Realtime Sensing while Drilling using the USDC and Integrated Sensors

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Summary: *The search for existing or past life in the Universe is one of the most important objectives of NASA's mission. In support of this objective, an ultrasonic based mechanism is being developed to allow probing and sampling of rocks and soil. The novel lightweight Ultrasonic/Sonic Driller/Corer (USDC) used in this study takes advantage of its ability to drill with low axial force and low power. These advantages overcome some of the major limitations of planetary sampling using conventional drills in low gravity environments. Sensors, such as thermocouple and fiberoptics, are integrated into the bit and used to perform real-time analysis while drilling.*

Keywords: *Ultrasonic drilling, piezoelectrics, sensors, fiberoptics*
Category: *10 (Applications)*

1 Introduction

Future NASA exploration missions to Mars, Europa, Titan, comets and asteroids are seeking to perform sampling, in-situ analysis and possibly the return of material to Earth for further tests. For this purpose effective instruments that can sample and conduct in-situ astrobiology analysis are being sought. As sampling devices, existing drilling techniques are limited by the need for large axial forces and torques, high power consumption and an inability to efficiently duty cycle. Lightweight robots and rovers have difficulties to accommodate the constraints of existing drills. To address these constraints and the challenges to the NASA objective of planetary in-situ sampling and analysis, an ultrasonic/sonic driller/corer (USDC) was developed [1 – 3].

1.1 The USDC as a piezoelectric based drill

The USDC consists of an actuator, free-mass and a bit. The actuator is a piezoelectric stack and a horn for the amplification of the displacement. The actuator is driven in resonance at 20kHz and a stress bolt holds it in compression to prevent fracture during operation. Unlike typical ultrasonic drill where the drill stem is acoustically coupled to the horn in the USDC the actuator drives a free flying mass (free-mass), which bounces between the horn tip and the drilling or coring bit at sonic frequencies. The impacts of the free-mass create stress pulses that propagate to the interface of the bit and the rock onto which the USDC is placed in contact. The rock fractures when its ultimate strain is exceeded at the rock/bit interface. Under a variety of conditions, this novel drilling mechanism has been shown to be more efficient and versatile than conventional ultrasonic drills. The low mass of a USDC device and the ability to operate with minimum axial load with near zero torque (see Figure 1) offers important capabilities for sample acquisition and in-situ analysis. Another important characteristic of the USDC is its ability to operate in the harsh environments of space, which include low or high temperature and/or pressure.

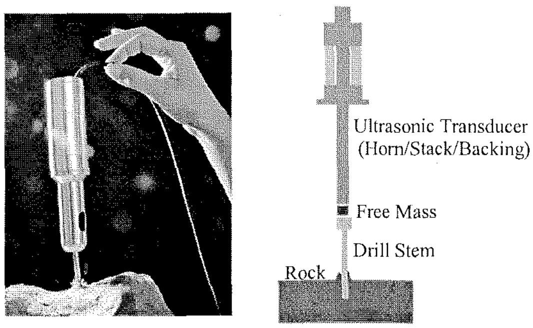

Fig. 1: The USDC is shown coring with minimum axial force and holding torque (left), and a schematic diagram of the USDC components (right).

1.2 Demonstrated characteristics

The USDC has been demonstrated to drill rocks that range in hardness from granite and basalt to sandstone and tuff. Other media that have been drilled include soil, ice and diorite, and limestone. This novel drill is capable of high-speed drilling (2 to 20-mm/Watt·hr for a 2.85mm diameter bit) in basalt and Bishop Tuff using low axial preload (<10N) and low average power (<12W). Drilling using average power levels as low as 5 Watts has been demonstrated. The USDC has drilled 25-mm deep, 6-mm diameter holes in basalt in a little over 2-hrs from a 4-kg platform using 10W average and 25W peak power. It has also drilled 15-cm deep, 5-mm diameter holes in sandstone in just over an hour using similar power as for the basalt drilling.

1.3 Comparison with conventional methods

The USDC ability to drill using low axial load creates new options for the exploration of low gravity bodies (e.g., comets and asteroids). A comparison between the USDC and conventional drills is given in Table 1. Unlike conventional drilling rigs, the USDC can drill or core rocks from very light and flexible platforms (e.g., Sojourner or Marie Curie rovers, robotic arms, etc.). Since the USDC does not have electrical motors, it can be duty cycled without significant loss of efficiency. This facilitates operations under very low average power (operation at 2 watts average power has been demonstrated). Unlike conventional drills, the drive mechanism of the USDC has only three moving parts, which are not physically connected and do not require lubricants. This design eliminates common mechanical failure modes and makes it easy to constrain during launch. The use of a piezoelectric stack as the USDC actuator permits the device to operate over a very wide temperature range. The drilling/coring bit does not rotate and does not require sharpening. The USDC can core arbitrary cross-sections (square, round, hexagons) and can accommodate drilling of vertical and overhanging rock faces.

The simplicity of the USDC based sampler reduces the number of possible contamination sources (e.g., lubricants and metallic filings from wear on the gears). The acoustic vibration of the bit provides for transport of the powdered cuttings away from the bit/sample interface. This design minimizes cutting edge wear and prevents particle entrapment unlike conventional composite drilling bits (e.g., diamond cutters on silicon carbide substrate with metal holders). The USDC can also use bits manufactured from a single element (e.g. Tungsten) and could thereby minimize the sources of trace metallic and abrasive elements.

Non-traditional (or "modern" in the oil industry terminology) drilling technologies (laser, electron beam, microwave, jet, etc.) usually are competitive only in applications that are time limited (time is money in oil industry) and not power/mass limited as is typical for space science applications.

Typically, the down-the-well energy that is required to remove a unit volume of rock for "modern" technologies is the same as grinding and melting. The required energy is 3 and 5 times higher, correspondingly, than that for shear drilling. Generally, the ratio of power delivered down-the-well vs. input power generation for these non-traditional approaches is below several percent vs. 10%-30% for conventional drills (comparable to USDC). Consequently, many space missions do not have enough power to employ these "modern" drilling technologies.

2 Lab-on-a-Drill

The USDC novel characteristics allow it to be used not only as a sampling tool where cores and dust can be acquired but also as a probing device. The sonic and ultrasonic hammering action on the bit allows using it as a sounder for probing the

TABLE 1: Comparison between the USDC and conventional Drills

	Conventional Drills	**USDC**
Axial preload	>100N (typically 150N)	<10N
Drill walk at core initiation	>30N·m induced torques and >100N tangential forces	<10N
Average power to create 10-mm core	>20-30 W. Can be reduced but the drilling efficiency goes down.	Can be as low as 2-3W (lower power requires longer drilling)
Duty cycling for a reasonable Period (10s)	loss of efficiency due to startup currents	Very little efficiency loss (2W average at 25W peak was demonstrated)
Start Current Overshoot	3-4 times larger than those during continuous operations	<20% even with duty cycling.
Drill chatter	Induces low frequency (2-10Hz) and high force perturbations on the drilling platform	Minimal disturbance to the drilling platform. Permits precise drilling in the desired location.
Support system	Requires stable and massive platforms with solid anchoring	Minimal
Mechanism of rock fracture	Shearing and spalling	Compression failure
Drilling/Coring hard rocks	Grinding with corresponding 300% increase in energy consumed per unit volume of removed rock	Spalling No need for drill bit sharpening

drilled medium. Further, the longitudinal displacement of the bit without rotation allows mounting of sensors for real-time analysis of the drilled medium. The combination of sampling probing and sensing allows the USDC to be used as a lab-on-a-drill system. In order to allow effective design of the USDC it was analytically modeled and predicted drilling rates and power levels were corroborated experimentally with a reasonable accuracy [1].

3 USDC with integrated sensor suite

Since the USDC bit does not turn and its vibration amplitude is relatively small one can easily mount sensors on the bit and conduct real-time tests during drilling or coring. Two types of sensors were successfully demonstrated todate: thermocouple and fiberoptic. The thermocouple was used to measure the rate and maximum rise of temperature and these values were found to correlate to the hardness of the rock being drilled. Even though these thermal variables are dependent on the heat conductivity and capacity of the drilled object, one can assume with a reasonable accuracy that most rocks have thermal properties within a comparatively narrow range. Compiling temperature rise rate and maxima as a function of time for variety of drilled materials has demonstrated the feasibility of using a thermocouple-on-the-bit as a means of assessing the drilled medium hardness (see Figure 2).

Other tests using an optical fiber that was approximately 160 μm in diameter was imbedded into 10-mm diameter coring bit with a 1-mm wall thickness. Reflection data in the wavelength range of 400-1200 nm were recorded. The results of this study will be reported.

4 Analytical modeling the operation of the USDC

Coring via the USDC mechanism involves rock fracture under impact loading (percussion). To

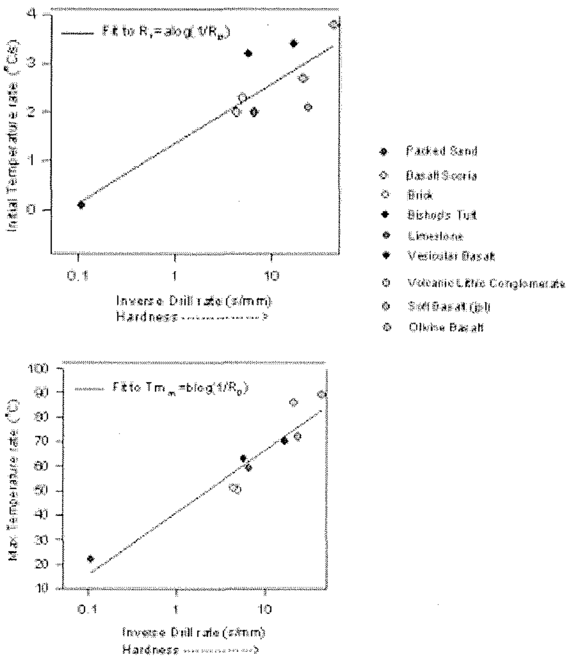

Fig. 2: The measured temperature maxima and initial temperature rate as a function of hardness (inverse drilling rate) for variety of media.

better understand the fracture of rocks under this impact loading, a finite element model using ANSYS (a finite element software package) was developed to investigate the propagation of the induced stress. Results were derived by assuming that the rock medium is made of isotropic material with a Young's modulus of 10 GPa and Poisson's ratio of 0.3. Examples of data for various soil and rock types and the related range of Young's modulus are listed in Table 2. Contour maps of the maximum principal strain were plotted and used to indicate the areas where the rock is fractured and to determine how the elastic waves propagate in the rock prior to fracture. This analytical capability allows for an estimate of the limitations on the diameter of the cored material that maintains

Soil conditions and/or Rock Type	Young's Modulus
Loose sand	10-25MPa
Medium dense sand	20-60MPa
Dense sand	50-100MPa
Sedimentary sandstone	10-60GPa
Igneous Basalt	60-80GPa
Sedimentary limestone	60-80GPa
Igneous Anorthosite	83GPa

TABLE 2: Typical values of the elastic modulus for soils and rocks

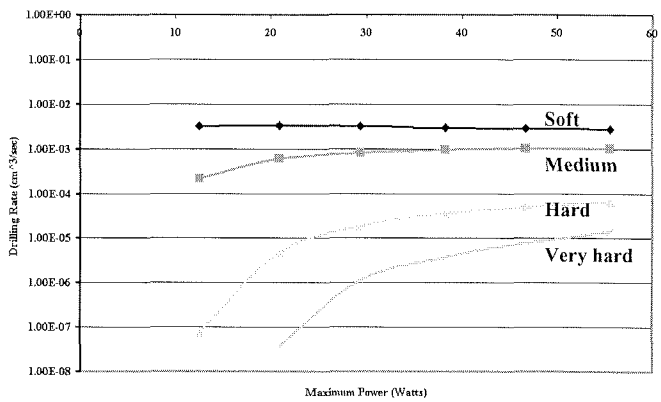

Fig. 3: Analytical drilling rates in rocks with various hardness levels using 10W average power. The rocks are classified by their compression strength, where: Soft: 0 – 50; Medium: 50 – 100; Hard: 100 – 200; and Very hard: >200 (MPa).

structural integrity. Using this analysis, it is estimated that the minimum diameter of intact cores that can be produced is about 4-5 mm for medium to hard materials. The drilling rates in various rocks at 10-W average power were calculated and a graph is shown in Figure 3 for various rock stiffness values. This capability to predict the performance of the drill allows optimizing the design of effective USDC units.

5 Summary

The USDC is being investigated for potential planetary applications as a Lab-on-a-drill. The capability to use it with integrated sensors was investigated and two types of sensors were examined including thermocouple and fiberoptics. The thermocouple was shown to assess the hardness of the drilled medium using the rate and maximum rise of the temperature. Further, reflection spectral data was examined using a imbedded optical fiber in a coring bit-. Other fibers using low wavelength UV excitation are being considered for detection of biological markers using biofluorescence.

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