AUTOMATED 3-METER-CLASS MARS DRILL PROTOTYPES.
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Abstract: Exploring and interrogating the shallow subsurface of Mars from the surface will require some form of excavation and penetration, with drilling being the most mature approach. A series of 0.5-5m automated rotary and rotary-percussive drills developed over the past decade by NASA and industry provide a TRL 6 capability that could fly on a Mars surface mission within the next decade.

Introduction: For sample return and in situ Mars surface missions, delving past the near-surface ice layers on Mars in search of organics and possibly signs of past/extant life will require lightweight, low-mass planetary drilling and sample handling. Unlike terrestrial drills, these exploration drills must work dry (without drilling muds or lubricants), blind (no prior local or regional seismic or other surveys), and light (very low downward force or weight on bit, and perhaps 100W available from solar power). Given the lightspeed transmission delays to Mars, an exploratory planetary drill cannot be controlled directly from Earth. Drills that penetrate deeper than a few cm are likely to get stuck if operated open-loop (the MSL drill only goes 5cm, and the MER RATs 5mm by comparison), so some form of local drill control is required. In the relatively near-term (prior to 2030), human crews cannot be presumed to be available for surface instrument teleoperation in the vicinity of Mars. Therefore highly automated drill and sample-transfer operations will be required, to explore the shallow Martian subsurface with the ability to safe the robotic drilling system and recover and continue on from the most probable fault conditions. [1]

Planetary Sampling Drill Concepts: Several past NASA-sponsored development efforts have attempted to test different aspects of automated drilling. The Mars Analog Rio Tinto Experiment (MARTE) went to a biological analog site with a local anaerobic ecosystem, to test life-detection instruments fed by a multi-string drill with automated string changeout, sample core extraction, handling and curation. It demonstrated fully automated topside operations, but all drilling was human-supervised in the field [2]. The Drilling Automation for Mars Exploration (DAME) project conversely went to an Arctic impact crater site (Haughton Crater) to develop and test fully automated drilling, including fault detection, recovery and resumption of drilling, without human intervention [3]. Put together, MARTE and DAME demonstrated end-to-end the automation necessary for a drilling mission beyond the Moon, with conventional rotary-drag drills.

However, given the presence of likely basaltic rocks and ice on Mars, rotary-percussive drills make more efficient headway and are faster than rotary-drag designs, at the cost of more complexity and the shock-loading of drill system components [4]. The Construction and Resource Utilization Explorer (CRUX) drill is a rotary-percussive prototype drill design that was tested with hands-off fully-automated controls, also at the Haughton Crater analog site and in Mars chamber tests, in 2009-10. The most recent generation of Mars-prototype robotic drills is the Icebreaker rotary-percussive drill (Figure 1, see separate McKay abstract on mission concept). Icebreaker has drilled through layers of frozen impact breccia in Haughton Crater field tests, through hard volcanic rocks in Antarctica, and in 2011 Mars chamber tests it was demonstrated to drill 1m/sol into perchlorate-laced regolith simulant sandwiched with clear ice layers.

Figure 1. Icebreaker Mars-prototype rotary-percussive drill, in automated Mars chamber tests in Sept. 2011.

Capabilities: Icebreaker operates under 100W power and at low downward forces (<100N). It was tested in the Dry Valleys of Antarctica (manual control) in December 2010, then with initial software automation at Haughton Crater in July 2011, followed by Mars chamber tests (with a sample transfer arm) in September 2011. It is considered to be at TRL 6.

Drilling Operations Concept Development: Past operations with planetary prototype drills had focused on automating the operation of conventional rotary-drag drill designs (DAME, MARTE). Mars chamber tests with the CRUX drill in 2007-08 indicated that a rotary-percussive design might demonstrate efficiencies in breaking through ice lenses and avoiding jams in hard materials, by comparison with the rotary-drag designs. Analog-site field tests and Mars chamber tests were used to reduce the operational risks, increase TRL, and improve our knowledge of the performance and durability of 1-5m class drills under Marslike conditions. Use of a rotary-percussive drill design in a future Mars polar mission (Icebreaker proposal for Discovery) also has required more technical maturity and test experience, as well as operations of both the drill and its software controls in relevant environments.

Fig. 2. The CRUX drill, in automated drilling recovery operations tests at Haughton Crater in July 2009.

Field Tests: Objectives for Haughton Crater tests in 2009-11 were to test the CRUX and then Icebreaker drills respectively in frozen impact breccia; to meet or exceed the maximum depth drilled by earlier rotary-drag designs (3.2m); to demonstrate the expected fault modes of these drills, for use in failure detection and automated control; and to compare the required energy and downward forces needed to make headway, compared with other drill designs at the same location.

The Haughton Crater planetary-analog drilling site is a high-fidelity analog for Mars landing sites with subsurface ice (as at the Martian higher latitudes) and the broken, depth-graded textures similar to impact regolith. However, the seasonal active layer in the Arctic is not an observed Mars characteristic, so the Icebreaker drill was also tested in Antarctica (McMurdo Station, and University Valley) in December 2010.

Results: The CRUX drill was tested at the Haughton crater site in 2009 and 2010 (Figure 2). CRUX considerably exceeded in total depth drilled all past prototype planetary drills tested at the Haughton Crater analog site, reaching 8.2m cumulatively over six boreholes drilled. Five primary drill hardware faults were encountered naturally in the course of drilling. On the next-to-last day, cold water was added to the borehole (past the permafrost layer), and covered and left overnight to intentionally freeze the drill. When the CRUX drill was next activated, the percussive action and software recovery algorithms quickly freed it from its encapsulated ice and enabling shaft rotation and further drilling. CRUX's larger motors, more-massive (50mm diam.) shaft and ability to apply up to 2000N downward force enabled it to punch easily through clear-ice layers, breccia, and hard rocks (gneisses), and it would be a good prototype for a heavy-lander-mounted drill, such as is proposed for the "Red Dragon" mission concept (see separate Karcz abstract).

However, for a Phoenix-sized lander platform, the lighter, less-powerful Icebreaker drill is capable of drilling 1-3m within the stowage and power and biobarrier constraints of that size mission (re: Discovery proposal). Icebreaker was tested under manual control in Antarctica in late 2010 as an initial shakedown. Drill control automation was integrated and tested successfully with Icebreaker at Haughton Crater in the summer of 2011. Figure 3 shows the successful detection, recovery, and resumption of drilling by the Icebreaker during an episode of downhole jamming.

Conclusions: The improved performance of the rotary-percussive designs (CRUX, Icebreaker) justifies their additional design complexity over simpler rotary-drag drills, and their ability to match or exceed the performance of other planetary drill designs under difficult analog-site extremes and in Mars chamber testing indicates that their maturity level is suitable for consideration in near-term planetary surface mission proposals.

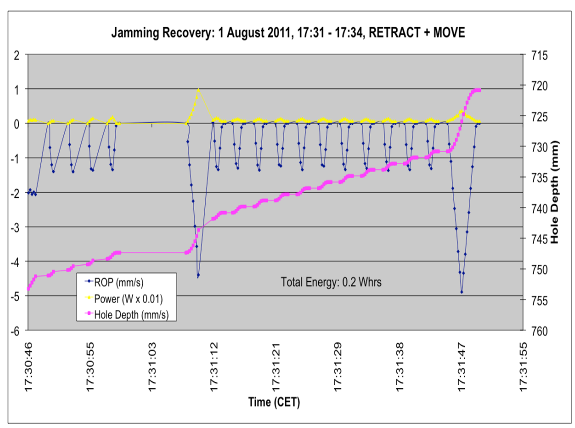

Fig. 3. Automated detection and recovery of a downhole jam by Icebreaker software, in 2011 field test.

References: [1] Glass, B. et al. (2006) *LPSC XXXVII*, Abstract 2300. [2] Stoker, C. et al. (2008) Astrobiololgy DOI:10.1089/ast.2007.0217 [3] Glass, B. et al, (2008) *Astrobiology.* [4] Zacny, K., et al, (2009) *LPSC XLI.*