LUNAR DRILL DEVELOPMENT. K Zacny[1], G. Paulsen[1], P. Chu[1], [1]Honeybee Robotics, 398 W Washington Blvd, Suite 200, Pasadena, CA 91103, zacny@honeybeerobotics.com,

Introduction: One of the lunar exploration goals is to search and quantify water and other volatiles in lunar regolith. To aid in this task, we developed and tested several drilling systems, as well as formulated low risk sample acquisition and delivery system [1-3].

Drill System: Since the 1990s, Honeybee Robotics has been developing drilling technologies for reaching below one meter depth on various planetary bodies, including Mars and the Moon (Figure 1 and Figure 2). The drilling approaches included rotary, percussive, sonic, and ultrasonic. These approaches were traded against each other in a number of formations. The most promising drilling approach was found to be rotary and percussive. We learned the rotary is most suited in weak formations while rotary-percussive in hard formations. By alternating between rotary and rotary-percussive, it is possible to penetrate formation with a lowest energy (not necessarily lowest power), which translates directly into low heat input into the formation. Keeping formation cold is of paramount importance not only because higher temperatures would drive volatiles away, but also because at higher temperatures, ice could locally melt and refreeze trapping the drill inside a hole.

The latest IceBreaker3 (IB3) rotary-percussive system is the fourth generation rotary-percussive drill. It is almost as powerful as previous versions (IB2, IB1, and CRUX) but substantially lighter. The ~150 Watt rotary actuator can rotate the drill at approx. 150 rpm while maintain a torque of up to 10 Nm if necessary. The ~150 Watt percussive actuator delivers 2.5 Joules per blow at approximately 1600 blows per minute. The IB3 drill is at TRL 5/6 and weighs approximately 10 kg.

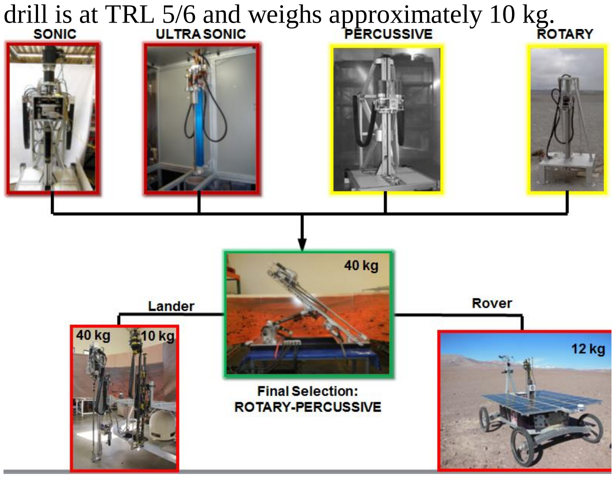

Figure 1. Progression of 1 m class drill technology.

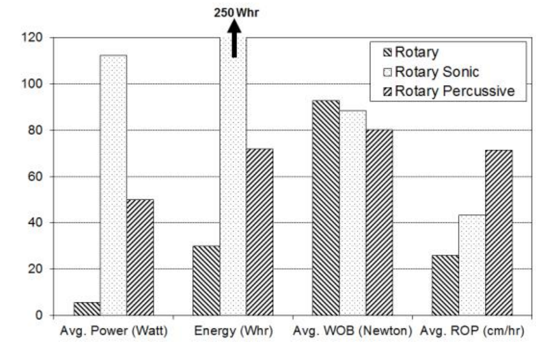

Figure 2. Drill technology trades.

Sample Capture: There are a number of approaches to the subsurface exploration. Figure 3 trades these against system complexity and scientific return. It can be seen that in general, a more scientifically desirable sample requires more complex sample acquisition system. For example, obtaining subsurface temperature data requires a drill to have a small temperature sensor integrated in its bit. Upon reaching the target depth, the drill could be left in place. On the other hand, capturing a core requires the drill system with integrated core break off, retention, and positive core ejection mechanisms – all these need to be integrated inside a slim drill string and kept warm.

The IB3 drill is a compromise between engineering complexity and science return; it captures cuttings rather than the core and measures subsurface temperature, while keeping mission risk relatively low.In fact, this approach greatly simplifies sample handling and the drill itself. Sample, in the form of cuttings, is captured within the deep flutes of a lower section of the auger, just above the drill bit.

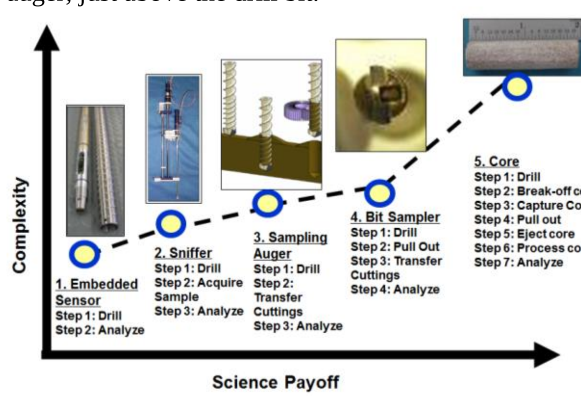

Figure 3. Approaches to subsurface investigation.

The sampling uses the 'bite' approach. After drilling a 10 cm interval and capturing sample on the deep auger flutes, the drill is pulled out and sample is transferred into an instrument (Figure 4). Therefore, while the sample is being analyzed by instruments, the drill is in a safe position above the ground, while the subsurface is allowed to cool. To capture next sample, the drill is reinserted into the same hole and after reaching hole bottom, it drills next 10 cm and captures the sample. This method allows preservation of stratigraphy in 10 cm intervals.

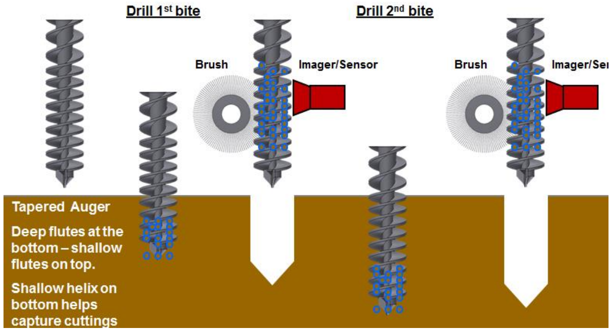

Figure 4. Bite Sampling.

Sample Transfer: In general, there are at least three ways to deliver a sample. In the first approach, a dedicated scoop could be lowered by the drill and capture samples as they come up the auger. This, however, requires deployment of a robotic arm. In the second approach, the drill can deposit sample into a gas chamber, and the sample could then be pneumatically transferred to an instrument (Figure 5). This approach is well suited to architectures where an instrument is relatively far from the drill. However, it requires gas tank and valves. Compressed gas is also viewed as consumable and in turn, the system can be designed for set number of transfers. An advantage of a pneumatic system, though, is that transfer path to an instrument could be cleaned with a puff of gas. This is the best approach in reducing cross contamination between samples.

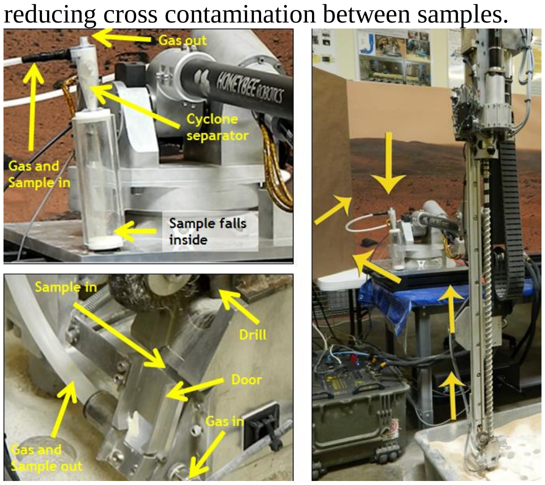

Figure 5. Pneumatic Sample Delivery.

In the third approach, an entire drill could be lifted and positioned above the drop off point. This approach does not need any additional hardware but it requires addition operational complexity due to drill movement and re-positioning.

Extra Science: The drill could also serve as a 'science' instrument. The telemetry can be used to assess strength of the formation and identify ice lenses, for example. The bit temperature can be used to plot thermal gradient and, potentially, determine heat flow property of the Moon. Figure 6 shows an example of drilling telemetry in ice cemented ground in Antarctica. Initially, the drilling power was low because the drill penetrated dry sand (desert pavement). Below 220 mm depth, the drill encountered ice cemented ground which triggered percussion (percussion is required to maintain penetration rate while keeping Weight on Bit below 100 N). In addition, the penetration rate dropped since icy soil formation is stronger, and temperature of the bit increased because more energy was put into the stronger formation by the drill. Figure 7 shows the Antarctic drill site. Note the insert showing ice-saturated cuttings which flow like dry sand, if kept frozen.

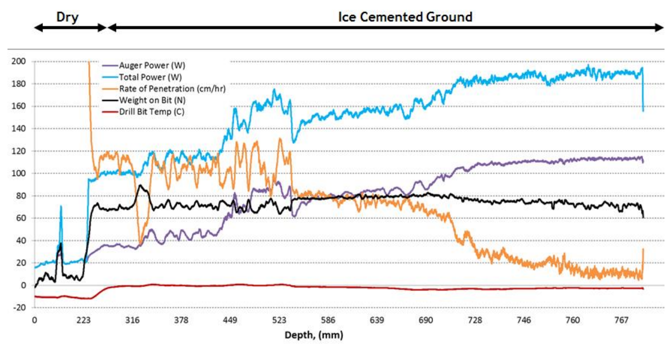

Figure 6. Drilling telemetry in ice cemented ground.

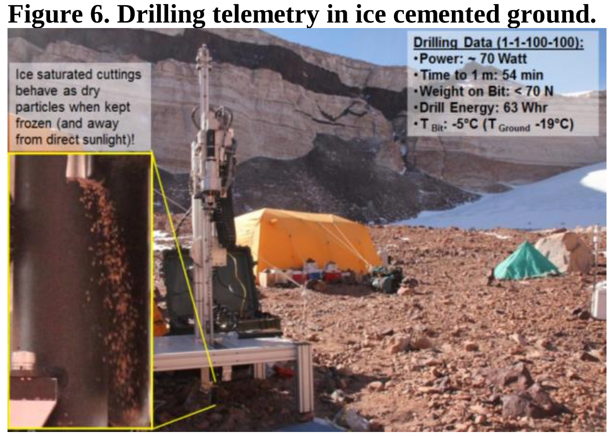

Figure 7. Drilling in ice cemented ground in Antarctica.

References: [1] Zacny et al., (2013), Reaching 1 m Deep on Mars: The Icebreaker Drill, Astrobiology. December 2013, 13(12): 1166-1198. [2] Zacny et al., (2013), LunarVader: Development and Testing of a Lunar Drill in a Vacuum Chamber and in the Lunar Analog Site of the Antarctica. J. Aerosp. Eng. [3] https://www.youtube.com/watch?v=fTNPokiXa0E, and https://www.youtube.com/watch?v=QE7aYUnAA9o