Robotic Planetary Drill Tests

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Abstract

Several proposed or planned planetary science missions to Mars and other Solar System bodies over the next decade require subsurface access by drilling. This paper discusses the problems of remote robotic drilling, an automation and control architecture based loosely on observed human behaviors in drilling on Earth, and an overview of robotic drilling field test results using this architecture since 2005. Both rotary-drag and rotary-percussive drills are targeted. A hybrid diagnostic approach incorporates heuristics, model-based reasoning and vibration monitoring with neural nets. Ongoing work leads to flight-ready drilling software.

1 Introduction

Sample return missions from Mars or from comets and asteroids, and delving past the surface ice layers on Mars in search of organics and possibly life, will require lightweight, low-mass planetary drilling and sample handling. Unlike terrestrial drills, these future exploration drills will work dry (without drilling muds or lubricants), blind (no prior local or regional seismic or other surveys), and weak (very low downward force or weight on bit, especially on small bodies, and perhaps 100W available) Given the lightspeed transmission delays to Mars, Europa, and even most Near Earth Objects (NEOs) accessible from Earth, an exploratory planetary drill cannot be controlled directly from Earth. Therefore highly automated operations will be necessary, with the ability to safe the drilling system and recover from the most probable fault conditions. [1]

On the Moon or Mars, eventual in-situ resource utilization (ISRU) will require deep drilling with probable human-supervised operation [2] of large-bore drills, but initial lunar subsurface exploration and near-term ISRU will be accomplished with lightweight, rover-deployable or standalone drills capable of penetrating up to 1-2m in depth.

The proposed Discovery/Scout-class "Icebreaker" mission would use an automated rotary-percussive drill to reach and retrieve samples from up to 1.2m deep in the ground ice at northern Mars latitudes (similar to the 2007
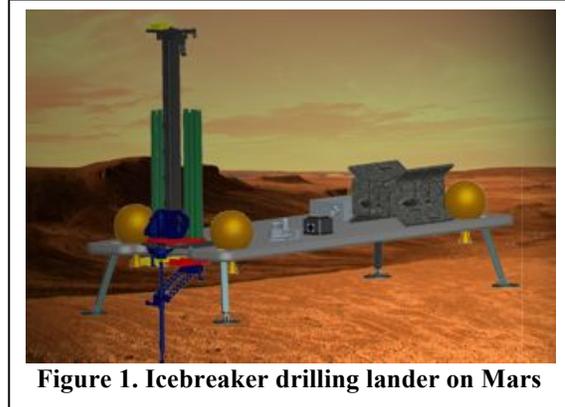

Figure 1. Icebreaker drilling lander on Mars

Phoenix landing site). Samples will be assayed by a suite of instruments. The Spanish SOLID3 instrument would perform life and biomarker detection. Chemical analysis of organics, habitability and hazards would be assessed by several instruments from JPL, APL and Canada. The Icebreaker lander (Figure 1) will fly to the region of near-surface ice and perform a propulsive soft landing similar to Phoenix. An automated drill would be deployed to test the Mars regolith properties while bringing up icy samples for organics, chemical, and biomarker analysis.

One of the concepts also being proposed for the next decade is the "MAX-C" or similar Athena-class rover carrying a small coring drill. Pencil-sized near-surface cores would be acquired and curated by the MAX-C in a small sample storage canister, left behind on the surface of Mars for a later sample return mission to hopefully retrieve. To the extent that the primary goal of MAX-C or other surface rovers (such as ExoMars) requires drilling, drilling becomes mission-critical and getting the drill stuck early in a mission could cause the loss of most science objectives. Automated, robust drill controls and onboard drill health management would lower those risks.

Several past NASA-sponsored development efforts have attempted to test different aspects of automated drilling. The Mars Astrobiology 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 change-out, sample core extraction, handling and curation. It demonstrated fully automated topside operations, but high-level drilling control was human-directed. [2] The Drilling Automation for Mars Exploration (DAME) project conversely went to an Arctic impact crater site (Haughton Crater) to develop and test fully hands-off 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. Figure 2 shows the DAME drill being tested at Haughton Crater.

However, given the presence of likely basaltic rocks and ice at the lunar north and south pole and on Mars, rotary-percussive drills make more efficient headway and are faster and more robust than rotary-drag designs, at the cost of more mass, power, complexity and the shock-loading of drill system components. They can operate at lower Weight on Bit levels, useful in reduced gravity. [4] Shown in Figure 1, the Construction and Resource Utilization Explorer (CRUX) drill is a rotary-percussive prototype drill that was tested with automated controls, also at the Haughton Crater analog site, in 2009. The Mars Science Laboratory (MSL) drill to be launched in 2011 is a much smaller rotary-percussive drill intended to go 5cm deep into surface rocks and acquire powdered rock.

Figure 3: CRUX rotary-percussive prototype drill

This paper will look at the problems of remote robotic drilling, at one specific approach to drilling automation (the DAME and CRUX architectures), and discuss field test results with these drills and evolving software capabilities over the past few years.

Figure 2. DAME Automated Drilling Tests on Devon Island

2 Problems in Robotic Planetary Drilling

2.1 Lightspeed delays

Given lightspeed delays in communications, and typical time-shared periodic access to the Deep Space Network, a spacecraft intended to drill on Mars, an asteroid, Europa, etc. must be capable of hands-off operation for hours at a time without human oversight or control. Unlike rover navigation problems, most planetary drilling will be blind (absent any precursor-mission seismic imaging of substrates, which is common on Earth prior to drilling for hydrocarbons). Terrestrial human monitoring and tracking of robotic drilling is impractical, as by the time Earth learns of a drilling problem, the drill will be at least several minutes further along and possibly stuck. And drilling conditions change, and the target strata are unknown, and the physical performance and response of the drilling machinery changes with increasing depth. One approach is a simple limit-checking scheme (as used for the Mars Science Laboratory drill) that simply pulls out and safes the drill whenever limits are exceeded – but it is more likely to trip often, then each time wait (possibly hours to days) for human troubleshooting from afar. This is not an efficient use of mission resources or spacecraft life, particularly for holes deeper than the MSL drill's few cm in depth. By using an automated, adaptive drilling controller, that can change forces and speeds in response to changing down-hole conditions, and remediate and continue onward from the most likely faults, drilling is both less likely to fail and more likely to make reliable progress.

2.2 Autonomy vs. Automation

While modern commercial drilling has increased the level of automation used in terrestrial applications, there are somewhat different meanings used for "automation" for space applications than in the oil and gas industry. In the latter, "automation" and "remote control" mean being able to watch values and open/close valves with a mouse-

click in a control room, rather than by sending out a human with a wrench – eliminating direct hand contact other than joysticks and touchscreens [5]. In space, these definitions are more self-contained and imply minimal or no direct human involvement at all, including monitoring and decision-making. So the hands-off automation of DAME and CRUX reflects a qualitative advance over teleoperated commercial drilling operations.

How do humans accomplish drilling? Engineers use a priori analysis of drilling areas (hard to do on Mars) to build models of expected strata and hence drilling environments at varying depths. And use a body of gained experience to assess logs and drilling state values. The drill shaft is a source of tactile and audible feedback, as its vibrations change. So to address drilling automation, we took these same approaches (model-based, heuristic, and vibration perception) as a starting point.

2.3 Spacecraft Integration Issues

Other issues relevant to robotic drilling and excavation include the means for acquiring cores, cuttings or other samples and transferring them to instruments, which are typically mounted on the deck or internal to a surface lander or rover. If precise location of organics or layer boundaries is desired, then cross-contamination between samples becomes an issue as well. Also, downhole imaging and surveying offers primary in-situ science observations, but requires the design of instruments or optics that can operate in a percussive-drill downhole assembly that is space-confined, data-constrained, dirty and with high shock loads.

3 Drilling Automation Architecture

3.1 MARTE/DAME Middleware

The MARTE Instrument Interface (MInI) was a simple and flexible communications package, based on a subset of CORBA, that was originally developed to ease the software development and integration process for MARTE [6,7]. The MARTE project had instruments and control systems developed concurrently across a number of widely separated institutions in Spain, Texas, California, Oklahoma, and New York. All of these pieces needed to be developed independently at the home institutions, but yet come together during a short integration period and communicate across a number of different platforms. MInI was developed in order to facilitate this process [8]. Figure 4 shows the overall MARTE software architecture. This modular, plug-and-play architecture consists of an executive, MInI instrument dispatcher, drill server, diagnosis and instrument client modules, diagnostic user interface, and drill controller. Any of these could be activated or deactivated during operations without a

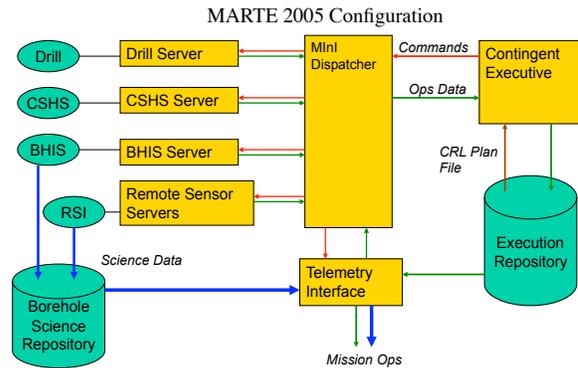system reset, because of the CORBA-derived publish-subscribe middleware layer.

Figure 4. MInI-based Architecture for MARTE [7].

3.2 Health Management Technologies

A single type of non-contact sensor – two laser vibrometers (LDV) -- were used in the DAME project, employing filters to remove rotation-components from the drill motor actuator, interferometry along with real-time Fourier transforms over moving measurement windows. These resulted in identified dynamic characteristics including natural frequencies and mode shapes of the drill shaft, which in turn became inputs to a neural network to perceive and identify different fault conditions.

The DAME model-based reasoning approach was focused on the primary drill failure modes. As a result, the drill model was simplified to only model those components that directly affected predictions for the given failure modes [9,10].

The underlying simulation engine for DAME's model-based diagnostic module is the Hybrid Diagnostic Engine (HyDE), capable of analyzing both discreet and continuous processes. HyDE incorporates into a simulation both the component model of the DAME drill and the modes that these components can assume (both nominal and off-nominal). It also describes what external conditions can cause the components to change from one mode to another. Throughout the drilling process HyDE tracks the evolution of the drill system state, comparing the observed system state to the one predicted by its model-based simulation. If any discrepancies are detected, suspected faulty components or conditions that can explain the abnormal situation are flagged. The results are then passed to the DAME Conditional Executive arbiter, along with the estimated probabilities of each possible cause. HyDE has been developed as a tool for integrated system health management of space systems, including crew and launch vehicles. [11]

3.3 Task Planning and Scheduling

The Contingent Executive was originally developed at NASA Ames Research Center to control planetary rovers.

It was tested extensively onboard NASA Ames' Marsokhod rover and the K9 Rover during numerous field tests occurring between 1999 and 2003 [12,13]. It was modified and used to control the drill, core sample handling and onboard science instruments for MARTE, and the drill and diagnostic and recovery modules for DAME. The Contingent Executive used a task planning and scheduling language known as the Contingent Rover Language (CRL). A CRL plan contains a sequence of tasks to be executed along with temporal and state conditions that must be met before, during, and after each task executes. A CRL plan may also contain branches, which allow different plan segments to be run based upon the conditions that are encountered at run time. The baseline plan is normally executed as specified, but may be interrupted by the insertion or replacement of an alternate plan (i.e. a recovery procedure when an obstacle is encountered or fault occurs).

For example, a baseline DAME drill plan generally contained CRL task commands to move to the bottom of the hole, drill a fixed distance, and then pull up off the bottom and wait in order to take a down-hole measurements. While taking the measurement, the drill was kept spinning at a slow RPM to prevent freeze up. The cycle of drilling and measurement was repeated for a set number of times. This baseline plan was representative of a daily operational plan that could be uploaded to a robotic lunar or Martian drill.

3.4 Parallels with Human Drilling

A drill shaft is a source of tactile and audible feedback, as its vibrations change. Humans compare drill behavior to their past theories or expectations of performance (models), to changes in sound or vibration (perceptive), or to violated sensor limits and alarms. So to address drilling automation, the DAME designers [1] took three parallel approaches (model-based, heuristic, and vibration perception) to detecting drill faults and changes in drilling conditions below.

The DAME approach was to apply three types of automation:

(a) real-time limit-checking and safing;

(b) near-real-time vibration measurement and fast frequency-domain pattern-matching using a neural net; and,

(c) monitoring system state parameters and inferring system state using both rule-based and model based diagnostic techniques.

DAME had one ongoing, natural input source of drill excitation -- the normal rotation of the drill string or the auger tube. A single type of noncontact sensor – two laser vibrometers (LDV) -- were used in DAME, employing speckle interferometry along with with real-time Fourier transforms over moving measurement windows. These resulted in identified natural frequencies and mode shapes of the drill shaft, which in turn became inputs to a neural

network to perceive and identify different drilling and fault conditions.

3.5 PLEXIL Executive

In 2008 the drill planner and executive were reimplemented in a more fault-tolerant set of controls implemented in Plan Execution Interchange Language (PLEXIL). Reimplementation of the prior DAME executive in PLEXIL allowed the control software to use a more expressive plan language than previously, allowing the specification of event driven tasks for fault remediation. The redesigned executive, with new drill-monitoring data displays, was then integrated with the automated monitoring and diagnosis software and then deployed along with the DAME drill for field tests.

3.6 Robustness and Flight Constraints
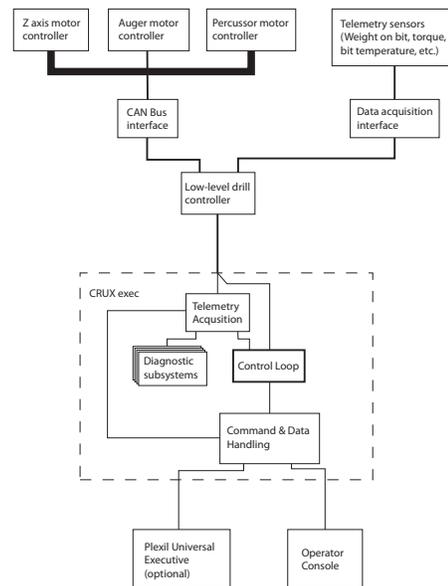
Figure 5. CRUX Drill Software Architecture

The CRUX drill control software roughly follows the structure that was used by the DAME drill, but is a ground-up rewrite aimed at allowing the code to run on flight hardware. Though the DAME code was very flexible and an excellent research platform, 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 CRUX control system consists of the following subsystems, as shown in Fig. 5:

Z axis motor controller. This is a CAN Bus device that integrates low level control and monitoring functions for the 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 CRUX'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.

CRUX executive. This subsystem implements the higher level control and diagnostics that are necessary to allow CRUX 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.

# 4 Test Results

4.1 Initial MARTE tests with humans

MARTE performed a simulation of a Mars drilling mission in September 2005 including interpretation of drill mission results by a remote science team in a blind test. The MARTE lander mockup with a rotary-drag drill (similar to the DAME drill, but including automated string change-out) was placed near the site of a microbiology drilling campaign at Rio Tinto, Spain. Science team participants included members of the planetary geology and astrobiology community. Science teams located in Madrid and at NASA Ames in California commanded the mission operation for two weeks each. During the mission simulation, the drilling achieved a depth of 6 meters into a weathered gossan deposit. Average core recovery was 20% in this unconsolidated material. Borehole inspection imaging and spectroscopic measurements of the hole walls supplemented the incomplete core record. Using the combination of instruments, the science team was able to correctly identify the geologic nature of the site, correctly interpreted the mineralogy, and selected sites for life detection experiments that yielded positive (for life) results. [7]

Surface drilling subsystem automation, through the use of MInI and the Contingent Executive for integration of topside operations, worked very well and helped to streamline operations at the borehole. Initial concerns that adding automation to the project would cause the overall field test to have difficulty reaching its depth target (because of the limited time for integration and system verification) proved groundless. The actual MARTE test operations experience was that the remote command sequences (drilling, sample handling, core processing, science measurements) required literally hundreds of commands to be executed. The drilling and science goals could not have been achieved manually in the limited timeframe. Likewise, by integrating the automation elements with a remote operations infrastructure, the MARTE science team was able to receive timely-enough information to enable them to specify plans for each work day. [9]

4.2 DAME tests at Haughton Crater

The DAME project's purpose was to develop and field-test drilling automation and robotics technologies for projected use in planetary surface missions in the 2016-22 period. [3,8] Figure 2 shows a lightweight, planetary-prototype rotary-drag drill, in DAME summer Arctic field testing. DAME includes control of the drilling hardware, and performed state estimation of both the hardware and the lithography being drilled and the state of the hole. Figure 6 shows fault identification, replanning and recovery of the DAME drill in 2008 field tests. The DAME robotic drilling approach is a
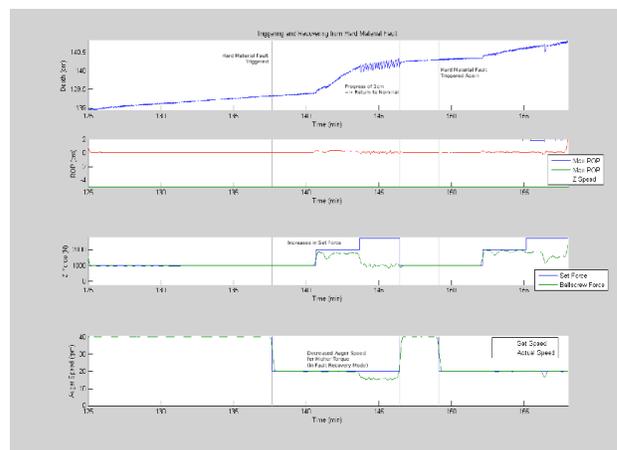
Figure 6. Drill Fault Detection, Response and Recovery from an Ice Lens

hybrid multi-level architecture including both reactive and deliberative components.

DAME field tests in 2004-2008 were conducted in frozen fallback breccia in an impact crater (Haughton Crater) in Arctic Canada. In the summer 2008 DAME tests, five of six known primary drill hardware faults were encountered naturally in the course of drilling, none had to be artificially induced. These drilling faults or state changes (such as encountering layers of ice or harder strata) were correctly identified, corrective actions were taken by the automation software and drill, and the drilling continued. Figure 6 shows the detection and automated response to hard material while drilling, as an example. It shows that the condition was triggered, then recovery actions made enough progress to return to nominal drilling, and then it was triggered again. There are 4 subplots - depth is on top, then there are 3 subplots for the parameters that were controlled by the PLEXIL executive (penetration rate, downward force, and auger rotational speed).

A total of 32 hours of autonomous, hands-off drilling was accomplished over five days in July 2008. And a total depth of 2.76m was reached (a 74cm pilot borehole was used for debugging and parameter adjustments with the new software, followed by a 202cm "production" borehole), into a frozen hydrothermal structure, with cores and cuttings obtained in 25cm sampling intervals.

4.3 DAME Tests at JPL

While field tests in impact crater permafrost are a good planetary drilling analog (and hence a realistic environment to test Mars and lunar drilling automation), it lacks repeatability or precise knowledge of the drilling target. In October 2007, tests at a JPL-developed Mars environment drilling testbed were conducted to provide a rigorous repeatable test of drilling automation, and provided calibration of the testbed by comparison with the past Arctic field testing experience.

In the JPL tests, the existing DAME automation capabilities were extended and demonstrated in a series of controlled, repeatable tests into simulated Mars and lunar regolith columns created confidentially by Space Materials Laboratory staff and presented as a black-box to the drilling test team. Spacecraft-level mass (downward force limits) and power limits (<110W) were maintained. A new subsurface testbed facility at JPL Bldg. 141 was created for the tests. The automation software successfully guided the DAME 48mm auger through 3.3m of hands-off drilling, during 35 hours of automated operations spread over two weeks.

4.4 CRUX tests

Past tests with planetary prototype drills had focused on automation for conventional rotary-drag drill designs. Laboratory tests with the CRUX drill indicated that it might demonstrate efficiencies in breaking through hard ice-soil layers and avoiding jams in hard materials, by comparison with rotary-drag designs. Possible use of a rotary-percussive drill in Icebreaker or a Mars sample return mission required more technical maturity of the CRUX design as well as credible operations of both the drill and its software controls in a relevant environment.

Beginning in 2009, the Astrobiology Rotary-Percussive Automated Drill (ARPAD) project began adapting the DAME models and software for automated operations of a rotary-percussive drill. Shown in Figure 3, the Construction and Resource Utilization Explorer (CRUX) drill is a rotary-percussive prototype drill that has been developed by Honeybee Robotics.

Objectives for the 2009 Haughton Crater tests were therefore to test the CRUX drill in frozen impact breccia; to meet or exceed the maximum depth drilled by earlier designs (3.2m); to demonstrate the expected fault modes of the drill, for use in failure detection and automated control; and to compare the required energy and downward forces needed to make headway, compared with previous drill designs tested at the same location.

The CRUX drill and automation software were deployed to Haughton Crater on 17 July 2009. The drilling site was chosen on a massive breccia deposit located inside the northwest crater rim [14].

The CRUX drill considerably exceeded in total depth all past prototype planetary drills tested at the Haughton Crater analog site, reaching 8.2m cumulatively over six boreholes drilled. Figure 7 shows the total depth, power, and weight on bit over the course of the testing. Five primary drill hardware faults were encountered naturally in the course of drilling, which will be used to verify and refine the CRUX fault models. A successful attempt to induce a sixth fault mode, bit impingement, required adding small 1cm diameter pebbles down the borehole, as the hammering motion of the CRUX drill otherwise easily handled the natural breccia clasts and ice. On the next-to-last day of testing, cold water was added to the borehole (past the permafrost layer), and covered and left overnight to intentionally freeze the drill in place. When the CRUX drill was activated the next day, the percussive action quickly freed it from its encapsulated ice and enabled shaft rotation and further drilling to continue.

5 Conclusions

By 2008, the combined topside automation demonstrated by MARTE tests in Spain, together with DAME's mastery of downhole drilling automation, demonstrated that remote robotic access to the subsurfaces of other planets was feasible. But these capabilities were not tested on the most likely drill hardware to be flown (rotary percussive) nor in a flight-like, constrained computing environment.

In the past two years, we have successfully updated and replaced major components of the DAME robotic drilling software, and ported it to the CRUX rotary-percussive drill. We have completed a series of field tests in a relevant planetary analog environment, leading to drilling automation maturation suitable for consideration in future missions.
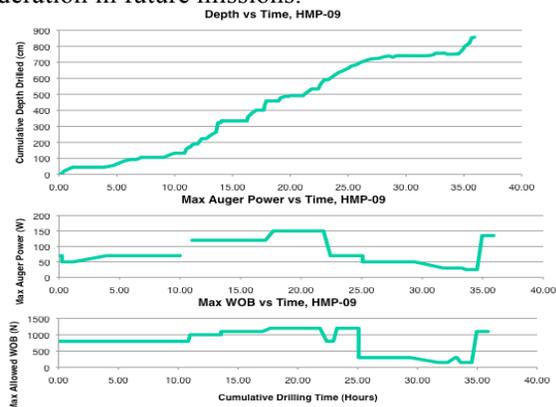
Figure 7. Depth, power and downward force in 2009 CRUX tests.

The CRUX rotary-percussive planetary prototype sampling drill met or exceeded all of its 2009 test goals. It did so at lower energy levels, with less weight on bit, and faster than the DAME drill at the same test site. The improved performance of the rotary-percussive design justifies its additional design complexity over simpler drills, and its ability to match or exceed the performance of other planetary drill designs under difficult analog-site extremes indicate that its maturity level is suitable for consideration in near-term planetary surface mission proposals.

Planned work in 2010-11 includes fully-automated field testing with the CRUX drill, completing the port of DAME capabilities, at the Haughton Crater site. The control software will be ported as well to a flight operating system environment (VXWorks or Green Hills) and tested in flight computing hardware testbeds.

Acknowledgements

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