Auto-Gopher – a Wireline Deep Sampler Driven by Piezoelectric Percussive Actuator and EM Rotary Motor

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Abstract

The ability to penetrate subsurfaces and perform sample acquisition at depth of meters may be critical for future NASA in-situ exploration missions to bodies in the solar system, including Mars and Europa. A corer/sampler was developed with the goal of enabling acquisition of samples from depths of several meters where if used on Mars would be beyond the oxidized and sterilized zone. For this purpose, we developed a rotary-hammering coring drill, called Auto-Gopher, which employs a piezoelectric actuated percussive mechanism for breaking formations and an electric motor that rotates the bit to remove the powdered cuttings. This sampler is a wireline mechanism that can be fed into and retrieved from the drilled hole using a winch and a cable. It includes an inchworm anchoring mechanism allowing the drill advancement and weight on bit control without twisting the reeling and power cables. The penetration rate is being optimized by simultaneously activating the percussive and rotary motions of the Auto-Gopher. The percussive mechanism is based on the Ultrasonic/Sonic Drill/Corer (USDC) mechanism that is driven by piezoelectric stack and that was demonstrated to require low axial preload. The design and fabrication of this device were presented in previous publications. This paper presents the results of laboratory and field tests and lessons learned from this development.

Keywords: Drilling, Deep drill, Auto-Gopher, USDC, Planetary Sampling

1. INTRODUCTION

As part of the Jet Propulsion Laboratory (JPL)/National Aeronautics and Space Administration (NASA)'s planetary exploration missions, its scientists and engineers are developing in-situ sample acquisition mechanisms. The mechanisms need to be compact, efficient, low mass, and consume low power. To support this need, researchers at JPL's Nondestructive Evaluation and Advanced Actuators (NDEAA) Laboratory and Cybersonics, Inc. have developed the Ultrasonic/Sonic Drill/Corer (USDC) [Bar-Cohen, et al, 1999, 2000, 2001 a, b], featured in Figure 1A.

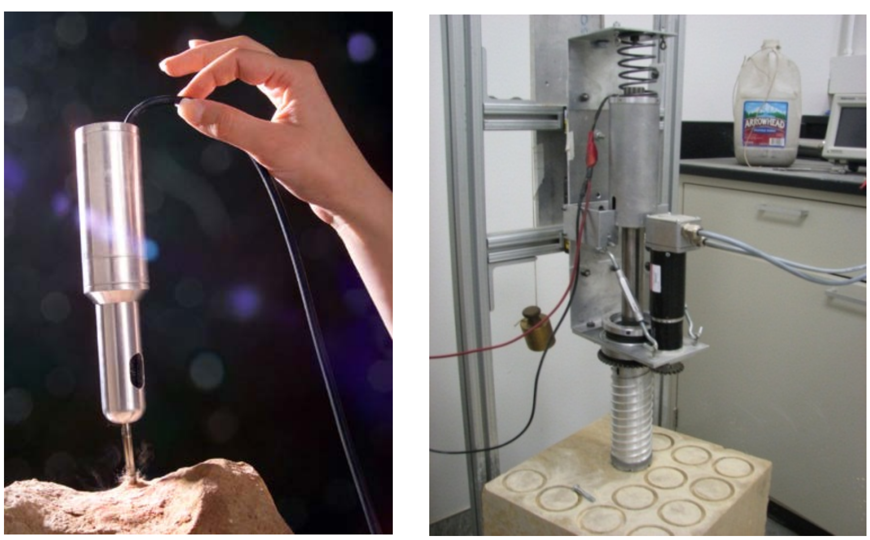

Figure 1 A. (Left) Ultrasonic/Sonic Driller/Corer (USDC); B. (Right) Lab version of the Auto-Gopher.

This drill is superior to conventional ones, particularly for its ability to be activated by low axial load, making it attractive for exploration of planetary bodies with low gravity. The USDC operates using a piezoelectric actuator to vibrate a horn, which then impacts a free mass. The free mass produces stress pulses on the drill bit which induces stress on the rock causing it to fracture [Bao et al., 2010]. Additionally, using a wireline design allows the USDC to drill to greater depths than conventional drilling mechanisms which use additional drill segments to reach similar depths, thereby adding to the volume, mass, and mechanical complexity of the sample-collecting system [Badescu et al., 2005, 2006a, Bar-Cohen et al., 2005, 2007, 2008, 2009]. A wireline drill is a suspended on a tether in the drill holes. All the subsystems required to provide the drilling mechanism, force control and cuttings managements need to be integrated into a tube that fits behind the drill head. A new drill design that employs a piezoelectric actuated percussive mechanism for breaking formations and an electric motor for rotating the bit to remove the powdered cuttings has been in development by a joint team from JPL and Honeybee Robotics [Badescu et al., 2006b, 2008]. A lab version of the Auto-Gopher (Figure 1 B.) was developed and tested at the NDEAA lab and the results were integrated into the wireline field version [Bao et al., 2002, 2003, Sherrit et al., 2000, 2001, 2004]. The operating parameters that were explored using the lab version are the duty cycle, the free mass size and geometry, preload, weight on bit, rotary speed, and the input voltage to the percussive actuator.

2. DESIGN, FABRICATION

The wireline Auto-Gopher operation requires that the drill whole body fits in the hole created by the drill head (Figure 2) [Paulsen et al., 2012; Zacny et al., 2012a, b, 2013]. All the drill components: drill bit, percussive component, rotary component and anchor and linear feed component have to be sized and packaged to fit the created cylindrical hole. The drill bit is a coring tube with outside flutes and three inner chambers: a core chamber designed to house the created core, a cuttings chamber to collect the cuttings created during coring, and a free mass cup for housing the free mass and the piezoelectric actuator horn tip. On the outside is has three flutes that guide the cuttings into the powder compartment. The active element is a crown threaded onto the bit that can have 3, 4 or 6 carbide cutting teeth. The hole created by the bit is 71 mm diameter and the core size is 60 mm diameter and 100 mm length. Upon creating a core the drill is extracted from the hole, the core is retrieved and the cuttings chamber emptied.

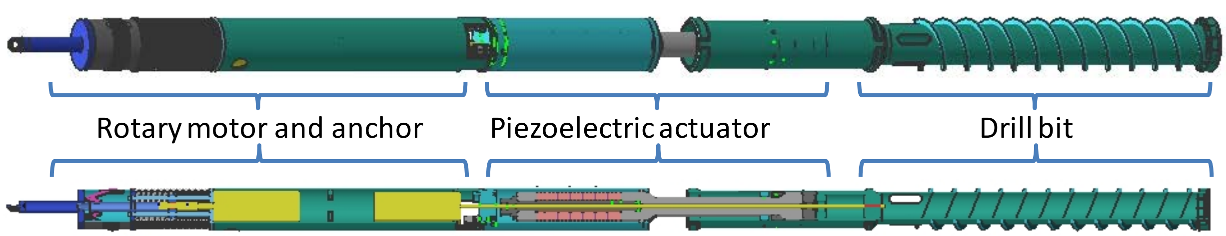

Figure 2 The wireline Auto-Gopher components

The percussive component includes the piezoelectric actuator, the free mass, and the preload mechanism. The piezoelectric actuator consists of a stack of PZT rings maintained in compression between a backing and a horn by a prestress bolt. The horn has a dog bone shape and amplifies the vibrations of the PZT stack. Its tip acts like a hammer and impacts the free mass that in turn transfers the impact to the bit. The free mass acts as a frequency transformer from high frequency vibration of the piezoelectric actuator to a sonic frequency of 60 to hundreds of Hz. For higher impact transfer efficiency the free mass was made out of a high hardness steel the same as the base of the free mass cup in the drill bit. As the free mass starts bouncing between the bit and the horn tip a gap is created in the space between the horn tip and drill bit. The preload mechanism applies a constant force on the actuator and the value of this force controls the size of the gap between the horn tip and the drill bit and hence the frequency of the free mass impacts.

The rotary component consists of a set of 3 EM actuators with a combined electrical power of 360 W and can provide to the drill bit a torque 15.5 Nm at 100 RPM. The liner feed component consists of an internally actuated ball screw and can provide the linear advancement of the drill bit while controlling the weigh on bit. The anchor uses a set of three compliant shoes to push against the borehole with a force of up to 1600N. This force is sufficient to overcome the reaction from the bit rotation and the axial weight on bit.

The lab version designed and built in our lab needed to determine the optimal design and operating parameters of the percussive component and so it is simpler than the full Auto-Gopher version. All components are still present but the implementation does not allow deep drilling. For ease of fabrication we chose to use a side mounted rotary component and a linear slide (Figure 1 B).

A block diagram of the experimental setup of the lab version is shown in Figure 3. The rotary and percussive components are controlled separately. A function generator produces the drive signal which is amplified and sent to the piezoelectric actuator. An oscilloscope reads the voltage and current of the drive signal and feeds the information to a computer program running Labview code. The computer program compares the phases of the two received signals and uses a hill climb algorithm to determine the signal frequency to drive the piezoelectric actuator in resonance [Aldrich et al., 2006]. As the boundary conditions change the resonant frequency of the transducer change and so the program is required to run a continuous loop to determine this frequency. In addition to that, the program can control the duty cycle of the actuator and amplitude of the drive signal. The rotary component controller can provide the power to drive the bit at a constant speed or can provide constant power to the rotary actuator.

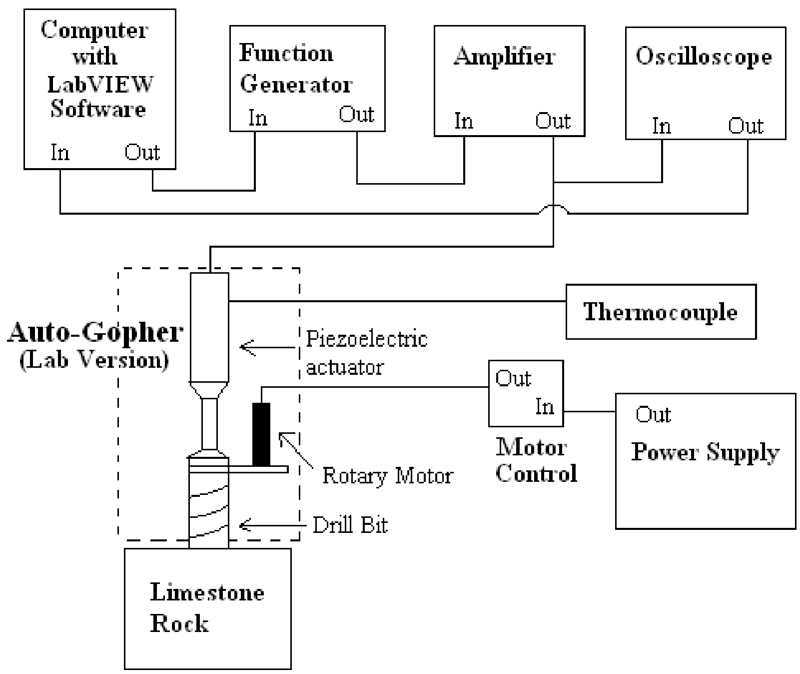

Figure 3 Experimental setup block diagram.

3. LABORATORY TESTING

The operating parameters that were explored during the testing of the lab version are the duty cycle, the free mass size and geometry, preload, weight on bit, rotary speed, and the input voltage to the percussive actuator. Duty cycle represents the percentage of the total drilling cycle during which the percussive actuator is in use. For example, for an "On time" of 5 seconds and a duty cycle of 25%, the Auto-Gopher's percussive actuator would vibrate for 5 seconds and rest for 15 seconds during a full 20 second cycle. The preload is the force applied to the piezoelectric actuator in contact with the free mass which in turn is in contact with the bit. The rotary speed is the rate at which the bit spins, which is controlled by the motor controller in Figure 3.

Two other parameters were constant during the series of experiments: the rock type and the start frequency of the drive signal. Limestone blocks were selected as the test drilling media as they offer consistent characteristics and so we could compare the test results. The initial frequency of 5250 Hz of the drive signal was selected by the user on the computer control program because it represents the resonance frequency of the piezoelectric transducer at room temperature. As the boundary conditions change the resonance frequency of the transducer change and is being tracked by the control algorithm.

Table 1: List of cases tested

Percussive Input Voltage (V)	Duty Cycle (%)	Rotary Speed (RPM)	Percussive Power (W)	Rotary Power (W)	Total Power (W)
0.3	65	80	59	33	92
0.3	55	100	50	46	96
0.3	45	120	41	58	99
0.4	40	80	60	33	93
0.4	35	100	52	46	98
0.4	25	120	38	58	96
0.5	30	80	60	33	93
0.5	25	100	50	46	96
0.5	20	120	40	58	98
0.6	15	100	52	46	98
0.6	10	120	35	58	93

Experiments were conducted to explore the effects of percussive input voltage, duty cycle, and rotary speed while remaining below a 100 W power limit for the system and complying with the overheating limits determined earlier. The effects were explored by testing different combinations of the three operating parameters and comparing the depth of the hole drilled over a specified amount of time to determine the drill's performance under those settings. During all of these tests, the weight on bit, preload, and free mass were held constant. The weight on bit was 43.7 N, the preload was 45.0 N, and a 150g donut shaped free mass was used. A list of these combinations can be found in Table 1 along with the corresponding amounts of power for the rotary system, the percussive system, and the total of the two. During the tests, the percussive input voltage, duty cycle, and rotary speed were varied according to Table 1 while the free mass, crown, bit load, and the preload were all held constant as experimental controls. Each test consisted of drilling a new hole into limestone for 20 minutes and measuring the depth of the hole. This process was performed for each combination of parameters in Table 1.

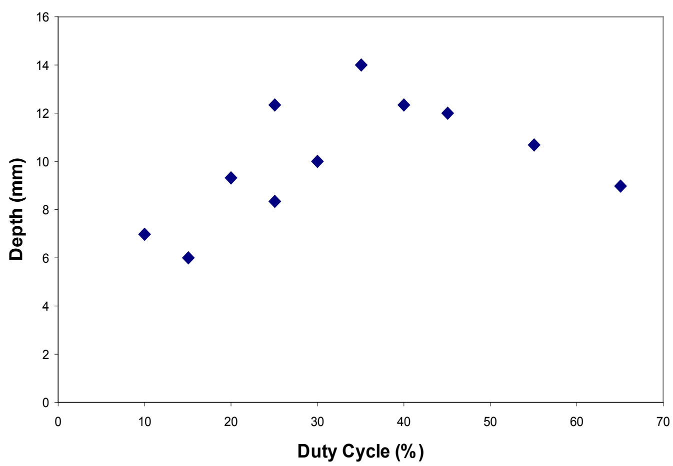

Figure 4 Drilling depth as a function of the duty cycle for a 100W total power system

The lab test results showed a range of the drive parameters for the limestone rock we were drilling and for power level initially selected for these tests. These parameters would need to be adjusted for the integrated system and for different drilling conditions.

4. FIELD TEST RESULTS

The purpose of the field test was to demonstrate the drilling to a depth more than the drill length and the core recovery and to obtain drilling telemetry to later extrapolate the drill time and energy required to drill at greater depth. After scouting to a few possible locations we selected a gypsum quarry of the US Gypsum Company outside Borrego Springs, California and performed the tests at the end of November, 2012. The location offers gypsum deposits of up to

200 feet depth with a rock hardness of about 40MPa. Figure 5 shows the drill field test team which included engineers and scientists from Jet Propulsion Laboratory, Honeybee Robotics, and University of Southern California. A total of 32 cores were extracted from a 3.07m deep drilled hole during the three days on the drill site (see Figure 6).

Figure 7 shows the rate of penetration (ROP) as a function of percussive power by varying the level of duty cycle. Note that one important issue in high power piezoelectric actuators is the resonant characteristics change with time due to the nonlinear characteristics of piezoelectric materials under high-power operation. Therefore, tracking the appropriate resonant frequency in real time is necessary to maximize the performance of ultrasonic vibration during operation.

Figure 5 The drill field test team

Figure 6 The drilled deployed in the field with the extracted cores (left) and a close-up of the drilled hole (right)

Based on the combination of hill climbing and estimation-based extremum-seeking control algorithms, a real-time tracking algorithm was developed in JPL and implemented in this device, allowing for the device to be operated near resonance at all times. As expected, the drilling performance showed a large improvement with the aid of ultrasonic vibration, from 40 cm/hr up to 180 cm/hr, with 100% duty cycles. However, it should be kept in mind that although an increase in the duty cycle resulted in an increase in the rate of penetration, this might cause the device overheating and damage the piezoelectric elements for long-term use. For both safe and efficient to run the device, 50% of duty cycle would be optimal as any generated heat would be dissipated during off-time without leading to a temperature rise during operation. From Figure 8, when the duty cycle was reduced to 50% (5s on and 5s off), the rate of penetration was down to 80 cm/hr; however, the rate of penetration was found to increase with reducing the duration of the ON-OFF cycle (1s ON and 1s OFF), offering the same level of penetration rate as 100% duty cycle operation.

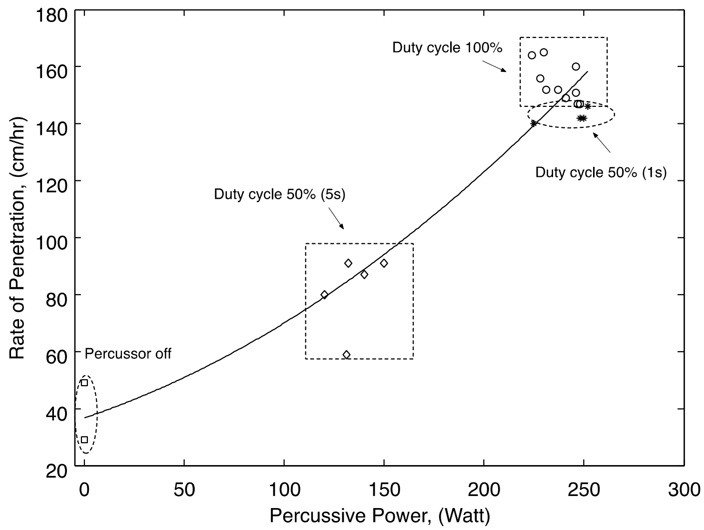

Figure 7 Penetration rate as a function the percussive power and duty cycle

The consumed total power (Auger power + Percussive power) required to drill one meter hole was evaluated from the energy E, where E = total power/ROP, and presented in Figure 8 as a function of duty cycle. Note that the average rotary component power was always in the range of 90-120 Watt, and the power required to actuate anchor and WOB control mechanism was negligible. From the figure, it is evident that the device consumed less energy per unit of drilled hole when ultrasonic percussion was on-state; decreasing energy consumption with increasing duty cycle. For 100% duty cycle, the device took approximately 220 Whr in order to drill 1 meter deep, while the energy consumption was increased to 250 - 280 Whr for 50 % duty cycle depending on the duration of on-off-cycle. However, the device still consumed less energy compared to the rotary drilling with no percussion, which consumed around 350 Whr.

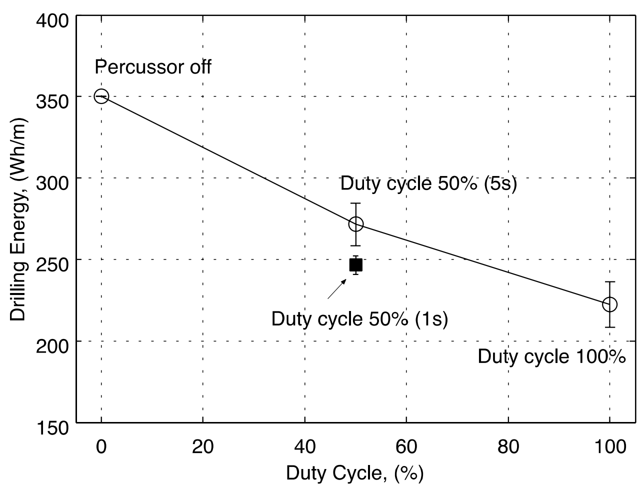

Figure 8 Drilling Energy per meter of depth as a function of duty cycle.

5. CONCLUSIONS AND FUTURE WORK

A wireline drill called Auto-Gopher that uses a piezoelectric device as a percussion mechanism and a set of EM motors for rotating the bit was developed and tested in laboratory and field conditions. The lab version developed by the NDEAA lab aimed at determining drive parameters of the piezoelectric actuator. This piezoelectric actuator was integrated into the wireline version of the drill developed in cooperation with Honeybee Robotics team.

The lab version of a rotary hammer corer was developed and preliminary tests were performed. The drill includes a drill bit assembly, a hammering piezoelectric actuator with an intermediate free mass, a rotary component, and a linear slide mounting. The drill bit creates a 2" diameter core and collects the cuttings in a separate chamber. The linear slide mounting has means of adjusting the preload between the actuator and the free mass and the weight on bit and provides linear feed of the drill down the hole.

Field tests of the integrated wireline Auto-Gopher showed that the chosen solution is viable for creating deep holes and that the percussion reduces the required energy to drill a unit length of hole. Future tests may include exploring additional drilling parameters and materials.

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