DAME: Planetary-Prototype Drilling Automation

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Abstract - **This paper describes the latest results from the Drilling Automation for Mars Exploration (DAME) project, including summer 2006 test results from an Arctic analog-site. The drill hardware is a hardened, evolved version of the Advanced Deep Drill (ADD) by Honeybee Robotics. DAME has developed diagnostic and executive software for hands-off surface operations of the evolved version of this drill. The DAME drill automation tested in 2004-06 included adaptively controlled drilling operations and the downhole diagnosis of drilling faults, and dynamic recovery capabilities when unexpected failures or drilling conditions were discovered. DAME has developed and tested drill automation software and hardware under stressful operating conditions during its Arctic field testing campaigns at a Mars-analog site.**

I. INTRODUCTION

Space drilling will require intelligent and autonomous systems for robotic exploration and to support future human exploration, as energy, mass and human presence will be scarce. Unlike rover navigation problems, most planetary drilling will be blind – absent any precursor seismic imaging of substrates, which is common on Earth prior to drilling for hydrocarbons. The search for evidence of extant microbial life on Mars drives the need for the eventual acquisition of core samples from subsurface depths estimated at hundreds to thousands of meters where, beneath permafrost, the increasing temperature would be consistent with the presence of interstitial water (as a brine) in its liquid phase. On the Moon, eventual in-situ resource utilization (ISRU) will require deep drilling with probable human-supervised operation [1] 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 1-20 meters in depth. These lightweight exploration drills have a direct counterpart in terrestrial prospecting and ore-body location, and will be designed to operate either human-tended or automated. NASA and industry now are acquiring experience in developing and building low-mass automated planetary prototype drills to design and build a pre-flight lunar prototype targeted for 2011-12 flight opportunities. A successful system will include development of drilling hardware, and automated control software to operate it safely and effectively. This includes control of the drilling hardware, state estimation of both the hardware and the lithography being drilled and state of the hole, and potentially planning and scheduling software suitable for uncertain situations such as drilling.

Drilling on Earth is hard – an art form more than an engineering discipline. Human operators listen and feel drill string vibrations coming from kilometers underground. A drill system for planetary deployment will differ in many ways from conventional drilling systems where mass, power and volume are not major considerations and where the speed of penetration is essential for economic operation. On the Moon or Mars, working in a very low temperature/pressure desiccated environment without drilling fluids, the basic task of reliably comminuting the rock and moving the cuttings away from the drill bit and up to the surface will itself be a challenge [2]. The environment will be minimally characterized and we can expect to encounter a range of different rock types ranging from regolith to ice to solid basalts, without knowing which rock type we will encounter next. Mass considerations prevent the transport and use of drilling mud.

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 mouseclick in a control room, rather than by sending out a human with a wrench – eliminating direct hand contact other than joysticks and touchscreens [3]. 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 reflects a qualitative advance over teleoperated commercial drilling operations.

Early attempts at automation in oil and gas exploration led to the development of rule-based systems in the 1980s for interpreting well logs as a drilling advisor or monitor [4]. These systems were successful only in narrowly-defined, offline applications, because the inflexibility and brittleness of

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An earlier version of this paper was originally presented at AIAA Space 2006, San Jose, CA, September 2006.

rule-based systems was not compatible with the poorly-characterized, dynamic drilling environment.

Meanwhile, this inflexibility in reasoning was overcome in the development of integrated system health management techniques for aircraft and spacecraft, adding model-based reasoning or hybrid approaches in parallel with faster rule- or table-lookup-based approaches [5,6]. Connectionist approaches using neural nets have been developed to identify and reconFig. aircraft flight controls [7]. Application of these newer diagnostic and control approaches to the drilling automation problem seemed to offer a hope of achieving hands-off drilling, at least for lightweight space drills.

The Drilling Automation for Mars Exploration (DAME) project's purpose is to develop and field-test drilling automation and robotics technologies for projected use in missions in the 2011-15 period [8]. Fig. 1 shows a lightweight, planetary-prototype drill, in DAME summer Arctic field testing [9]. DAME includes control of the drilling hardware, and state estimation of both the hardware and the lithography being drilled and the state of the hole. A sister drill was constructed for the MARTE project and demonstrated automated core handling and string changeout in 2003-05 field tests [10,11]. DAME focused instead on the problem of drill control while actively drilling – "making hole" while not getting stuck.

Fig. 1. The DAME drill hardware was a Mars-prototype derived from the Honeybee Advanced Deep Drill.

This paper will describe briefly the original goals and motivations for DAME, summarize the parallel-diagnostic and executive approach taken, describe the July 2006 field results with examples and make a few conclusions about the state of this drilling automation and future directions.

II. MOTIVATION AND GOALS

A. *Future drilling missions require hands-off operation for hours at a time*

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. Even human monitoring and tracking is impractical, as by the time Earth learns of a drilling problem, the drill will be at least several minutes further along and probably stuck. But drilling conditions change, and strata are unknown, and the physical performance and response of the drilling machinery changes with increasing depth. A simple limit-checking scheme that pulls out and safes the drill whenever limits are exceeded is likely to trip often, then each time wait days for human troubleshooting from afar. An automated, adaptive drilling controller than can change forces and speeds in response to changing downhole conditions, and remediate and continue onward from the most likely faults, is both less likely to fail and more likely to make drilling progress. But no mission manager is likely to put a drill, or drilling automation, on a spacecraft without first making a credible demonstration that lightweight low-power dry drilling can be conducted and automated under terrestrial conditions. And to achieve a technology readiness level adequate to justify developing flight hardware, that demonstration should be in a flight-like analog environment, drilling-wise.

B. *3-year milestones: discover, observe, control*

The DAME project's goals were therefore to first conduct manual low-power dry drilling under relevant conditions, both in the laboratory and at an analog site, in order to discover and model the behavior of the drill under a range of operating conditions including problems and faults. Then in the second year, to take initial software controls and diagnostic models and place them in observation (but not control) of the drill in the same drilling locations and conditions. Then with the knowledge gained from these tests, to refine the automation, close the control and operations loop and in a third year to test hands-off drilling in the same drilling locations and conditions.

III. DAME APPROACH

A. *Human drillers use heuristics, reasoning, vibration perception*

How do humans accomplish drilling? Roughnecks and 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, DAME designers took these same approaches (model-based, heuristic, and vibration perception) as a starting point. Table 1 lists the major fault modes of the DAME drill, obtained from theory and field observations, along with recovery actions.

TABLE I.
MAJOR FAULT MODES AND RECOVERY ACTIONS FOR THE DAME DRILL

Fault	**Fault Definitions**	**Recovery Procedure**
Auger Binding	The auger is rubbing up against something along its length which results in an increased auger torque.	Raise drill while rotating at high speed.
Auger Choking	Cuttings are accumulating near the bit and are not flowing up the auger flutes. The cuttings expand and cause an increase in torque.	Slowly raise drill and reverse rotation to clear cuttings.
Bit Jamming	The auger can no longer rotate due to the bit jamming against a rock, or an extreme case of auger choking is present.	Decrease set force. Raise and reverse till auger free.
Bit Inclusion	A pebble, or rock, at the bottom of the hole causes periodic torque spikes, roughly at the frequency of the auger rotation.	Raise drill and then slowly lower to shave a flat surface or pick up rock.
Bit Hard Material	Minimal rate of penetration, even though the auger torque is low and WOB is high.	Increase set force. If at max set force, change to coring bit.
Auger Corkscrewing	Auger flutes catches on protruding material and begins to screw into the ground. Identified by large tensile force on drill strings.	Stop, reverse rotate and raise at auger pitch till free. Then up down motion to shear off protrusion.

B. *Three Diagnostic Approaches In Parallel*

Lightweight dry drills may break or become stuck quickly in some failure modes, or may degrade progressively in others (such as ice-necking or bit wearout). And on Mars or other nonterrestrial locations, the layers being drilled are not likely to be known a priori, lacking prior seismic or other regional surveys… so aliasing is a risk, as some apparent wearout or rapid drill choking faults may actually reflect penetration into subsequent strata (with different mechanical properties). The DAME approach is 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.

Part (a) was implemented in the drill executive and control software for rapid response, while (b) and (c) were separate diagnostic software modules as shown below.

C. *Modular architecture overview*

Fig. 2 shows the software architecture for the DAME system. The Drill Controller, at the far right, is the low level control system responsible for controlling the drill motors and retrieving and converting the sensor signals into engineering units. This sensor data is supplied to the drill server, which either broadcasts the information to the other modules, or provides it upon request. The three diagnostic modules (Model Based, Vibration Classification, and Rule Based) use this data to estimate the state of the drill system. The state is represented as a set of fault modes with associated probabilities. These estimates are provided to the Contingent Executive. An Arbiter function within the Contingent Executive combines the fault probabilities to determine whether or not to recommend a recovery procedure.

The Contingent Executive normally executes a baseline plan, which may consist of a number of "drill to depth" operations interspersed with science measurements. If a recovery procedure is recommended, it pauses the baseline plan, and inserts the recovery procedure. Once the recovery procedure is completed, it resumes the baseline plan. The Contingent Executive executes the baseline plan and recovery procedures by sending commands and drilling parameter modifications through the Drill Server to the Drill Controller. All of the data transferred between the modules in this architecture utilizes a communications backbone known as the Tiny Instrument Interface (TInI). This is a very small client/server string interface layered on top of TCP/IP Sockets for speed and efficiency.

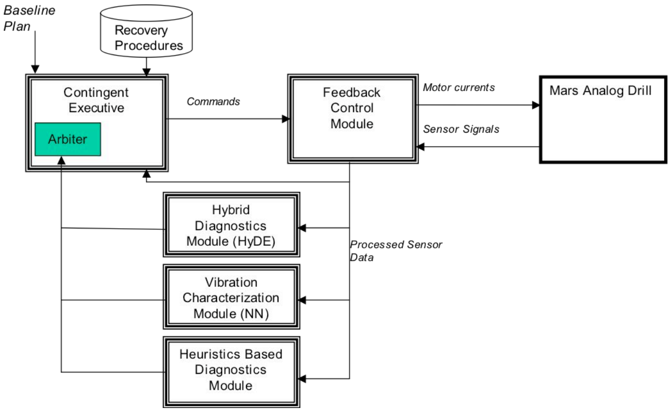


Fig. 2. DAME Software Architecture.

D. *Contingent Executive*

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 also modified and used to control the drill, core sample handling and onboard science instruments for a sister drilling project, the Mars Astrobiology Research and Technology Experiment (MARTE), which was field tested in 2005 [14].

The Contingent Executive uses a plan language known as the Contingent Rover Language (CRL) to serve as the communication medium for receiving instructions from the ground operations team. 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. recovery procedure).

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 temperature measurement. The temperature measurement was simply an example of ascience measurement that could be taken at fixed intervals in depth. 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 is representative of a daily operational plan that could be sent to a drill on a remote planetary surface.

E. Arbiting and merging multiple diagnoses

For the DAME project, the Contingent Executive was modified to control the drill system as well as to accept state estimates from multiple diagnostic systems via the insertion of an Arbiter. The Arbiter receives reports of probabilities for the various drill faults from each of the diagnostic systems. It weights the probabilities for each fault, based on the criticality of the fault, as well as the given diagnostic modules' prior performances and efficacies in predicting the given fault. The weighted probabilities for each fault are then summed to find the highest probability fault. If this fault probability exceeds a pre-defined threshold, the Arbiter recommends a recovery procedure. Each of the faults and corresponding recovery procedure used in the DAME project is shown in Table 1.

F. Rule/table based

The Rule Based Diagnostic module is a simplistic and inflexible approach to fault detection, but it is easily implemented and serves as a failsafe. It relies on thresholds and heuristics to determine when a fault occurs, and operates by reading in all data values and then applying a median filter. Once this filtering completes, the server determines which faults are eligible and then computes the probability of the eligible faults.

Simple rules are used to compute the probability of each fault. These rules are given below in Table 2. The first three probabilities are scaled by magnitude and time factors. Since these are auger faults, the magnitude factor is proportional to the auger torque, and the time factor is proportional to the length of time that the fault is eligible. The next two faults, jamming and hard material, are faults related to the drill bit. Jamming can occur suddenly and is therefore not weighted by time, but depends solely on the auger rotational speed. The hard material fault is dependant on the average rate of penetration over a fixed time duration. The final fault, corkscrew, becomes more severe as the z-axis (depth) force becomes more negative.

These rules were derived by observing faults while testing in the laboratory at NASA Ames, as well as from the results from the previous two DAME field seasons. The rules all rely on various thresholds, such as MINIMUM_PENETRATION_RATE. Some of these thresholds are lab-calibrated and depend heavily on the drilling medium, while other thresholds are determined by the physical limitations of the drill. As such, the Rule Based Diagnostic module requires tuning to function properly. This tuning was accomplished during initial testing in the field.

TABLE II.
DAME INITIAL FILTERING RULESET.

Equation	When Eligible
BINDING_PROBABILITY = (1 – MIN(1.0, BIT_TORQUE / AUGER_TORQUE)) * TIME_FACTOR * MAGNITUDE_FACTOR	AUGER_TORQUE > AUGER_TORQUE_THRESHOLD
CHOKING_PROBABILITY = MIN(1.0, BIT_TORQUE / AUGER_TORQUE) * TIME_FACTOR * MAGNITUDE_FACTOR	AUGER_TORQUE > AUGER_TORQUE_THRESHOLD
INCLUSION_PROBABILITY = MIN(1.0,MAX(0.0,(1.0 – (MEAN_TIME_BETWEEN_CYCLES – TIME_PER_REVOLUTION) / TIME_PER_REVOLUTION))) * TIME_FACTOR * MAGNITUDE_FACTOR	AUGER_TORQUE > AUGER_TORQUE_THRESHOLD
JAMMING_PROBABILITY = MIN(1.0, MAX(0.0, (1 – ACTUAL_AUGER_SPEED/DESIRED_AUGER_SPEED)))	AUGER_TORQUE > AUGER_TORQUE_THRESHOLD
HARD_MATERIAL_PROBABILITY = 1.0 – (AVERAGE_Z-AXIS_SPEED / MINIMUM_PENETRATION_RATE)	AUGER_TORQUE < AUGER_TORQUE_THRESHOLD and DESIRED_ROP > 0
CORKSCREW_PROBABILITY = MIN(1.0, (CORKSCREW_THRESHOLD – Z-AXIS_FORCE) / Z-AXIS_FORCE_THRESHOLD)	AUGER_TORQUE < AUGER_TORQUE_THRESHOLD and DESIRED_ROP > 0

G. Vibration identification with a neural net – perception-based

To design a successful vibration-based automated drill diagnostic module, the identification challenges included (1) the sudden and unexpected changes in the material that is being drilled (rock, ice soft material etc.); (2) changes of the drill system with time, such as the addition of additional drill strings, a new drill bit or changes in the environment; (3) modeling the encountered geological systems that the drill encountered and affects the diagnostic model; (4) different conditions encountered inside the drill hole: such as the encroachment of the drill string by the drilled material; collapse of the surrounding material on a portion of the drill string; drill bit failure; and changes of the mechanical and thermal characteristics of the drilled material; (5) the auger encountering a partially-hard material on one side and a soft material on the other side; (6) the dynamic stability (for example, pitching) of the entire drill system, including the support; and (7) uncertainties due to unmodeled dynamics.

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 as shown in Fig. 3, 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 fault conditions. Fig. 4 shows the monitoring procedure.

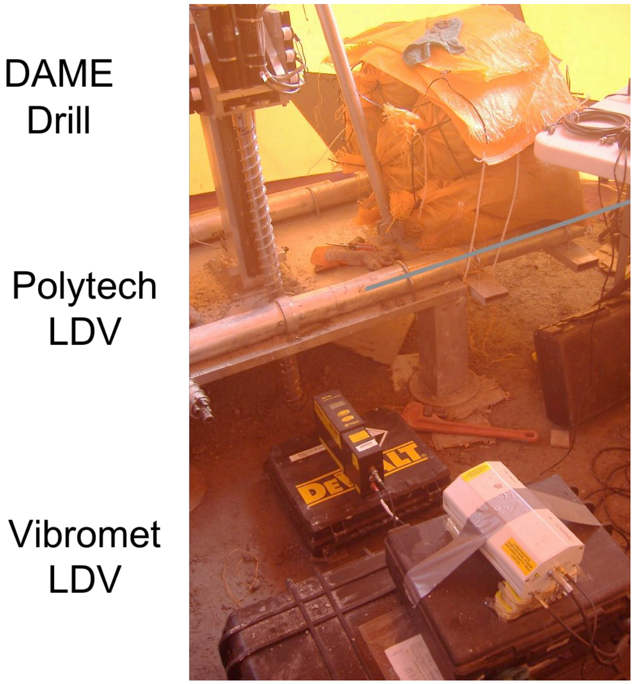


Fig. 3. Vibration monitoring for DAME field tests.

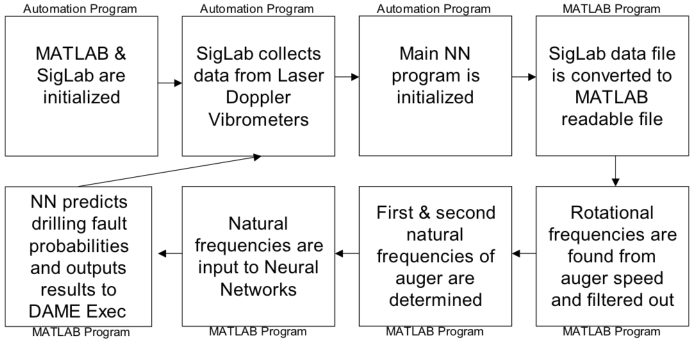


Fig. 4. Vibration-neural-perception based diagnostic process flow.

H. Model-based reasoning

The DAME model-based reasoning approach focused on the primary drill failure modes shown below in Table 1. As a result, the drill model, shown in Fig. 5, was simplified to only model those components that directly affected predictions for the given failure modes.

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.

IV. FIELD TESTING

Laboratory simulation and drilling into frozen simulants would be needed to verify and calibrate models before taking the system to an unpredictable, unforgiving analog test site. The software drilling simulator Payzone from U.C. Berkeley [15], was modified for a shallow breccia permafrost model, and used to help in initial software diagnostic model verification. The DAME drill was tested in May 2004 with frozen simulant at Honeybee, and during 2005 at the Georgia Institute of Technology with artificially-induced faults [16].

For DAME, a Mars-analog drilling site was needed – someplace with subsurface ice (as at the Martian higher latitudes) and the broken, depth-graded textures similar to impact regolith. Similar morphology, such as a crater site, was considered a plus. And to forestall sloppy hardware or software design and impose maintainability and long-term operations in hostile conditions, a terrestrial frontier location – away from electronics stores, easy software downloads, ready repairs or resupply – was desirable. And autonomous operations on a terrestrial frontier analog site was more credibly flight-like than simply drilling in one of the created "Mars yards" used in rover development locally at NASA Ames, the Jet Propulsion Laboratory or Johnson Space Center.

A. Haughton Crater Research Station

The Haughton-Mars Project operates a research station in the Canadian Arctic adjacent to Haughton Crater, on Devon Island, Nunavut at 75.2N, 89.7W, jointly supported by NASA and the Canadian Space Agency. The Haughton Crater Research Station (HCRS) base provides seasonal logistical support for up to 40 researchers and staff working in or around the 22-km wide Haughton Crater impact site during summer months. DAME selected the HCRS because Haughton Crater satisfied its analog site requirements (textures similar to regolith, subsurface ice, impact crater, remote) while being relatively close to commercial airline and air cargo flights to and from Resolute Bay, Nunavut.

B. 2006 Test Plan

In two previous sets of summer field tests at the HCRS site, DAME tested its lightweight, low power Mars-prototype drill (2004) and then tested initial diagnostics and controls in parallel with manually-controlled drilling (2005) [15]. The top-level goal of the 2006 DAME test plan was to verify and demonstrate a capability for hands-off automated drilling.

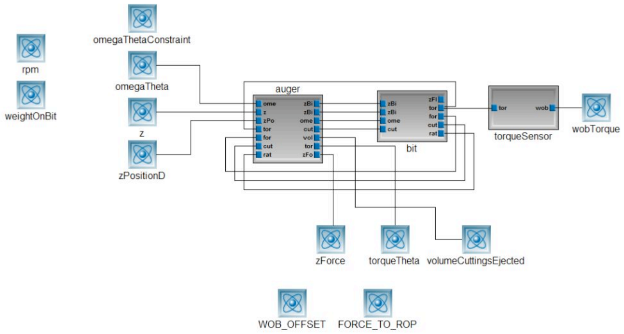


Fig. 5. Diagnostic component model for the DAME drill.

There were three sets of 2006 test goals. The first was to demonstrate the recognition, while drilling, of at least three of the six major fault modes for the DAME drill (shown in Table 1). And to employ the correct recovery or safing procedure in response. Any faults not seen naturally in the course of drilling would be manually induced at the end of testing. The second set of 2006 goals was to operate for three or more hours autonomously, hands-off. And the third 2006 goal was to exceed 3m into the permafrost with the DAME drill (it had not gone further than 2.2m previously). And ground truth drilling would use small commercial drilling equipment in parallel in order to obtain cores and ice profiles from the permafrost.

V. RESULTS

The DAME drill and automation software was deployed to the HCRS for testing from 15-28 July 2006. The drilling site was chosen on a massive breccia deposit located inside the northwest crater rim. A large 5m-diameter dome tent covered the drill and support equipment. A portable generator provided power, although the drill itself was constrained to use no more than 150W peak. A communications relay to HCRS base camp provided data access back to NASA Ames and JPL for a later live field demonstration on 27 July.

All three DAME 2006 test goals were completed successfully. All six faults from Table 1 were encountered naturally in the course of drilling, none had to be artificially induced, and the last of the six occurred on 24 July, a week into drilling. Five of the six faults were correctly identified, repeatedly, corrective actions were taken by the automation software and drill, and the drilling continued. The lone fault that was routinely mis-identified was Auger Choking – there was not sufficient torque to distinguish it from Bit Jamming, in large part due to parasitic drag because of incidental reaming along the vertical length of the auger shaft. Figs. 6 and 7 show two of the faults (corkscrewing and hard material) detected and corrected while drilling. Two bits were used in drilling: a cutting wedge bit in frozen soils and softer rocks, and a coring bit used on hard rock and ice lenses. The automation could request a bit change when choking or hard material was detected.

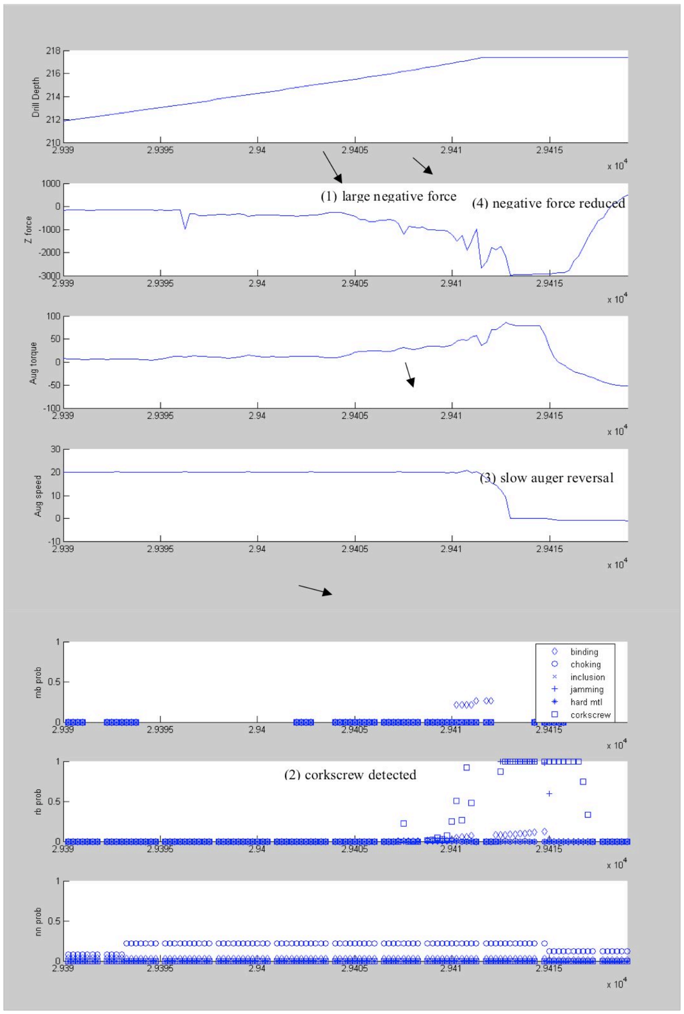


Fig. 6. Corkscrew Fault Detection and Recovery

In Fig. 6, a large negative force is encountered during drilling (1), and the auger torque rises steeply. This is indicative of a corkscrewing problem, where a rock embedded within the sidewall gets keyed in between the auger flights. When the auger tries to turn, it actually pulls the drill toward the ground, causing the bit to push harder into the material. Although this actually causes a slight and temporary rise in the rate of penetration (ROP), the problem can lead to a catastrophic jamming failure if the situation is not remediated. At approximately 29410 seconds, the problem was detected by the rule based diagnostic system (2). In response, the DAME executive stopped drilling, and reversed the auger rotation at a slow rate (3) in order to reduce the negative force (4).

Fig. 7 shows hard material faults that were detected and recovered near the end of the field test (28 July). In the beginning of this scenario, the auger torque is low, and there is a very low ROP (which is an indicator for a hard material such as ice because the spade drilling bit literally skates on top of the material) (1). At approximately 47400 seconds, the rule based diagnostic system detects the hard material (2), and the executive responds by increasing the set force to 2000 N (3). This results in a slight increase in ROP (4). Eventually the increased force proves to be insufficient, and the ROP again decreases (5). Hard material is again detected a second time via combined probabilities from the rule based and model based diagnostic systems at 48450 seconds (6). The executive responds by increasing the set force again to 2700 N (7). This time there is no increase in ROP (8). The executive enforces that the higher set force be attempted for a fixed period of time. But after this expires, the model based and rule based systems' combined probabilities indicate hard material a third time (9). The DAME executive then gives up increasing the set force and instead pulls the drill out of the hole to change to the coring bit.

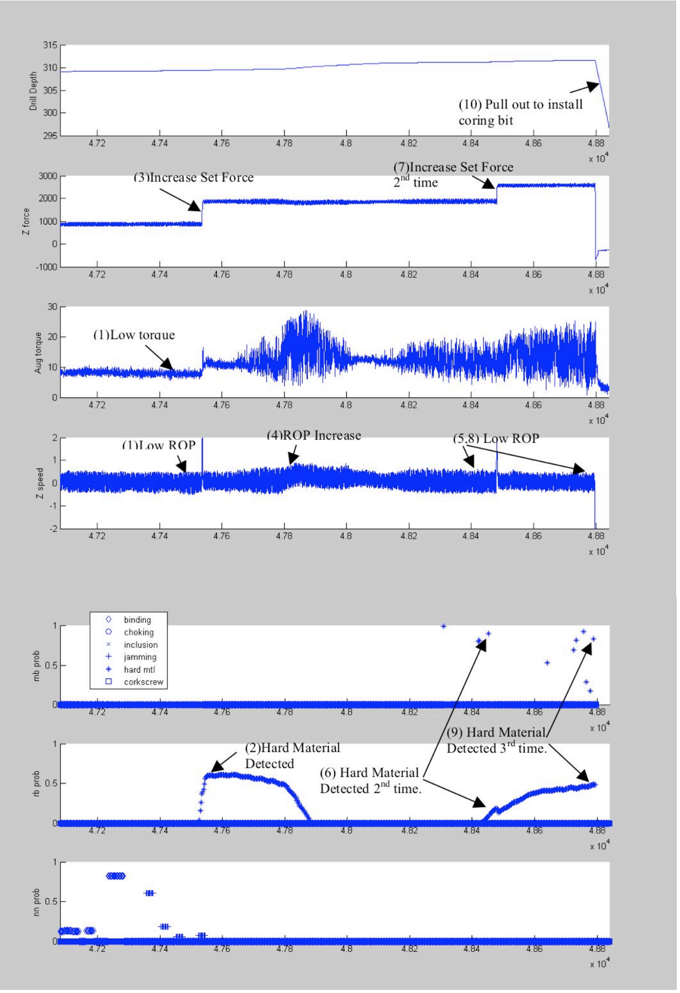
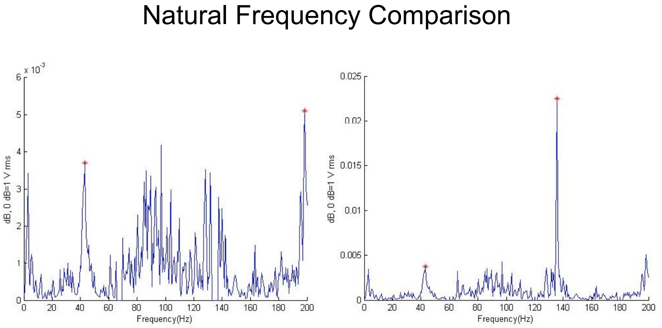


Figure 7. Hard Material Detection and Recovery

The hands-off duration goal was met – and greatly exceeded. A total of 44 hours of autonomous, hands-off drilling was accomplished, with the longest period being just over five hours. Session durations were limited not by the automation, but by power management -- the need to periodically refill the generator. And a total depth of 3.2m was reached, into the frozen breccia, with cores obtained.

All three diagnostic methods (rule-based, model-based, and vibration-neural-net) were used together and demonstrated robust, reliable monitoring and analysis of the drill and drilling operations. False-positives were less than 10%. The vibration-analytical neural net was able to detect changes from shifts in natural frequencies and mode shapes. Fig. 8 compares nominal frequencies with a given faulted case (hard material).



Binding & Hard Material Drilling Frequencies

Nominal Drilling Frequencies

Fig. 8. Nominal vs. binding/hard material frequencies show shifts and amplitude changes that are detectable with a neural net.

Once all DAME field test goals had been met, and a live demonstration given via video and audio link back to NASA on 27 July, an extended, higher-risk test series was conducted during the last two days in the field. Previous hands-off tests had been run with humans nearby, monitoring drilling progress and software responses at the drill site, ready to intervene in order to save the equipment in case of a general system failure. A "bare" or "exposed" test was run on the evening of 27 July. This consisted of starting an automated drilling sequence, and then directing the human staff to leave the equipment completely unattended while having dinner several miles away at the HCRS base camp. This caused some nervousness among the programmers and engineers, but was a success -- as upon their return four hours later. the automated sequence was still going on and the DAME system had detected and successfully responded to a fault and continued in safemode. A remote test was run early on 28 July, initiating a drilling sequence and monitoring the progress remotely via the data link from the crater floor to the HCRS base. Remote "uplink" and "downlink" of drilling data and commands was not a DAME project requirement, but will be necessary for a flight instrument.

VI. CONCLUSIONS

The Drilling Automation for Mars Exploration (DAME) project has developed and tested standalone automation at a lunar/martian impact crater analog site in Arctic Canada. The search for resources and past/present life on other planetary bodies will require subsurface access, which requires exploratory drilling. Drilling has been a hard, human-intensive problem in terrestrial applications, but planetary drills require automation. The DAME project has developed hardware and software, complementary diagnostic approaches, and completed a series of field tests in a relevant environment, leading to drilling automation maturation suitable for consideration in future missions.

DAME's overall goal was to develop and test a capability for hands-off, unmonitored drilling operations, including responding to changing drilling conditions and strata. Together with the drill-string changeout and core-handling automation demonstrated by its sister MARTE project, DAME has demonstrated the comprehensive remote control and management of science drilling that is required for future subsurface access to other planets. This capability gains credibility from its validation and testing outside the laboratory at a remote Mars-analog site.

Future work is needed to bring together the DAME drilling automation with the MARTE core handling and topside automation technologies as an integrated whole. And flight versions of drilling automation will require that the current source code be hardened and rewritten, with another round of validation. The vibration-analysis monitoring technique is novel and lacks maturity compared to the rule-based and model-based techniques, and could benefit from more development and research. DAME has been shown to work with one specific Mars-prototype drill, and the approach needs to be broadened and demonstrated with other drilling architectures (such as wireline bailing drills, and inchworm drills with tethers instead of extended shafts) that are proposed for future planetary missions in the next decade.

ACKNOWLEDGMENTS

The authors would like to thank Karen McBride and Dave Lavery of the Mars Instrument Development Program at NASA Headquarters for their respective support of the DAME project, as well as Samad Hayati's support through the Mars Technology Program at JPL. Honeybee development and testing of the DAME drill hardware was led by Kiel Davis, and final tests were supported by Kris Zacny at Honeybee. Scott Christa made invaluable contributions to the executive and TINI dispatcher, Edward Balaban took the beta-version HYDE model-based reasoning engine and made it work operationally, and Shannon Statham developed the final laser vibrometer and neural net software at Georgia Tech. Sarah Huffman kept the servers and networks up in remote places while also keeping the DAME team fed and happy in the Arctic.

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