Drilling, Coring and Sampling Using Piezoelectric Actuated Mechanisms: From the USDC to a Piezo-Rotary-Hammer Drill

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ABSTRACT

NASA exploration missions are increasingly including sampling tasks but with the growth in engineering experience (particularly, Phoenix Scout and MSL) it is now very much recognized that planetary drilling poses many challenges. The difficulties grow significantly with the hardness of sampled material, the depth of drilling and the harshness of the environmental conditions. To address the requirements for samplers that could be operated at the conditions of the various bodies in the solar system, a number of piezoelectric actuated drills and corers were developed by the Advanced Technologies Group of JPL. The basic configuration that was conceived in 1998 is known as the Ultrasonic/Sonic Driller/Corer (USDC), and it operates as a percussive mechanism. This drill requires as low preload as 10N (important for operation at low gravity) allowing to operate with as low-mass device as 400g, use an average power as low as 2-3W and drill rocks as hard as basalt. A key feature of this drilling mechanism is the use of a free-mass to convert the ultrasonic vibrations generated by piezoelectric stack to sonic impacts on the bit. Using the versatile capabilities of the USDC led to the development of many configurations and device sizes. Significant improvement of the penetration rate was achieved by augmenting the hammering action by rotation and use of a fluted bit to remove cuttings. To reach meters deep in ice a wireline drill was developed called the Ultrasonic/Sonic Gopher and it was demonstrated in 2005 to penetrate about 2-m deep at Antarctica. Jointly with Honeybee Robotics, this mechanism is currently being modified to incorporate rotation and inchworm operation forming Auto-Gopher to reach meters deep in rocks. To take advantage of the ability of piezoelectric actuators to operate over a wide temperatures range, piezoelectric actuated drills were developed and demonstrated to operate at as cold as -200^{o}C and as hot as 500^{o}C. In this paper, the developed mechanisms will be reviewed and discussed including the configurations, capabilities, and challenges.

Keywords: Sampling, Ultrasonic/Sonic Driller/Corer (USDC), Auto-Gopher, Subsurface exploration, extreme temperatures drilling

1. INTRODUCTION

NASA exploration missions of the various planets in the solar system are increasingly consisting of in-situ sampling and analysis in search for life as well as presence of water and resources. Rotary mechanisms of sampling require high axial forces and holding torques, high power consumption without ability to efficiently duty cycle, and they also require heavy equipment. To address these limitations, the JPL's Advanced Technologies Group [http://ndeaa.jpl.nasa.gov] developed the USDC

(**Figure 1**) [Bar-Cohen et al., 1999; Bao et al., 2003; Bar-Cohen and Zacny, 2009]. This development was followed with many innovative designs that were developed and disclosed in NASA New Technology Reports and patents [for example, Aldrich et al., 2008; Badescu et al., 2006a; 2006b; Bao et al. 2004; 2010; Bar-Cohen et al. 1999; 2001; 2003; 2008; 2010; Bar-Cohen and Sherrit. 2003a; 2003b; Dolgin et al. 2001; Sherrit et al. 2001; 2002; 2003; 2006; 2006; 2008; 2009; 2010a; 2010b]. The USDC requires low axial force making it attractive for operation in low gravity environments allowing to drill and core hard formations using relatively small preload and low mass hardware. The USDC was demonstrated to: 1) drill ice and various rocks including granite, diorite, basalt and limestone; 2) not require bit sharpening; 3) operate at low and high temperatures; 4) operate at low average power using duty cycling; and 5) hosting integrated sensors for measuring various properties. A series of modifications of the USDC basic configuration led to the development of the Ultrasonic/sonic Rock Abrasion Tool (URAT), Ultrasonic/Sonic Gopher for deep ice drilling, the Auto-Gopher for deep drilling in rocks and regolith, the Lab-on-a-drill and many others.

The USDC consists of three key components: actuator, free-mass and bit (see **Figure 1**) [Bao et al, 2003], where the actuator acts as a hammering mechanism hitting the free-mass and thus the bit fracturing the medium underneath. The actuator is driven by a piezoelectric stack having backing designed to forward the generated impact power and in the front a horn for amplifying the induced displacements. The piezoelectric stack is driven in resonance, which is about 20-kHz in the basic configuration, and is held by a stress bolt in compression to prevent fracture during operation. In contrast to typical ultrasonic drills, which have the bit physically connected to the horn, in the USDC the actuator hammers a free flying mass (free-mass) that bounces between the horn tip and the top of the bit converting the ultrasonic impacts to sonic frequency hammering. The impacts of the free-mass generate stress pulses at the interface of the bit and the rock that propagates and fracture the rock when its ultimate strain is exceeded.

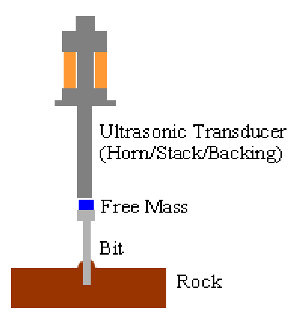

Figure 1: A schematic diagram of the USDC cross-section (left), and a photograph showing its ability to drill with minimum axial force (right).

2 ANALYTICAL MODELING THE USDC OPERATION

The USDC operates as a percussion mechanism and it drill via impact loading by fracturing rocks under the Kerf (the bit cutting zone). To better understand the fracture of rocks, a finite element model 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 Poisson's ratio of 0.3 and Young's modulus of 10 GPa. The maximum principal strain contour maps were investigated in order to determine the where the rock fractures and how the elastic waves propagate prior to the rock fracture. The developed analytical capability provides the needed tool for designing effective drills. Using this analysis, it was determined that for medium to hard rock hardness values the minimum diameter of intact cores that can be produced is about 4-5 mm [Bao et al., 2003]. Also, the tool was used to determine the drilling rates of various hardness rocks when using 10 W average power and the results are shown in **Figure 2**. This capability to predict the performance of the drill allows designing effective USDC mechanisms and examining the performance of various configurations.

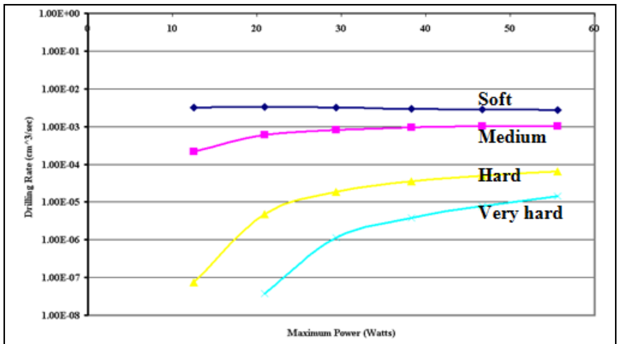

Figure 2: Analytical drilling rates in rocks with various hardness levels using 10W average power. The rocks are classified by their compression strength, where: Soft: 0 – 50; Medium: 50 – 100; Hard: 100 – 200; and Very hard: >200 (MPa).

3. LAB-ON-A-DRILL

Since the USDC is a percussive mechanism where the bit is not rotated, sensors can be attached to the bit and operated while drilling with no concern to wire entanglement. Also, the hammering action on the bit makes it a sounder and allows for probing the drilled medium. The combination of functions that the USDC can provide in a single device, including sampling, probing and sensing enables making a lab-on-a-drill system. For testing integrated sensors, two types were successfully demonstrated to date: thermocouple and fiberoptic [Bar-Cohen and Sherrit, 200b].

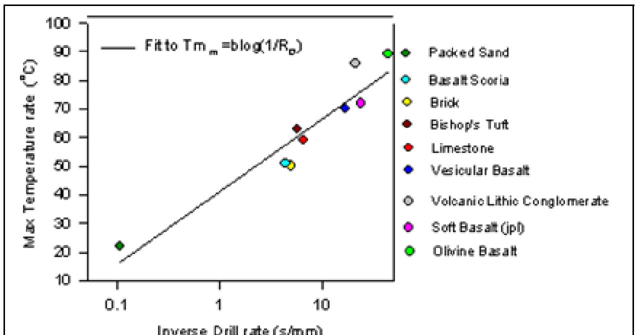

Figure 3: The measured temperature maxima and temperature rates as a function of hardness (inverse of the drilling rate) for variety of media.

A thermocouple was used to measure the rate and maximum rise of temperature and the measured data was well correlated 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 a 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 3**). The use of optical-fiber provided a sensing capability where a fiber with approximately 160 μm 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. Generally, fiberoptics with UV light in the range of 200-nm wavelength may allow for identifying biological markers offering important sensing tool for future NASA exploration missions.

4. USDC-BASED DEVICES

4.1 Ultrasonic/Sonic Anchor

The USDC capability to drill via low axial load enabled the development of an anchoring capability for legged rovers to climb steep slopes as well as secure inflatable structures for accessing rugged extraterrestrial terrains. This U/S anchor is a low mass device, using relatively low power. The device was designed and fabricated using a modification of the USDC mechanism and was demonstrated to allow supporting objects mounting on rock surfaces. Operating the hammering action of the USDC in reverse allows its extraction from the medium onto which it is anchored avoiding potential jamming. Schematic illustration of the developed anchor is shown in **Figure 4** and includes an in-and-out hammering capability [Bar-Cohen and Sherrit, 2003a]. Initial breakout tests using prototype bits showed that they withstood bending moments of 18 N-m. The tests, made on a vertical face block of Santa Barbara Limestone, showed that rock breakout occurs at hole depths of about 10 mm for a 9 mm diameter bit (at 15^{o} horizontal). Deeper holes (17 mm) allowed for 18 N-m moments without breakout.

Figure 4: The in-and-out anchoring USDC.

4.2 Packed Soil Penetrator

Penetrating packed soil to a depth of about 1 m using up to 2 mm diameter probes via low axial load is a great challenged that was addressed using. Generally, pushing a rod into a packed soil requires several hundred pounds force and may cause buckling of the probe. A novel Ultrasonic/Sonic Impacting Penetrator (USIP) was developed and demonstrated to greatly reduce the required push force [Bao et al., 2004]. An illustration of the drill cross-section is shown in **Figure 5**. In demonstrating the USIP it was shown that the required push force to penetrate highly packed soil down to about 1-meter was reduced from about 200 to 3 kg.

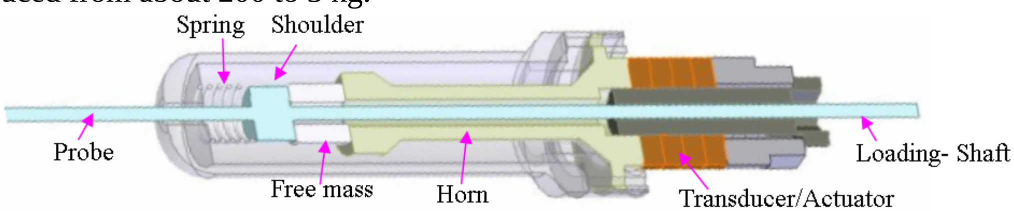

Figure 5: A schematic view of the USIP.

4.3 Ultrasonic/Sonic Gopher for penetrating ice

Penetrating ice to great depth, a USDC-based Gopher with a 6.4 cm diameter bit was developed [Bar-Cohen et al., 2001; Badescu et al, 2006]. This drill was made with an actuator that is slightly smaller in diameter than the bit in the form of a wireline penetrator (**Figure 6)**. This drill creates cores up to the internal length of the bit then the Gopher is removed from the borehole and this process is repeated till the desired borehole depth is reached. Since the developed drill was intended for operation at low temperatures the USDC was tested in a cold chamber for various periods in as low as -60^{o}C. To demonstrate the capability of the Gopher it was tested to drill glacier ice at Mt. Hood, OR and the lessons learned were implemented into the design of an enhanced Gopher that was tested in Antarctica. The field test in Antarctica was conducted at Lake Vida and it provided an important opportunity to demonstrate the feasibility of this technology while determining the associated challenges and requirements to enhance its capability for future drilling objectives. The unit was successfully used to reach 1.76-m deep and it is significantly deeper than the length of the whole Gopher and its support elements.

4.4 Deep penetration of sub-surfaces using the Auto-Gopher

Deep penetration of the sub-surface of extraterrestrial planets and acquire samples are critical capabilities for future NASA in-situ exploration missions to bodies in the solar system. For missions to Mars, deep penetration thru several meters is necessary to penetrate the subsurface beyond the oxidized and sterilized zone in order to acquire pristine samples. Using lessons learned from the development of the U/S [Bar-Cohen et al., 2008], jointly with Honeybee Robotics an Auto-Gopher is currently being developed. This device is a rotary-hammering drilling and coring mechanism that employs a piezoelectric actuated percussive mechanism for breaking formations while electric motor-generated rotation removes the cuttings. To provide preload for the rotary mechanism an anchoring mechanism is used. The percussive and rotary motions of the Auto-Gopher are activated simultaneously to reach optimal penetration rate. The percussive action is generated by a USDC-based mechanism and is duty cycled to maintain low power operation. Similar to the U/S Gopher, the Auto-Gopher is a wireline mechanism that allows thru cyclic coring and core removal to reach great depths in sub-surfaces. The Auto-Gopher (**Figure 7**) is being developed to reach as deep as 3 to 5 meters in rocks and regolith. .

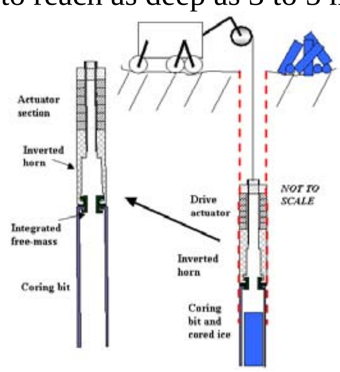

Figure 6: Schematic view of the ultrasonic/Sonic Gopher inside the borehole.

Figure 8: Using the Auto-Gopher, the first core (57.25 mm diam. and 97.25 mm long) that was produced of limestone (Photo courtesy K. Zacny, Honeybee Robotics).

Percussive Augmenter of Rotary Drills (PARoD)

Rotary drills are widely used in commercial applications. While rotation offers an effective method of cutting removals, hammering is superior in fracturing the formation. In order to enhance the performance of rotary hammers, a percussive augmenter was developed using piezo-actuated mechanism [Aldrich et al., 2008]. These include one with vibrating free-mass (sonic impacts) and one that operates without a free-mass. The bit employs electric and mechanical slip-rings to transfer electric power while freely turning the bit. The use of the hammering augmentation was shown to increase the rate of drilling by as much as 10 times when using 6.4 mm diameter bit and a fix total power of 160 Watts compared to drilling with rotary only.

5. ACTUATORS WITH NOVEL HORNS

The horn is one of the most important parts of the USDC actuator. It amplifies the vibration amplitude that is generated by the piezoelectric transducer. The most common horn configuration is the step down diameter from the one that the piezoelectric stack has and thus gaining in amplitude from the related reduction in the surface areas.

5.1 Dog-bone shape horn

To improve the drilling performance, to enable effective bit mounting, and operating with dual free-mass forward and in reverse a dog-bone horn design was introduced and demonstrated [Chang et al., 2004; Sherrit et al., 2001]. For this purpose, various horn designs were examined analytically and compared to conventional horns and it was shown analytically that the dog-bone design has superior performance. For this purpose, various designs were modeled using finite elements analysis to determine optimal parameters and it was shown that dog-bone horn excites much larger tip displacement and velocity.

5.2 Folded/Flipped horn

In applications with volume constrains, the length of the horn poses a concern and it can be critical to shorten it. For this purpose, folded and flipped horns were developed with hollow configuration that amplifies vibrations of high power actuation mechanisms [Chang et al., 2004; Sherrit et al., 2001]. This horn can be configured in axis-symmetric and planar shapes to enable various manufacturing options. The use of reflectors at the folds allows for control of the phase of the reflected strain wave and for the introduction of constructive bending vibrations that enhance the amplification of the actuation.

5.3 Rotary-hammering sampler actuated by a single piezoelectric actuator

To minimize the complexity of using multiple actuators in rotary-hammering drills, a solid-state rotary-hammer drill driven by a single piezoelectric stack actuator was developed and demonstrated [Sherrit et al., 2009]. The actuator consists of a horn that has a helical slots configuration that apply rotation forces that turn the bit (acting like a rotor) onto which it is pressed but it is also subjected to longitudinal vibrations (**Figure 8**). Effectively, the slots convert some of the axial vibrations from the piezoelectric stack into twisting motion on the horn surface. The produced tangential force on the horn surface turns the bit that is pressed against it via a compressive force from the bolt through a bearing, and a high stiffness spring. The impacts and shear forces fragment the drilled medium directly under the bit kerf by exceeding the medium tensile and/or shear strength. This fracturing process is highly enhanced by the shear forces from the rotation and twisting action. To remove the formed cuttings, the bit is constructed with an auger on its surface. Generally, one of the problems with pure hammering is that as the teeth become embedded into the sample the drilling efficiency drops unless the teeth are moved away from the specific foot-print location. By rotating the teeth, they are moved to new areas that were not fragmented and enhance the rock fracture via shear forces. The shear motion creates ripping or chiseling action to produce larger fragments to increase the drilling efficiency and reducing the required power.

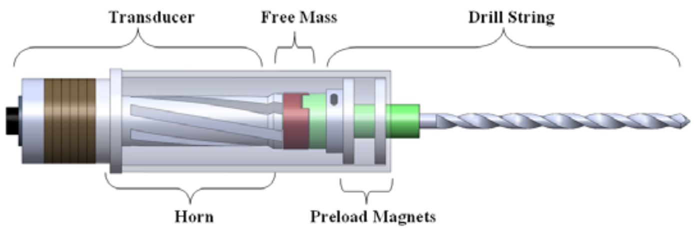

Figure 8: The piezoelectric rotary-hammer drill consisting of a transducer and amplifying horn, a keyed free mass, and a drill bit that is preloaded against the free mass and horn using repelling magnets.

6. USDC WITH VARIOUS BITS

6.1 Ultrasonic/Sonic Rock Abrasion Tool (URAT)

Abrasion of the surface of a rock using low axial force and limited average power is needed to remove weathered layers from rock surfaces and expose pristine surfaces. Conventional rotating mechanisms require high axial loads and they are involved with contamination sources such as lubricants and ground filings from their motor gearbox. The use of the USDC offers significant advantages in requiring low axial force, low average power, low number of components, and the capability to produce a mechanism of removal of powered cuttings from the borehole. In its original configuration, the USDC was not designed to remove layers of weathered material from rocks. To address this need an Ultrasonic Rock Abrasion Tool (URAT) was developed consisting of an abrasion bit with a hammering surface similar of a meat tenderizer [Dolgin et al., 2001]. Teeth were machined onto the bottom of the disk that is part of the abrasion bit. These teeth amplify the drilling pressure and enhance the action of the URAT. The URAT was designed with abrasion disk having 40-mm that is attached to a shank that fits around the horn. The free-mass is placed inside the shank between the horn and the bottom of hole along the inner part of the bit. On the bottom of the disk teeth, were machined in the form of pins that stick out of the disk.

6.2 Interchangeable bit

One of the most promising benefits of the USDC is the simple interface it provides to the bit, and the simplicity of the shape of the bit itself. The use of multiple bits is essential in order to perform multitude of tasks with a single USDC device including drilling, coring, surface preparation, and sampling. For this purpose, a USDC system with interchangeable bits and a manipulator arm was developed [Bar-Cohen et al., 2002].

6.3 All in one bit

The use of multiple bits requires a manipulation system to exchange bits as needed. If a manipulation system is not available it is highly desirable to accomplish as many functions as possible using a single bit. For this purpose, an all-in-one bit and was developed and demonstrated. The bit consists of a tube with a wedge at the top of the inner surface, a set of springs near the tip and a push rod that is inserted thru a center hole in the bit [Bar-Cohen et al., 2001]. Once a core is produced at a length of the inner section of the bit, the wedge introduces transverse forces at the top of the core to cause maximum stress near the root and shear fracture. The side springs hold the produced core for removing from the borehole. The core from the bit is extracted when needed using the push rod from the top of the bit.

6.4 Powdered cuttings sampler

In prior development of powder cuttings samplers, the authors have shown that the USDC produces powered samples directly from rocks. This include the design of a bit with trapping cavities that acquire the upward traveling powder that enter a hollow inner section of the bit and retain the particles until they need to be collected or disposed of. Using analytical models that the authors developed for the planar folded horn configuration [Chang et al., 2004] a compact sampler weighing 265-g was designed. A hollow bit was made with an end-effector section that is brazed on the bit and has teeth to enhance the cutting performance. The bottom of the bit was made with holes that allow for the penetration of the produced cuttings to enter into the hollow section. In order to trap the powder, the holes were made with a narrower section on the bottom such that the odds of exiting the hole once the powder enters the trap are minimized. Tests of the powder that is produced by USDC based mechanisms have shown that it does an outstanding job of generating powders for high quality X-ray diffraction spectra [Blake et al, 2003 and Chipera et al, 2003]. XRD patterns obtained from USDC generated powder essentially indistinguishable from powders that were obtained using a laboratory Retsch mill. Also, the particle size distributions are quite comparable to the costly standard laboratory Retsch mills.

7. SUMMARY

The ultrasonic/sonic driller/corer (USDC) has been the subject of extensive studies at JPL exploring various potential planetary applications. To allow effective design and construction of various modifications of the USDC an analytical model was developed to predict its behavior towards the goal of optimizing its performance. Physical models were developed for each section of the device and their interfaces. The developed models were integrated to allow investigation of the various interactions of the USDC and effective designs to support various applications. Various designs were developed and demonstrated including the Lab-on-a-Drill, Ultrasonic/Sonic Gopher, Auto-Gopher, soil penetrator and many others and various configurations of the horn and the bit were used to provide multifuncitonality. The Lab-on-a-Drill was conceived to take advantage of the probing capabilities of the USDC, its ability to sample cores and powdered cuttings as well as the fact that sensors can be easily mounted on the bit and allow real time data acquisition while drilling. The URAT was demonstrated to remove surface layers from rocks as hard as basalt. The Ultrasonic Gopher operates in a cyclic mode of coring, uploading, core caching and downloading. This device was demonstrated to drill in ice in Antarctica reaching about 1.76-meter depth. The lessons-learned from this Gopher was followed with the current development of the Auto-Gopher. The potential of the USDC is continuing to be investigated with the goal of taking the most benefits from its potential.

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