Technologies for Exploring the Martian Subsurface

Suparna Mukherjee[1], Paul Bartlett[2], Brian Glass[3], Jose Guerrero[4], Scott Stanley[5]
[1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena , CA 91109.
Suparna.Mukherjee@jpl.nasa.gov
[2]Honeybee Robotics, 460 W. 34th Street, New York, NY 10001. Bartlett@honeybeerobotics.com
[4]Ames Research Center, Moffett Field, CA 94035. brian.glass@nasa.gov
[5]Swales Aerospace, 404 N. Halstead Street, Pasadena, CA 91107. jguerrero@swales.com
[5]Alliance Spacesystems Inc., 1250 Lincoln Avenue, Suite 100, Pasadena, CA 91103. sstanley@asi-space.com

Abstract—The Mars Technology Program has invested in a number of development efforts with the collective goal of providing robust access to the Martian subsurface for future landed missions. Currently funded technologies include a sampling system that will be able to penetrate hard rock to 20 m in a highly autonomous manner and at flight-like power levels; shallow (0.5 m) regolith samplers appropriate for low-force platforms such as a rover-mounted robotic arm; a light-weight, low-force hard rock sampler that collects 1 cc powdered samples; and an advanced automation task for permafrost drilling. A summary of capabilities and current status of each of these technologies is presented here.

In addition, the program supports the development and integrated testing of a number of science instruments for exploring the subsurface directly, including downhole IR, neutron and x-ray fluorescence spectrometers. Given the increased uncertainties associated with operating such systems, the program's goal is to bring these technologies to high Technology Readiness Levels (TRLs) so that they may be readily utilized by future missions. Recent efforts to facilitate the necessary field and laboratory testing to achieve this high level of maturity will also be discussed.[1,2]

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1. INTRODUCTION

Providing robust access to the subsurface of Mars is a critical element to answering many of the science community's fundamental questions. The Mars Technology Program (MTP) funds the inception and maturation of technologies that enable these exploration goals. MTP develops mission-specific technologies needed in the near term, such as shallow coring tools for the Mars Science Laboratory (MSL). And looking ahead, the MTP attempts to anticipate the subsurface access needs of future Mars missions. Currently, this effort includes deeper drilling, sampling ice-bearing and highly heterogeneous materials, and the integration of downhole instrumentation for in situ analyses. The focus is on investing early in the complex challenges and proving out technologies that have not yet been used for planetary exploration, but provide the promise of lower masses, higher efficiencies, or new sample types, enabling missions that otherwise would not be possible

MEPAG (Mars Exploration Program Analysis Group) contributes to Mars exploration plans by attempting to provide current consensus views from the science community to mission planners and engineers. In the active version of the MEPAG "Goals" document, "access to the subsurface, from a meter to hundreds of meters, through a combination of drilling and geophysical sounding," was identified as a critical capability in need of development[1].

In response to the needs of the Mars science community, MTP established the Subsurface Access Base Technology area. This paper highlights some currently funded efforts in drilling and subsurface sampling. All five tasks described here were competitively selected among responses to the NASA Research Announcements, NRA-03-OSS-01-MT and NRA-03-OSS-01-MIDP. Details of each task are presented here, as well as technology evaluation tasks undertaken by MTP to encourage infusion into future missions.

The duration of each technology task is three years. The first system described, the Low Force Sample Acquisition System, is completing its final year of development at the time of writing. Two other low-force, shallow sampling tools (MIDAS and Ultrasonic Sampler) utilize ultrasonic/Sonic drill/corer technology [2]. Both tasks are concluding their first year of work, and are beginning the fabrication and integration of their sampler prototypes. A deeper drilling technology effort (MDPS) is also beginning its second year, and beginning subsystem integration.

Depth, power, mass, and reaction forces are typical and straightforward metrics for subsurface sampling tools. Table 1 lists the current MTP goals for shallow (< 1 m) and deep (< 20 m) sampling systems.

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[1] 0-7803-9546-8/06/$20.00© 2006 IEEE

[2] IEEEAC paper #1349, Version 4, Updated Jan 3, 2006

Table 1. MTP goals for Subsurface Access Tools

Depth	Power (W)	Mass (kg)	Stowed Volume (cm)	WOB (weight on bit)
Shallow (< 1 m)	30	4	50 x 25 x 25	<80 N
Deep (< 20 m)	80	40	100 x 100 x 100	<800 N

In addition to these spacecraft system constraints, some level of autonomy is necessary for operation on the surface of Mars. In order to map the progress of drilling and sampling autonomy, a number of automation milestones have been defined in Table 2. These are intended to provide guidelines and a common language for sampling systems that vary widely in design and operation.

Table 2. Sampling System Autonomy Milestones

Category	Fault Response				Description/Notes
	Detection	Diagnosis	Prognosis	Remediation	
A0	Identify off-nominal condition(s)	Evaluate state of system	None	None	**Automated:** Open loop control for drilling, sample acquisition and delivery
A1	Identify off-nominal condition(s)	Evaluate type of drilling fault	None	Abort drilling operations and put system in "safe" standby	**Semi-autonomous:** Some closed loop control: closed-loop drilling control with respect to drill rate and platform reaction forces
A2	Identify off-nominal condition(s)	Evaluate type of drilling or sampling fault	None	Abort drilling and sampling operations and put system in "safe" standby	**Semi-autonomous:** Primarily closed loop control: closed-loop drilling, sample acquisition and delivery
A3	Identify off-nominal condition(s)	Evaluate type of fault	None	Recover from fault and continue drilling/sampling operations	**Autonomous:** Primarily closed loop control; failure diagnosis and recovery for drilling and sampling
A4	Identify off-nominal condition(s)	Evaluate type of fault	Predict future off-nominal condiditons	Recover from fault and continue drilling/sampling operations. Prevent future fault using preemptive actions	**Fully autonomous:** Closed loop control; failure diagnosis, failure recovery/avoidance, and performance optimization for drilling and sampling

The A0 level of automation is the equivalent of a telerobotically operated drill that would be appropriate for earth-based field testing, critical in the development of an automated flight system.

The A1 level is similar to the operation of the Rock Abrasion Tool (RAT) on the Mars Exploration Rovers (MERs). This "MER-level" of autonomy checks limits on current and contact sensors to decide whether to continue or abort grinding. This task may well be sufficient for some future science missions where more frequent input from the ground is desirable for the science decision-making process.

The A2 level of automation includes integration of the sample acquisition and delivery processes, and represents a large step in system robustness and efficiency. The higher levels (A3, A4) that involve fault diagnosis, recovery, and prognosis may have particular utility on long-duration drilling events where contacts with the ground may be minimal.

2. SHALLOW SAMPLING

Three shallow sampling technology tasks are presented here. Each utilizes a combination of percussion and rotation to penetrate and sample. This approach is a far more efficient method of comminution, and makes these systems prime candidates for low-mass and low-force platforms such as small rovers and robotic arms.

Low Force Sample Acquisition System

The LSAS is a percussive drill with integral sample acquisition capability developed by Alliance Spacesystems, Inc. (ASI). Intended to drill into a wide variety of rocks and frozen soils while being supported by light-weight platforms, the primary design goals were to minimize force, mass, envelope, and power. This simple and elegant mechanism uses a single motor to acquire ~1.5 cc of powdered sample by drilling into the surface of a target material.

The drill bit (made of very specific materials to ensure life and minimize contamination issues) is driven by a space-qualified brushless DC motor. The drilling action is hammer driven, which allows the mechanism to acquire a sample with the minimum amount of force necessary. As material is removed from the target surface or hole it is fed into the mechanism by the bit flutes which deposit the sample into a storage bin via holes for later delivery to the support platform's instruments. Further details of the mechanism are shown in Figure 1.

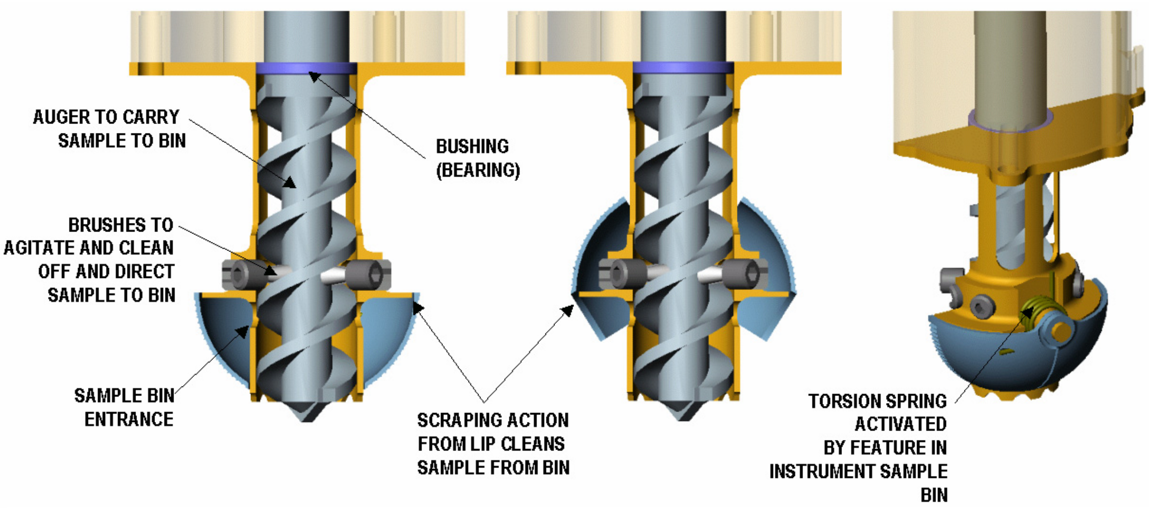


Figure 1. LSAS shallow sampling tool

LSAS operation is straightforward and readily autonomous. (Figure 2) First, the sampling tool is placed against a target. Preload is set and maintained by compressing an internal spring that supports the hammer drill system. Redundant contact sensors indicate that the bit has been depressed to the correct position, automatically resulting in the tool being placed against the target with the correct amount of force. Once in position, the motor spins the bit at approximately 800 rpm and the bit begins to drill into the surface of the target. Hammering action, the primary drilling effect, occurs three times per revolution. The hammering action is driven by the same motor and is accomplished via the cam-follower that forces the hammer up as it rotates, compressing a spring, and then releases the stored energy very quickly, driving the bit into the target. As material is removed it is carried into the mechanism by the fluted bit. Material travels up the flutes and is forced into the sample bin by brushes riding along the side of the gaps between the flutes. The sample bin gradually fills to the desired volume, and any excess material simply travels past the bin and out of the mechanism. Once the required amount of sample is acquired, it can be delivered to any instrument on the support platform. To allow for sample delivery, the LSAS incorporates a passive clamshell storage bin. Features on each instrument (also developed as part of this effort) force the clamshell open as the tool comes into contact with the instrument. A simple scraper ensures all material is removed from the bin as it is opened, actuating the hammer a few times helps remove particularly cohesive material, minimizing cross-contamination between samples.

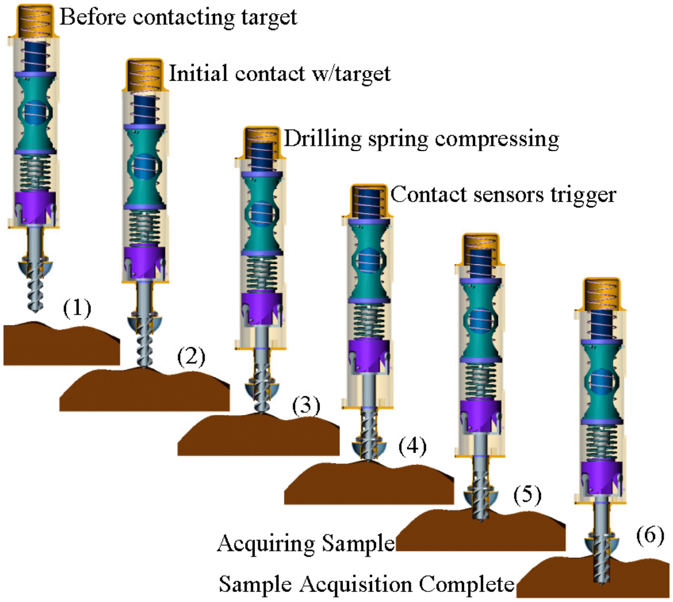


Figure 2. LSAS operational sequence

Following extensive development tests, the final prototype is currently in functional test (Figures 3 and 4). Figure 5 shows a series of test results generated during recent drill and bit evaluation testing.

Table 3 provides a summary of LSAS capabilities.

Table 3. LSAS system summary

System Parameters	LSAS
Power (W, average) in basalt	20
Mass (kg)	0.44
Stowed volume (cm)	23 x 3.3 x 3.3
Weight on bit, WOB in basalt (N)	35
Maximum depth (m)	0.02
Borehole diameter (cm)	0.6

Sample type	1.5 cm^3 powder
Automation target (see definitions in Table 2)	A2
Prototype completion; start of TRL5 testing	October 2004

Figure 3. LSAS prototype

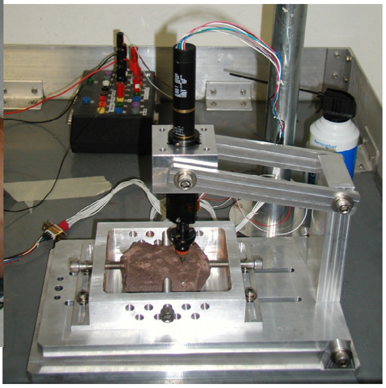


Figure 4. LSAS in test fixture

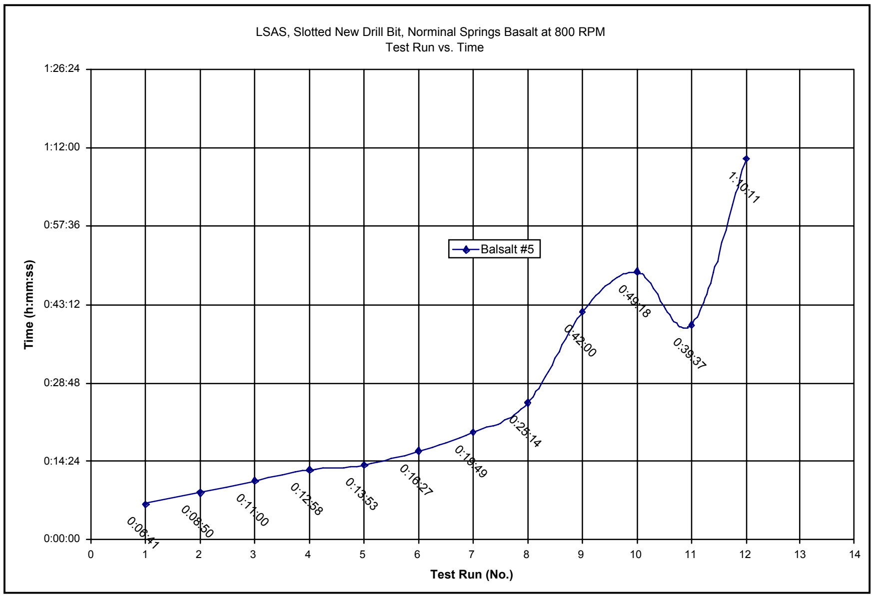


Figure 5. LSAS drill bit testing

Mars Integrated Drilling and Sampling

The lightweight Mars Integrated Drilling and Sampling (MIDAS) System is being developed by ASI to allow for the automated retrieval of multiple samples from rock and regolith up to a depth of 0.5 m from a low-mass, mobile platform. MIDAS combines two relatively mature technologies, a 5 degree-of-freedom (DOF) robotic arm from the Mars Exploration Rovers and an Ultrasonic/Sonic Driller/Corer (USDC) technology, with an interchangeable bit mechanism and bits capable of retrieving samples from up to 0.5 m and depositing them into an instrument for further analysis or a storage container for return to Earth. The complete system will be approximately 1 m in length, weigh less than 6 kg, and consume less power than traditional drilling systems (as little as 2 W).

The 5 DOF robotic arm is based on the Instrument Deployment Device (IDD) also developed by ASI for the Mars Exploration Rovers launched in June 2003[3]. This low-mass robotic arm provides very precise positioning and feedback, allowing MIDAS to:

- Control the rate of progress and weight-on-bit
- Sense the depth of drilling
- Automate the acquisition of multiple samples

The major benefits of utilizing the USDC are:

- Low-force requirements that allow operation from flexible, low-mass platforms
- Power-effective and mass-efficient drilling
- Very simple bits that are reliable, do not need sharpening, and reduce contamination
- Simple mechanical bit interface making possible the use of multiple function-specific bits to accomplish a wide variety of tasks

The interchangeable bit mechanism and a tool caddy enable the system to:

- Replace damaged or worn-out bits

- Repeatedly return to the worksite with different bits or to collect multiple samples

- Place different tools and instruments on the target

The USDC approach combined with the dexterity of the robotic arm make multiple, interchangeable tool bits a practical means of accomplishing a wide variety of tasks and provide a very powerful tool for exploring the Martian subsurface. Utilizing different tool bits is an efficient way to perform many tasks, but has traditionally required an overly complicated mechanism. MIDAS solves this problem by providing a very simple interface for transferring the mechanical energy of the USDC to the bit.

Rotation at the bit is provided to expose a fresh work surface to the bit and aid in debris transfer, minimizing the need to transfer torque or have complicated couplings. The interface is essentially a spring-loaded detent that allows the bit to be snapped on and off with ease, then locked in place to provide sufficient holding force for all operations.

The MIDAS system, consisting of the USDC with interchangeable bit mechanism, integrated to the end of a 5 DOF robotic arm, and a tool caddy containing multiple, interchangeable bits to acquire, handle, and deliver samples for storage or analysis, is shown in Figure 6.

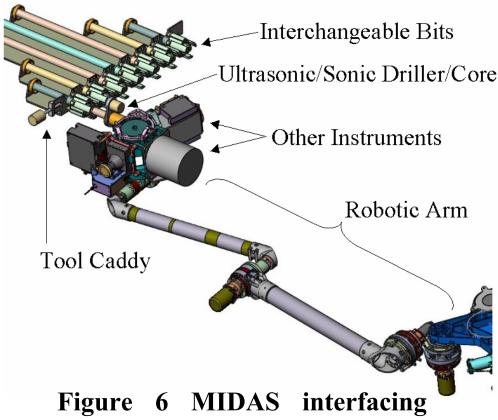


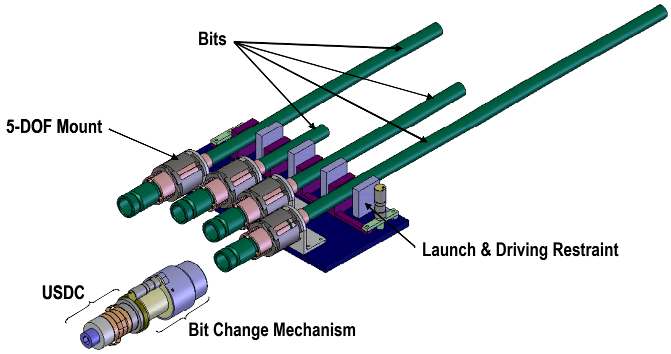
Figure 6 MIDAS interfacing with tool caddy

MIDAS will utilize encoders at each joint for position feedback and a force sensor to measure the applied drilling force and sense contact with a target. Motor and sensor electronics are flight-like (capable of performing in a Martian environment) for the current stage of development and will be controlled via commercial electronics and software. Standard interfaces will be utilized so that MIDAS may be driven and controlled by any future flight or testbed platform.

This approach will allow MIDAS to control the rate of progress, weight on bit (WOB), and drill depth during such operations as drilling, rock abrading, and coring. MIDAS will have capabilities very similar to those of the IDD (positioning within ±4 mm and 10 deg). For this prototype system, an arm assembled primarily from flight spare MER IDD hardware will be used as the robotic arm for MIDAS. This approach will allow MIDAS to consistently retrieve and release any bit in the tool caddy and return to the target with enough accuracy to guarantee alignment with a previously drilled hole. This accuracy enables the retrieval of multiple samples and access to the target by multiple instruments. It also allows the sample to be delivered to a storage container or instrument very precisely.

Two of the most promising benefits of the USDC are the simple bit interface and the simplicity of the bit itself. The use of multiple bits is essential to accomplish the multitude of tasks envisioned for future missions using a single tool. These tasks can, however, be accomplished by a single actuator that utilizes multiple bits for drilling, coring, surface preparation, and sampling. The USDC makes multiple bits and the exchange of those bits very practical. Many of the bits are as simple as a tube of a single material joined to the standard bit interchange mechanism interface. The bits typically do not require sharpening, but if a bit were damaged or jammed it could be readily replaced. The interface is not required to transmit high torque, nor is it required to have power or communications connections. The interface must simply keep the bit reasonably straight and allow a very light axial force to be applied to the bit by the USDC.

Bits are carried in a tool caddy mounted on the support platform in a location accessible to the arm. The bits are stored in spring-loaded detents and are restrained during launch, landing, and potentially platform positioning by means of a retractable drawbar. The USDC engages the bits via three spring-loaded features that lock the bits axially but allow it to "float" in any direction laterally (over a limited distance) with a minimum of force. In addition, the USDC tip fits within the bit interface with a predetermined amount of clearance, which allows for a limited amount of angular play once engaged. This approach allows the robotic arm with the USDC to couple with the bit even though the USDC may not be perfectly aligned to the bit on its approach path, a likely scenario due to robotic arm joint inaccuracies. A conceptual design is shown in Figure 7.



The first MIDAS prototype is currently being manufactured by ASI and testing is anticipated to begin early in 2006. Table 4 provides a summary of MIDAS capabilities.

Table 4. MIDAS system summary

System Parameters	MIDAS
Power (W, average) in basalt	2 (< 80, peak)
Mass (kg)	< 2 (without arm)
Stowed volume (cm)	15 x 5 x 5 (without bits)
Weight on bit, WOB in basalt (N)	20
Maximum depth (m)	0.5
Borehole diameter (cm)	1.2
Sample type	1 cm diameter core, up to 0.5 m long
Automation target (see definitions in Table 2)	A2
Prototype completion; start of TRL5 testing	March 2006

Ultrasonic Sampler

The Ultrasonic Sampler is being developed by Honeybee Robotics. This tool utilizes ultrasonic vibration to penetrate Martian regolith as deep as 0.5 meter, using very low weight on bit, acquires roughly 0.5-cm^2 samples at pinpointed depths, and precisely transfers samples to instruments for observation.

Making direct measurements of the near subsurface regolith on Mars supports scientific analysis of soil and Aeolian processes, as well analysis of the radiation environment relevant to future human missions. To extend the sampler's mission applicability, testing will be conducted to investigate what concentrations and forms of H_2O and CO_2 ices the sampler can penetrate.

The fully robotically operated flight-like sampler design utilizes ultrasonic vibration to require loads on the order of only 10 N. This penetration method enables operation from low-strength manipulators, low-mass landed spacecraft, and/or in low-gravity environments. The fully mechanized sampler design is nearing completion and fabrication is underway.

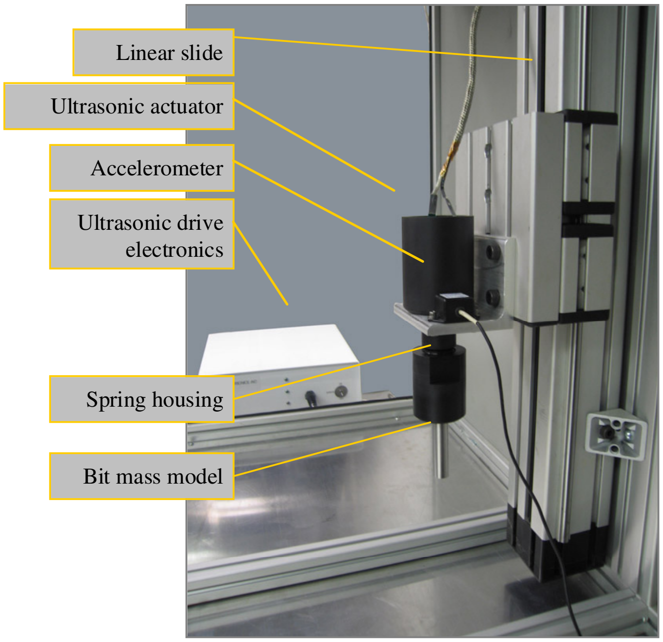


Figure 8 Breadboard setup of new generation ultrasonic actuator

The control algorithm that drives penetration into the subsurface based upon vibration feedback information is also being developed. Typical drilling methods, such as rotary-drag, achieve higher rates of penetration (ROP) with increased WOB. In ultrasonic drilling the ROP is optimized at a certain WOB, below which hammering impulses are not imparted sufficiently to the ground and above which hammering is damped out. This optimized performance regime can be characterized most directly by the maximized vibration in the system, which is the precise dynamic phenomenon responsible for the optimized performance. So, instead of closing the penetration control loop on WOB, the system responds to vibration data from an accelerometer mounted on the sampler structure, hence loading the sampler bit into the ground in its optimized performance range.

Plans for FY06 include:

- Development of penetration algorithm under active drive
- Testing of bit and auger types for penetration and clearing the borehole
- Testing the sampler mechanism
- Integrate test unit with full functionality
- Begin operating test unit in simulated operational environment, simulating temperature, atmospheric pressure and content, and regolith

Table 5 provides a summary of the Ultrasonic Sampler's capabilities.

Table 5. Ultrasonic Sampler system summary

System Parameters	Ultrasonic Sampler
Power (W, average) in basalt	< 30
Mass (kg)	< 4
Stowed volume (cm)	55 x 15 x 15
Weight on bit, WOB; in basalt (N)	< 20
Maximum depth (m)	0.5
Borehole diameter (cm)	1
Sample type	0.5 cm^3regolith
Automation target (see definitions in Table 2)	A2
Prototype completion; start of TRL5 testing	August 2006

3. DEEP SAMPLING

Deep (> 5 m) drilling on Mars presents a significant engineering challenge that can be addressed using the conventional drilling technologies adapted to the unique environment of the Mars surface missions, as well as novel approaches that are not typically used on Earth. The MTP is currently funding a deep drilling development that takes the former path. The Modular Planetary Drill System (MPDS), developed by Swales Aerospace, is a multi-segmented drill concept with a maximum depth capability of 20 m. (Figure 9)

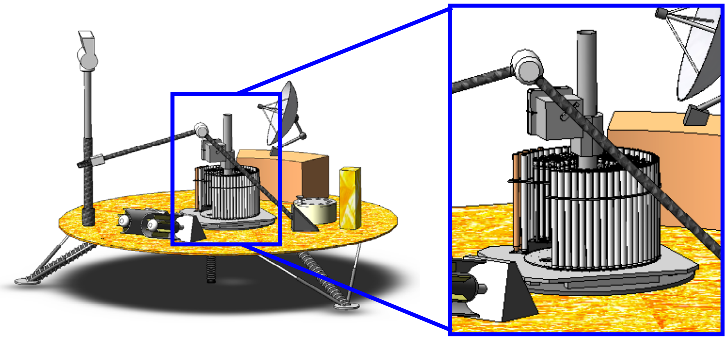


Figure 9. MPDS flight concept shown on a lander platform

The MPDS is a three-year technology development program to advance a 10-m deep drilling system to address 20-m subsurface access needs and possibly beyond. The resulting TRL-6 technologies will provide advanced capabilities for subsurface access on future planetary and lunar exploration missions.

The Modular Planetary Drill System (MPDS) is based on the Subsurface Planetary Exploration Core Extracting System (SPECES) drill system. This drilling technology was demonstrated in a 2002 field test in Arizona (Figure 10). SPECES was able to drill through 10 meters of sandstone without fluids using 80 to 100W (about the power of a light bulb) with a single drill bit [4]. Core samples were collected mechanically using core retainer features within the sample containers and delivered manually to the surface. The SPECES drill system used limited critical sensors. Load cells were integrated with the drill spindle to record force data, encoders to obtain rotational speed, power logger to obtain accurate power usage data, and a handheld IR temperature sensor to monitor heating of the sample container tip were used to evaluate drilling performance. Field-test force data indicated that the weight on bit (WOB) ranged from 22 to 220 N. Sample container tip temperature increased 5 to 10 ºF, which provided insight into sample heating, corresponding to the 8 to 30 W of actual drill power used to comminute the rock. Segment coupling and decoupling were conducted by remote control using a custom LabView interface.

The MPDS drill will semi-autonomously connected Multiple, 0.5 m drill segments. Swales' technology uses a custom bottom-hole assembly to minimize drilling power. The bottom-hole assembly contains the rock destruction and sample removal mechanisms. All subsurface samples are removed immediately after acquisition. The cuttings and 1.5-cm-diameter cores are collected and regularly brought to the surface via wire-line assembly without removing the drill segments from the borehole. Both types of sample, cuttings and cores are stored in individual, separate tubes at the surface. This approach isolates samples from different depths from each other, and preserves the sample for later investigation by in situ instruments. The drill segments serve as a casing to provide borehole stability, and are removed when the hole is complete and all needed samples have been collected.

While MPDS is based on the same solid drilling methodology as the SPECES system, the MPDS drill system will incorporate a more complete suite of sensors for operational controls, drilling performance and evaluations. Several critical subsystems are custom designed to optimize drilling performance and facilitate automation. MPDS will provide continuous subsurface samples while maximizing sample recovery and maintaining sample integrity.

Given the uncontrolled and unknown nature of the Martian subsurface, sensing, controls, and automation will be key elements in advancing this technology. So, a main focus of this development is testing the system in a wide variety of credible Mars-analog field sites. Three field tests will be conducted during the program. The first field test is scheduled for February 2006 at Idaho Falls, Idaho (hard, homogenous basalt). The system is being designed to drill and sample autonomously in hard heterogeneous materials, where it must deal with embedded rocks of various strengths (second field test). Understanding borehole deflection and dealing with stresses on the drill system in such scenarios are significant challenges that will be addressed in the remaining two years of this development. MPDS will also be field tested in permafrost to better understand the performance of this type of multi-segmented sampling system in this environment (third field test).

Figure 10. SPECES 10-m drilling field test, 2002

Swales' MPDS research is focused on understanding, characterizing, and solving issues related to planetary drilling to optimize future flight drill systems. Drill field test data will be studied to improve bit and system/component design. Failure and recovery modes will be evaluated and studied. Methods to optimize drilling performance into regolith, rock and ice mixtures will be developed. Modular system form factors will be determined for 0.5m, 2-4m and 20m drill systems. A suite of sensors will evaluate drilling performance and collect reaction force, torque, and vibration data to support drill platform requirements. A system analysis of mass and evaluation of design options necessary to achieve flight mission mass goals will be completed. Key MPDS mechanisms will complete Mars environment testing. The final result will be a TRL 5/6-drill system capable of drilling to 20m depths using low power while operating semi-autonomously.

MPDS technology development benefits and features include:

- Advancement of low-power drill technology
- Automated collection and delivery of core samples to the surface
- Minimization of sample contamination and heating to preserve sample integrity
- Advancement of automation of drilling operations
- Collection of reaction force data to support future drill platform requirements
- Drill field test data to improve bit and system/component design
- Evaluation and study of drilling failure and recovery modes
- Analysis of flight-like system mass
- Optimized modular system (form factors) for 0.5, 2-4m and 20m drill systems
- Optimized drilling performance into regolith, rock and ice mixtures

Table 6 provides a summary of MPDS capabilities.

Table 6. MPDS system summary

System Parameters	**MPDS**
Power (W, average) in basalt	< 100
Mass (kg)	< 100 (includes drill system, segments, sample containers, and sample management system)
Stowed volume (cm)	100 x 100 x 100
Weight on bit, WOB; in basalt (N)	< 400
Maximum depth (m)	20
Borehole diameter (cm)	3.4
Sample type	1.5 cm diameter, 10 cm long cores
Automation target (see definitions in Table 2)	A1
Prototype completion; start of TRL5 testing	February 2006

4. DRILLING AND SAMPLING AUTOMATION

In addition to the significant challenges of penetrating and sampling hard and heterogeneous substrates given low power and mass constraints, subsurface tools for Mars must possess robust and reliable automation. The systems just described have automation levels of varying sophistication and applicability. Because the level of autonomy called for can be driven by other mission operations parameters, such as the desire to keep the science team in the decision loop, advanced technology for automated drilling focuses on deep drilling, where significant improvements in overall drill times can be made.

Drilling Automation for Mars Exploration

The Drilling Automation for Mars Exploration (DAME) project's purpose is to develop and fieldtest drilling automation and robotics technologies for projected use in missions in the 2011-20 period. In this project, we developed a diagnostic approach taken for drill failures and fault identification and recovery, as well as the robotic and executive control aspects of a lightweight, 20-kg Mars-prototype drill, shown in Figure 11 during DAME summer Arctic field testing. This includes control of the drilling hardware, state estimation of both the hardware, and the lithography being drilled, and the state of the hole, as well as potentially planning and scheduling software suitable for uncertain situations such as drilling.

The possibility of significant per-hole drill time reductions and lowered drilling risks exists (perhaps to a few sols per hole on Mars), if drill automation can be increased to a level comparable to demonstrated Remote Agent-levels [5] or more.

Figure 11. 20-kg Mars prototype drill tested with vibration sensors in Haughton Crater on Devon Island, Nunavut, Canada

DAME included the study and benchmarking of hybrid diagnostic techniques in drill diagnosis, as well as applying fuzzy learning methods to the structural dynamics of drilling systems [6]. The latter was derived from previous work on the identification and control of helicopter shafts and other rotating structures [7]. The DAME approach used three types of automation:

a. Real-time limit checking and safing using a rule-based approach to monitor motor torques and temperatures

b. Near-real-time vibration measurement and fast frequency-domain pattern-matching using a neural net

c. In-line prognosis of degradation and wearout using model-based reasoning

Part (a) was implemented in the DAME drill executive and control software, while (b) and (c) were separate diagnostic and prognostic software modules.

The drill was deployed in 2004 and 2005 at two sites at Haughton Crater, operating at Mars-relevant power levels (max 150-200 W). Over eight days, it drilled 2.2 m in permafrost and the regolith-like breccia found in the Haughton impact crater. Eight drill faults were demonstrated during testing, as well as nearly 50 hours of nominal operations.

Table 7 provides a summary of DAME capabilities.

Table 7. DAME system summary

System Parameters	**DAME (Drilling Automation Testbed)**
Power (W, average) in permafrost	200
Mass (kg)	20
Stowed volume (cm)	150 x 50 x 50
Weight on bit, WOB; in permafrost (N)	400
Maximum depth (m)	2.2
Borehole diameter (cm)	4.8
Sample type	n/a
Automation target (see definitions in Table 2)	A3
Prototype completion; start of TRL5 testing	2004

5. TESTING

Field Testing

Field testing of drilling and sampling systems is essential not only for technology demonstration but as a developmental tool. Particularly for deeper systems (> 3 m), lab testing becomes impractical. A number of system aspects are uniquely tested in the field test scenario. Just as analog regolith simulants can be generated to test measurement precision of instruments, analog field test sites can be chosen to test various aspects of a drilling sampling system.

To aid the development and benchmark the performance of deeper subsurface sampling systems, MTP is supporting a series of Mars analog field tests. Testing locations are being chosen to provide successively more difficult engineering challenges to deep subsurface sampling systems (up to 20 m) in materials similar to those that may be encountered on Mars.

The timing and location for the first field test has been identified. Hard and relatively homogenous basalts of the Snake River basin in Idaho Falls has been chosen for the first field test in February 2006. Specific locations for the second and third field tests have not yet been determined. However, the second field test will take place in the Fall of 2006 at a site with heterogeneous mixtures of hard and soft rocks and unconsolidated materials. The third field test will be conducted in the Spring, 2007, at a permafrost site.

Benchmark Testing

In addition to field testing the MPDS 20-m sampling system, the MTP plans to conduct laboratory testing of the two 0.5-m regolith sampling systems. At the conclusion of their three-year awards (Fall 2007), MIDAS and Ultrasonic Sampler will be benchmarked in a shallow testbed with challenging Mars analog materials at JPL.

The motivation for this type of evaluation tests is two-fold. Providing a common testbed will allow mission planners, technologists, and the science community to evaluate the advantages and disadvantages of each particular sampling system. Typically, testing is conducted individually, with the test set-up and target material tailored to the system. Too often it is impossible to compare the strengths and weaknesses of various approaches because performance can be strongly linked to test specifics such as platform characteristics and target material properties.

6. MISSIONS OF INTEREST

Near-term missions addressed by these technologies include Mars Scout concepts that could utilize the low-force, low-mass sampling tools detailed here. The LSAS, MIDAS, and Ultrasonic Sampler systems use rotary percussive drilling techniques to penetrate the subsurface efficiently and collect samples with low-force requirements. This makes them ideal for low-mass and low-stiffness platforms such as small rovers and robotic arms. They also have the potential to sample from hard rocks and icy regolith mixtures.

Deeper drilling technology developments (MPDS), coupled with advanced automation (DAME), are providing viable options for the static lander plaform envisioned for the Mars Deep Drill Mission concept [8]. The small packaging volume and scalability of such multi-segmented drills also affords the possibility of a "mid-level" drill (2 to 5 m) that could be integrated on a large mobile platform, such as the Astrobiology Field Laboratory (AFL), in the future.

7. CONCLUSIONS

The need for access to the subsurface of Mars is critical to addressing the exploration objectives of the Mars science community. Complex tools that can operate reliably in the uncontrolled and largely unknown Martian environment necessitate innovative and flexible approaches. These are long-term developments that must be coupled with a relevant and thorough test plan to encourage integration in future landed missions.

Here we have presented five Mars Technology Program development tasks. The tools described range widely in function and applicability, from shallow regolith samplers to deep coring tools. Some may be appropriate for missions as early as 2011, while others are setting the groundwork for the highly complex deep sampling systems that will become necessary in future decades. In anticipation of the needs of future missions, MTP is constantly re-evaluating its technology goals for relevancy and directing funds to enabling technology concepts.

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10. BIOGRAPHY

Suparna Mukherjee is a systems engineer in the Mars Mission Concepts group at JPL. She is the technical lead for Subsurface Access in the Mars Technology Program. Previously she served as Director of Engineering Development at Honeybee Robotics, which specializes in the sampling of planetary surfaces and where the Mars Exploration Rovers' grinding tool was developed and tested. She has a BS in Mathematics from NYU, a BSME from the Stevens Institute of Technology and a MS in Applied Physics from Columbia University.