover. The large drill rig rover would be lighter than Curiosity or Perseverance – even if the borebots are heavier than anticipated – due to the large storage volume they consume, thereby offering less room for far heavier science payloads. Therefore, increasing borebot mass primarily threatens borebot efficiency and can threaten mission goals even if launch mass is less than similarly-sized rovers. Strategies to mitigate and prevent excessive borebot mass will be evaluated.

Another challenge the mission would face is maintaining the integrity of samples, including samples that will be processed and analyzed in re-used sample containers. The first use of each container would provide the only results known to be free of contamination, but containers and sample processing equipment could be cleaned to increase confidence in follow-on samples. Perchlorate exposure could also be a challenge to sample-processing hardware. Strategies to mitigate these sample-processing challenges will be evaluated. Evaluation of these challenges, as well as the challenges listed in Table 1, will help to answer the question of whether it is reasonable to proceed with the proposed mission concept and the borebot drilling strategy.

Work Plan

Evaluate concept feasibility: We will evaluate the fundamentals of the borebot architecture as incorporated into a large rover drilling mission to the Mars SPLD. Previously discussed challenges and as-yet-unknown challenges will be evaluated in the course of this work, unless listed in another section of the work plan below. Challenges will be considered carefully, and mitigation strategies evaluated. Alternative approaches will be evaluated, including careful consideration of the ESA's ExoMars Drill, Honeybee Robotics Planetary Deep Drill, and other Honeybee Robotics drilling systems. Other alternative approaches that will be evaluated include (but are not limited to) the following: the Mars Technology Program Coring and Abrading Tool, the ATK Space Deep Drill, the Mars/Arctic Deep Drill, the Raytheon/NASA Johnson Space Center Autonomous Tethered Corer, and the Insight lander Heat Flow and Physical Properties Package (HP^3) mole drill. An attempt will also be made to compare this approach to a large and diverse class of drills called thermal drills, although the energy usage required by such drills likely prohibits their use, and they may not be able to penetrate dust layers of any considerable thickness. The feasibility of the borebot concept will be compared and contrasted with the feasibility of these alternative approaches. The criteria for comparison will focus on the following: energy usage, adaptability to autonomous operations, ability to retrieve scientifically-valuable samples, mechanical resilience, and overall viability in the context of SPLD autonomous deep drilling.

Assess science instrumentation relevant to ice core analysis: The immediate value of collected cores can only be realized if the sample can be properly analyzed and the information sent back to Earth. For these reasons, a survey of relevant science instrumentation will be conducted, and if no adequate instruments exist, a recommendation for future development will be made. Most flight hardware has focused on analyzing powdered rock, or water-bearing minerals. This work will evaluate the possible adaptation of proven hardware to water ice and the SPLD strata. Mass, volume, and other integration factors will be considered.

Evaluate strategies to preserve sample integrity: When taking and handling samples in an astrobiology context cleanliness must be maintained (Bar-Cohen, 2009, p. 349). Sample handling systems will be evaluated, with close attention to the Curiosity and Perseverance systems. Strategies to mitigate the challenges of contamination, equipment sterilization, sample processing, caching, and integration with science instruments will be evaluated. It is believed that pristine samples can be extracted from the center of the full-sized cores (Bar-Cohen, 2009, p. 488).

Determine the range of possible borehole travel speeds: Hardware options for the drive system will be evaluated, and a narrower, more firm recommendation for the range of borehole travel speeds will be made. This section of the work plan includes coordinating with NASA and its partners to discuss the properties of a SPLD borehole, including potential simulants.

Evaluate power consumption and power sources: Lessons learned from evaluation of the borehole travel speed can be leveraged to narrow the power consumption estimates for both driving and drilling. This information can be used to create a recommendation for borebot power sources.

Bring concept to TRL 2, outline a path to TRL 3 (if plausible): The borebot drilling system will be critically reviewed, formulated, and documented. This part of the work plan will focus on assisting future mission planners when determining if the concept and architecture align with their mission requirements. If feasibility is shown, a path will be outlined for all of the necessary technology development required to take the concept to TRL 3. If not feasible, this work will outline possible contributions that the concept can make to robotic drilling as a field (for later industry use). This may include Earth-based robotic drilling (Arctic/Antarctic, ocean floor, etc.), or perhaps future ocean world drilling on Callisto, Enceladus, or Europa.

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