ROBOTICS AND AUTOMATION FOR "ICEBREAKER"

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ABSTRACT

The proposed "Icebreaker" mission is a return to the Mars polar latitudes first visited by the Phoenix mission in 2007-08. 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 Ames and Honeybee Robotics provide a capability that could fly on a Mars surface mission within the next decade. Surface robotics have been integrated for sample transfer to deck instruments, and the Icebreaker sample acquisition system has been tested successfully in Mars chambers and analog field sites to depths between 1-3m.

1. INTRODUCTION

Looking for organics and signs of past or extant life on Mars will require the ability to search beneath the surface where biomarkers are protected from harmful UV radiation and harsh surface chemicals such as perchlorates [1]. The only potential indication of life on Mars previously was one of the four Labeled Release experiments of Viking in 1976—it happened to be the only sample collected from under a rock [2]. Hence, life-detection missions will incorporate a drill capable of breaking through up to one meter of ice layers that were a barrier to the Phoenix scoop. Given lightspeed delays, teleoperation of a drill on Mars is not feasible and hence drilling placement and control, both nominal and in fault modes, must be fully automated. A spacecraft intended to drill on Mars must also be capable of hands-off operation for hours at a time without human oversight or control, as by the time Earth learns of a drilling problem, the drill will be at least several minutes to hours further along and possibly stuck [3].

Lander or rover missions that are specifically investigating potential Martian life will be COSPAR Category IVc missions. As with the Robotic Arm and Icy Soil Acquisition Device (ISAD) on Mars Phoenix, planetary protection requires that the part of any drill extending below the ground be dry heat sterilized following the Viking protocol. The current approach is to heat-sterilize the components that will either be placed below the ground or be in contact with the components that will penetrate below the ground, and place these inside a biobarrier. To prevent spores from traveling onto the drill auger/bit via sample transfer, there must be an air gap between the sterilized drill and a less-sterilized robotic sample delivery subsystem that could contact the "dirty" spacecraft instruments (which will not be heat sterilized to Viking standards).

Since 2006, NASA has developed a Discovery-class mission concept, called "Icebreaker" (Fig. 1), which is a Lockheed-Martin (Phoenix-derived) Mars polar lander with life and organics detection instruments and a 1m sampling drill [4]. The Icebreaker science payload has since 2010 also been the baseline science payload for developing a joint NASA-commercial Mars astrobiology mission concept with Space Exploration Technologies Corp. (SpaceX) called "Red Dragon," (Fig. 2), using a largely-unmodified version of the crewed future SpaceX commercial Dragon spacecraft.

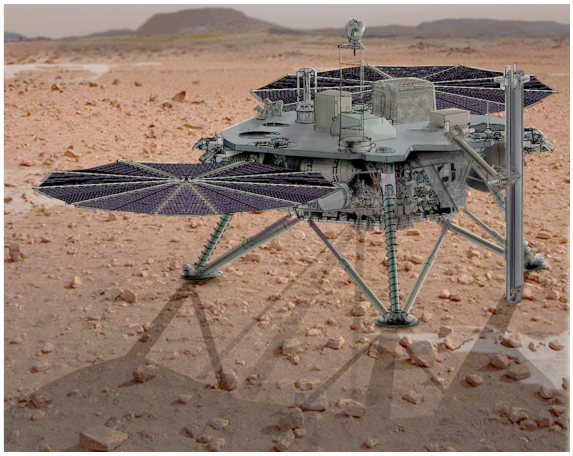

Figure 1. Concept of "Icebreaker" Phoenix-derived polar drilling lander

Automated sample delivery while maintaining sterile/nonsterile separations from a drill is an issue that must be addressed before astrobiology missions can penetrate Category IVb areas on Mars. We have developed prototypes and tested an approach using a robotic system for retrieving and conveying drill or scoop samples to instruments, without drill contact. Testing in 2006–2011 demonstrated these prototypes in the field and Mars chamber tests, showing automated hands-off operations.

The Icebreaker rotary-percussive flight-prototype drill has been developed by NASA Ames and Honeybee Robotics, following on a series of earlier prototype drills – DAME, MARTE, and the CRUX rotary-percussive drills (Figs. 3-5). Icebreaker's performance in permafrost in field conditions meets the design constraints and requirements for the subsequent Icebreaker and/or Red Dragon flight drills. Through Mars chamber and field tests in relevant analog environments, NASA and Honeybee have increased the technical maturity of planetary drilling, improved the potential astrobiology science quality (through mitigation of sample contamination) and reduced planetary-protection mission risks in Category IVc areas to acceptable levels [5,6].

2. MARS SURFACE DRILLING

The proposed "Icebreaker" mission is a return to the Mars polar latitudes first visited by the Phoenix mission in 2007-08. Given the hard icy layers and perchlorates found there, Icebreaker (Fig. 1) is based on the Lockheed-Martin Phoenix spacecraft bus but would carry an automated 1 meter rotary-percussive drill, the Signs Of Life Detection (SOLID) instrument (Spain) [7], the Alpha Particle X-Ray Spectrometer (APXS, Canada), and a non-pyrolytic Wet Chemistry Lab (WCL, JPL) [1] capable of detecting organics in the presence of perchlorates. Downhole materials would be captured in the bottom 10cm of the drill string and raised to the surface where they would be mechanically removed and robotically transferred to the on-deck instruments. This spacecraft architecture is flight-proven and could be ready for a 2018 mission opportunity.

Figure 2. "Red Dragon" concept for a Dragon-based low-cost Mars science lander. [SpaceX]

The unique aspects of the Red Dragon mission concept (using a Dragon capsule as a Mars lander, fixed price including launcher, and an order of magnitude greater volume and payload mass to the surface of Mars, compared to Phoenix) would allow much larger payload mass and volume budgets than a Phoenix-based mission. Additional instruments, more instrument consumables, and winter survivability are possible benefits. Another benefit could be the integration of Icebreaker's astrobiology science payload, including its drill and sample transfer system, with an in-situ resource utilization (ISRU) module that could be fitted in the normally-pressurized internal capsule volume. This also reduces specimen wastage, as the Icebreaker drill generates about 100g per 10cm drilled, but current instruments only require about 5-10g of sample, so the bulk excess specimen could become ISRU feedstock specimens.

The joint ESA-Roscosmos ExoMars rover will search for organic componds that could have derived from any past and extant near-surface life on Mars beginning in 2018, using a 2 meter multi-string drill developed by Galileo Selex in Italy. This coring drill will deliver 1x3 cm core samples to a rover payload module that includes laser desorption, infrared imaging and Raman spectrometers. It will also incorporate a small infrared imaging spectrometer inside the drill for in-situ borehole measurements. The multi-string

Figure 3. DAME Drill

Figure 4. MARTE Drill

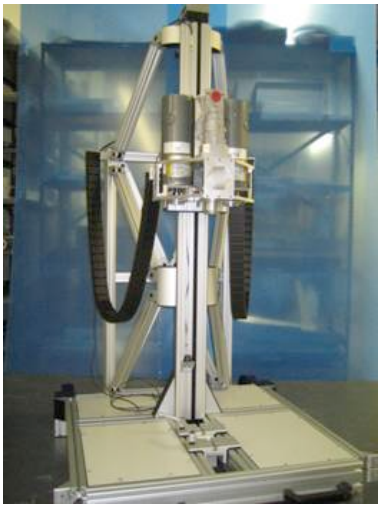

Figure 5. CRUX Drill

drill will operate autonomously, including drillstring changes. ExoMars is not exploring a region known for water, hence its probability of detecting any extant biota is limited, whereas its probability of detecting the remnants of ancient biota is better

For future sample return and *in situ* Mars surface missions, delving past the near-surface ice layers on Mars in search of organics and possible 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 no more than 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 penetrates 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. [8]

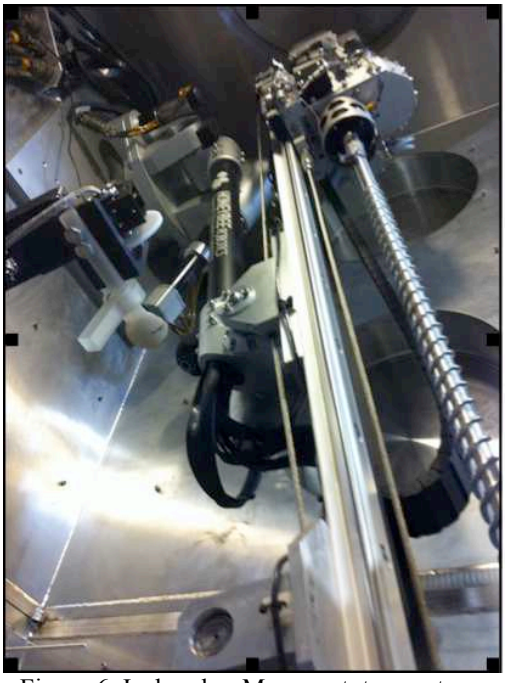

Figure 6. Icebreaker Mars-prototype rotary-percussive drill, in automated tests in a Mars chamber tests in Sept. 2011.

3. AUTOMATION AND SAMPLE TRANSFER ROBOTICS

3.1 Icebreaker Drill

The most recent generation of Mars-prototype robotic drills is the Icebreaker rotary-percussive drill (Figs. 6,7). Icebreaker has drilled through layers of frozen impact breccia in Haughton Crater (Devon Island, Canada) field tests, through hard volcanic rocks and ice-cemented ground 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.

The Icebreaker drill operates under 100W power and at low downward forces (<100N). It was tested in the Dry Valleys of Antarctica (under 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.

The Icebreaker flight-prototype drill (Fig. 6) is designed to be a flight-like prototype capable of rotary-percussive drilling in a vacuum, which is necessary to test cuttings adhesion under Mars conditions.

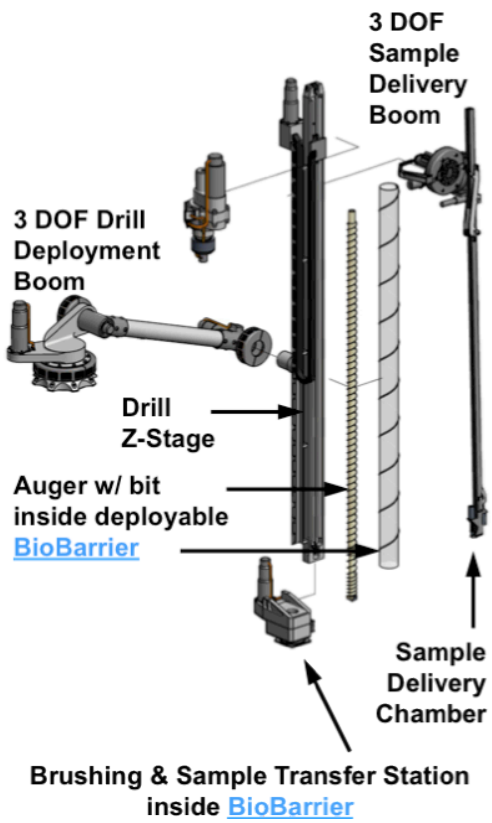

Figure 7. Components of Icebreaker drill system.

This new flight-prototype drill, given possible Mars polar lander missions, uses three different drilling modes: rotary, rotary percussive and percussive. Decoupling the percussive and rotary actuators (Fig. 7) means that the frequency of percussive impact (indexing) can be varied. The drill has a total linear stroke of 1 meter. Its rotary and percussive actuators are 200 W each to allow for margins and maximum weight on bit (force pushing the drill down) is limited to 100N to simulate drill deployment from a lightweight platform in low Martian gravity. To control the weight on bit during the drilling process, a load cell is axially aligned with the drill segment to provide accurate feedback of drilling loads to the control system. An embedded temperature sensor provides data on downhole temperatures near the bit.

3.2 Drill Automation Software

The Icebreaker drill control software was ported from the CRUX rotary-percussive drill software, which in turn follows the structure that was used by the DAME drill [7], but is a ground-up rewrite aimed at allowing the code to run on flight hardware. Though the DAME code was very flexible, it ran on a network of laptop computers running a combination of Linux and Microsoft Windows, so a different approach was necessary in order to fit within the memory and CPU limitations of contemporary flight computers.

The drill control system consists of the following subsystems, as shown in Fig. 8:

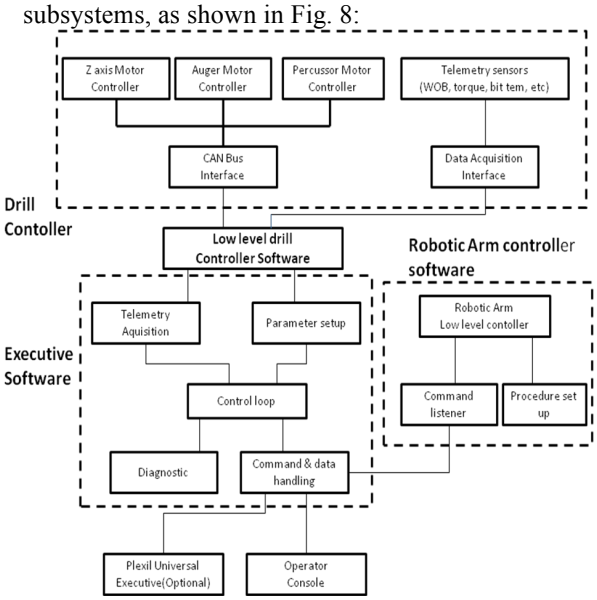

Figure 8. Drill Software Architecture

Z axis motor controller. This is a Controller Area Network (CAN) Bus device that integrates low level control and monitoring functions for the vertical (Z) axis, including position feedback sensors.

Auger motor controller. Also CAN Bus based, the auger motor controller is responsible for rotation of the drill string and for position (angle), RPM and torque telemetry.

Percussor motor controller. The percussor motor drives the hammer device that is key to the drill's ability to achieve rapid penetration efficiently and with low weight on bit. The controller is also CAN Bus based, and provides confirmation feedback that the percussor is operating correctly.

Telemetry Sensors. These sensors are primarily integrated down-hole at the bit, and provide useful telemetry that, in addition to the telemetry gathered from the motor controllers, allows the diagnostic subsystems to identify faults.

Low – level drill controller. This integrates connectivity to the CAN Bus and the telemetry sensors and also implements some of the low-level control necessary to maintain intended levels of torque, penetration and weight on bit during drilling.

Drill executive. This subsystem implements the higher level control and diagnostics that are necessary to allow Icebreaker to operate autonomously. The diagnostic subsystems monitor the telemetry feed and raise exceptions when faults are detected, which causes the main control loop to alter its behavior in response. Command and data handling provides external interfacing via TCP/IP that allows the executive to be controlled by a higher-level executive such as the PLEXIL Universal Executive, and for an operator console interface to be provided. In a flight version of the executive, the command and data handling subsystem would interface to the spacecraft's communications subsystem, allowing commands to be sent from Earth and data to be returned.

Fault detection and recovery. The diagnostic subsystem contains system health monitoring capabilities that monitor drilling status, detect faults, and run recovery procedures. The diagnostic subsystems monitor the telemetry feed and raise exceptions when faults are detected, which causes the main control loop to alter its behavior in response. Then the system will enter fault recovery mode. After a successful recovery, the system can resume drilling operations.

3.3 Sample Handling Surface Robotics

As with the Phoenix arm and scoop, for Icebreaker and other future planetary sampling missions the components that will penetrate below the ground will be heat-sterilized before launch and placed inside a biobarrier. To prevent spores from traveling onto the drill auger/bit via sample transfer, there must be an air gap between the sterilized drill and the sample delivery subsystem that itself contacts the "dirty" instruments (which cannot be heat sterilized to Viking standards). At

the same time, clumping and sticking experiences with samples within the Phoenix scoop mean that future Mars sampling missions must have positive actuation, not relying solely on gravity. This complicates the air-gap issue, effectively requiring samples to be actively propelled by some means across the air gap [9].

Icebreaker uses both active and passive scrapers and brushes that can move drill cuttings from the auger/bit assembly into a sample catchment, while not contacting the sample catcher itself with the brushes. A relatively simple four degree of freedom (DOF) manipulator arm moves the samples from the catchment up to the spacecraft deck with input hoppers, and places the samples in them.

The existing Icebreaker prototype sample handling arm (upper left in Fig. 7 above, with scoop) is a lightweight 4 DOF arm with specialized end effectors dedicated to sample transfer. The aim of this prototype is to support chamber testing of various alternative end effector designs. The arm control system comprises a Linux-based graphical user interface that communicates with a microcontroller-based arm interface via USB. The arm itself is powered by servo motors which respond to pulse width modulation signals from the arm interface – two extra servo control channels support the testing of end effectors with up to two actuators. The arm controller supports coordinated multiple axis moves, morphing automatically between control points, making it straightforward, for example, to ensure that a scoop-like end effector will retain correct orientation for the entire duration of a move. The arm is capable of autonomous operation (e.g., in coordination with the drill executive orchestrating the drill subsystem and one or more analysis instruments), and also for testing purposes a user interface is provided to control the arm manually and to develop movement sequences.

A larger flight-like arm in development for Icebreaker will retain the existing arm's 4 degree of freedom geometry, replacing the existing servos with vacuum-rated rotary actuators. Though the low-level control system will be modified to support different motor controllers, higher-level control will most likely not require significant changes. Since the sample handling capacity will match or exceed that of the current prototype, the current Icebreaker end effector designs are reuseable.

The existing arm prototype (Fig. 7) is relatively small, roughly equivalent in geometry to a small human arm (Fig. 10). While this scales well for small Phoenix-sized platforms and medium-sized rovers, a larger SpaceX Red Dragon platform is likely to require a larger arm with up to approximately 2-3 meter reach. The same 4 DOF arm geometry can be straightforwardly scaled up, with more powerful actuators. If a Red Dragon *In Situ* Resource Utilization (ISRU) experiment is also flown that requires greater material input volumes than for instruments, then the end effector designs will be modified (scaled up) appropriately.

A Technical Readiness Level (TRL) 5 sample ejector has been prototyped at NASA Ames [9]. It is designed for working with icy sticky soil, and relies on positive displacement of the sample (a piston/cylinder mechanism) rather than gravity feed. It has been tested in a relevant environment (Honeybee Mars chamber) and is slated for field testing on Devon Island, Canada July-August 2012, along with realistic supporting elements. It was operated within a Mars chamber at Phoenix-site pressure and temperatures. It brought samples produced by the Icebreaker drill in soil and ice mixtures that best represent the Phoenix site to the current prototype SOLID life-detection instrument.

4. FIELD AND CHAMBER TESTS

4.1 Tests at Mars-Analog Sites

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 (3.2 meters); 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.

4.2 Results: Automation and Health Management

The CRUX drill was tested at the Haughton crater site in 2009 and 2010 (Fig. 5). CRUX considerably exceeded in total depth drilled all past prototype planetary drills tested at the Haughton Crater analog site, reaching 8.2 meters 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, 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.

However, for a Phoenix-sized lander platform, the lighter (30mm shaft diameter), less-powerful Icebreaker drill is capable of drilling 1-3 meter within the stowage and power and biobarrier constraints of that size mission. Icebreaker was tested under manual control in Antarctica (near McMurdo Station) in late 2010 as an initial shakedown of the hardware. Drill control automation was integrated and tested successfully with Icebreaker at Haughton Crater in the summer of 2011. Fig. 9 shows an example of the successful detection, recovery, and resumption of drilling by the Icebreaker during an episode of downhole jamming.

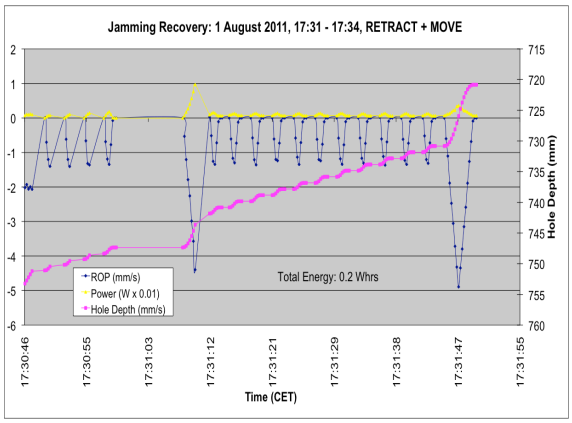

Figure 9. Automated detection and recovery of a downhole jam by Icebreaker software, 2011 field test.

4.3 Instrument and Sample Transfer Integration Tests

Integrated sample-handling and automated drilling tests were performed in September 2011 in a Mars vacuum chamber at Honeybee Robotics (Figs. 7 and 10**).** This chamber is a box-shape, approximately 1m x 1m at the base and 3.5 m high and allows drilling to 1m depth under Mars-like conditions of low temperature, pressure and atmosphere. It can reach Martian atmospheric conditions (~4 torr) in 15 minutes. The chamber is instrumented with relative humidity sensors, temperature sensors and a pressure sensor. Pressure is maintained to 0.1 torr accuracy.

Sample cooling to cryogenic temperatures was achieved using liquid nitrogen. A separate closed loop cooling system also allowed longer-term sample steady-state cooling at -30C, allowing testing within a range of Mars surface temperatures. Large chamber windows allowed easy direct viewing of the drilling and/or digging progress. Test samples included 2% perchlorates and some samples seeded with biomarkers, which were acquired and transferred and detected successfully by the SOLID instrument.

5. CONCLUSIONS/FUTURE WORK

Field and chamber tests in Mars-relevant environments have shown that the maturity of automated drilling and robotic surface sample transfer are sufficient to merit consideration for Icebreaker and Icebreaker-like (*viz*., Red Dragon) in the 2018-2022 timeframe. These components have been integrated to create a subsurface sample-acquisition capability that has been demonstrated in

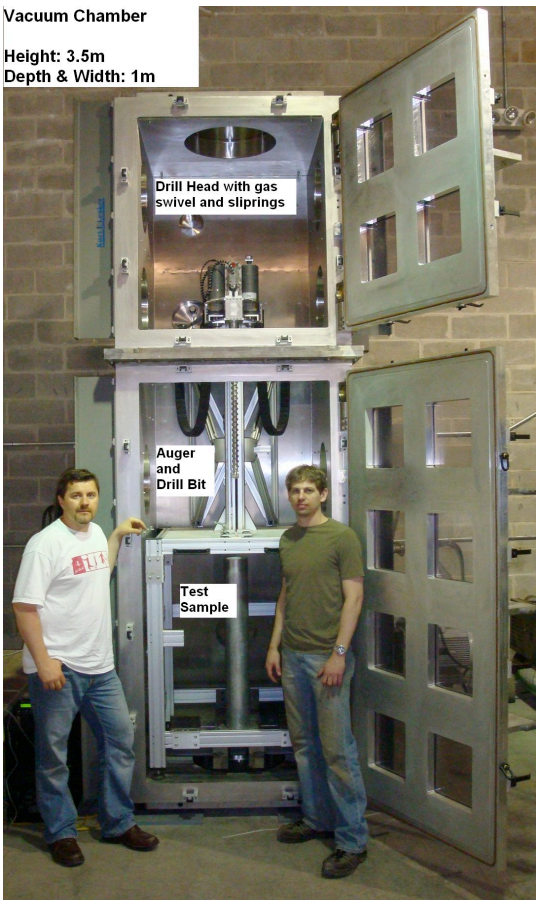

Figure 10. Honeybee Mars environmental chamber in Pasadena, used for 1m drilling and sample transfer testing.

initial Mars chamber tests. The improved performance of the automated rotary-percussive drill 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. Tests in 2012-2013 will demonstrate that the Icebreaker integrated subsurface sample acquisition system is capable in Mars-analog field test environments in Arctic Canada (Haughton Crater) and Antarctica (Dry Valleys). Future work in robotic space drilling will look at the integration of 5m-class drills with MSL-class (1 ton) rovers, with planetary-protection issues, and with support for sample caching for Earth sample return missions.

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