Auto-Gopher-2 – Wireline deep sampler driven by percussive piezoelectric actuator and rotary EM motors

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Abstract. Two of the key purposes of future NASA's solar system exploration of planetary bodies are the search for potentially preserved bio-signatures and for habitable regions. To address these objectives, a biologically inspired wireline deep rotary-percussive drill, called Auto-Gopher, has been developed. This drill employs a piezoelectric actuated percussive mechanism for generating impulsive stresses and breaking formations, and an electric motor to rotate the bit to break material and remove the cuttings. Initially, the drill was designed as percussive mechanism for sampling ice and was demonstrated in 2005 at Lake Vida, Antarctica, reaching about 2 m depth. The lessons learned suggested there is a need to augment the percussive action with bit rotation in order to maximize the penetration rate. The first generation implementation of the rotary augmentation was focused on the demonstration of this capability. In 2012, during the 3-day field test, the drill reached a 3-meter deep in gypsum. A separate mechanism was used to break and remove the cores. The average drilling power consumption was in the range of 100-150 Watts, while the rate of penetration was approximately 2.4 m/hr. Currently under development is the second-generation drill, called Auto-Gopher 2. The drill will be fully autonomous. In this paper, the capabilities that are being integrated into the Auto-Gopher-2 are described and discussed.

Introduction

One of the most pressing questions in space science is whether life has ever arisen anywhere else in the universe. Since water is a critical prerequisite for life-as-we-know-it, NASA exploration missions are targeting bodies in the solar system that are known to have or have had flowing liquid water. In the latest Planetary Decadal Survey (Vision and Voyages for Planetary Science in the Decade 2013-2022), three solar system bodies with accessibility to aqueous regions were specifically recommended for future exploration: Mars, Europa, and Enceladus. These bodies have the highest likelihood of finding either extant or extinct life but they pose related drilling challenges and require adequate strategy of acquiring samples. Drilling on Mars requires penetrating dry regolith that have physical properties (i.e. tensile strength, hardness, etc.) that potentially vary many orders of magnitude though the entire drill depth. On the other hand, drilling on Enceladus and Europa needs to be performed through ice at temperatures below 100 K and account for the low gravity on Enceladus or the high surface radiation on Europa. However, the common requirements for drilling into these bodies involve penetrating the subsurface, capturing samples, and delivering the unaltered sample to instruments for analysis.

In developing the Auto-Gopher (**Figure 1**), the goal was to demonstrate a scalable technology that makes deep drilling possible when using current launch vehicles and power sources. The Auto-Gopher-1, which was the first generation, has been demonstrated to drill 40 MPa gypsum to a depth of 3 m in the field (**Figure 2**) [Bar-Cohen and Zacny, 2009; Bar-Cohen et al., 2014; Zacny et al., 2013]. Essentially, this drill is a wireline mechanism that consists of a tube structure that drives the bit in rotation and percussion, and it includes actuators for bit extension and pre-load, and an anchor.

It is suspended at the end of a light weight tether and, therefore, the maximum penetrated depth is limited only by the capability to package a long tether, which does not cause significant increase in system mass or complexity.

One of the limitations for drilling in planetary bodies is the available power, and the proven power sources for landed missions are solar panels and Radioisotope Thermoelectric Generators (RTG). In order to drill through ice with the Auto-Gopher, two to three hundred Watts of power allows drilling quite effectively. In contrast, an ice-melt probe would likely require kWs of power and could necessitate developing a small, space-rated nuclear reactor, which could require a significant investment and a long development time.

A major concern in wireline drilling is the borehole collapse that can take place above the drill. Also, the hole can get smaller through creep and, therefore, pinch the drill at a choke point. However, this is not an issue for ice drilling, since ice creep is a function of the ice temperature and gravity. The gravity and ice temperatures on Mars, Europa and Enceladus are quite low, and therefore minimal creep may take place as the penetration depth scales with the inverse of the gravity. Since the Auto-Gopher is periodically retracted to extract the cuttings, a mechanism of counter rotating reamers can be used to keep the borehole open.

The Auto-Gopher-1 was operated as a semi-autonomous corer. Currently, the Auto-Gopher-2 is being developed as a fully autonomous wireline system and it is being incorporated with 1) Core breakoff; 2) Core capture; 3) Core ejection; 4) Embedded electronics; and 5) Autonomous drilling with fault detection. Once it is fully developed, the prototype will be tested to drill rock, permafrost, and ice in an environmental chamber having a simulated Martian ambient environment.

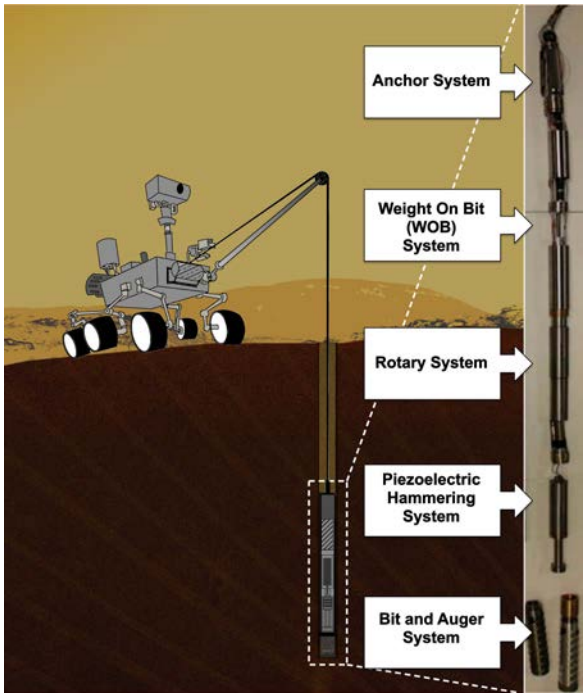

Figure 1: Illustration of the Auto-Gopher, concept as a wireline deep drill.

Figure 2: The Auto-Gopher-1 and the acquired cores from drilling 3 m deep in gypsum.

Deep drilling options

Planetary drilling, particularly to great depth, is significantly more challenging than on Earth. Some of the challenges result from the limitations of mass, volume and power, and the harsh environment of low temperature, and pressure (or vacuum) as well as operation in low gravity that limits the available preload. Using continuous drill strings for deep penetration is constrained by the mass limitation and, unless the strings are made of low density material, adding sections with depth very quickly makes the entire system very heavy. In addition, the feeding of the strings requires a

robotic mechanism that includes a carousel and mating connections between the drill strings. This mechanism increases significantly the mass of the system and is also much more complex and, in turn, involves much greater risk of failure. If the drill system requires sensors (e.g. temperature sensor) on the bit for monitoring the environment around the drill (e.g. making sure water-ice does not approach freezing temperature, which would be catastrophic to the mission), then the drill strings would also need to have an electrical feedthrough mating system. A robotic system with autonomous drill string management and downhole power/data capability has previously been built for planetary applications, but it was quite complex [Zacny et al., 2008].

Since the formed cuttings on a continuous drill string need to be extracted up all the way to the surface using an auger (i.e. screw), the process requires prohibitively large torque and power. This is the result of the parasitic drag of the rotating auger against a borehole that is coupled to the even larger frictional drag produced by the cuttings as they are moved up the hole. The drag in the continuous drill string approach is the most important factor limiting the penetration depth to about 10 m. A possible solution is to incorporate the "bite" approach [Zacny et al., 2013], where the drill is periodically retracted to clear the cuttings. Auger drag due to cuttings removal can be limited to short (e.g. 1 m) drilling "bites", and the parasitic losses due to auger rubbings against the wall of the borehole remains an issue. The main drawback to the "bite' approach is the need for the drill string management that has to be very robust to handle the countless drill string connections and disconnections during the course of drilling a deep hole.

An approach which solves most of the continuous drill string problems is the use of wireline. The latter drill mechanism is suspended on a tether and all the motors and mechanisms are built into a tube that ends with a drill bit. The tether provides the power, data communication and the mechanical connection to a planetary platform on a surface. Incrementally, the drill reaches the designed step size depth, then the drill is retracted from the hole by a winch/pulley system, which can be either on the surface or integrated into the top part of the drill itself. Once the core and cuttings are removed, the drill is returned into the borehole to reach the next step drilling depth.

Generally, wireline systems involve the mechanical complexity of packaging motors and actuators into a slim tube. As opposed to a continuous drill string system, where the Weight on Bit (WOB) also known as a preload, is provided by a surface platform (lander or rover), the WOB in the wireline system is provided by anchoring the drill to the borehole wall (locking the upper section) and using an internal screw to push the drilling mechanism downward during drilling. The main disadvantage of wireline systems is the possibility of borehole collapse. This issue may be addressed using a deployable (e.g. mesh type) casings but its complexity is currently prohibitively risky for these missions. Therefore, the practical drilled formation is restricted to stable subsurface materials such as ice or ice-cemented grounds, where the probability of finding life would be highest. In turn, plausible targets may include the Northern and the Southern Polar Regions of Mars, Enceladus, and Europa.

The Auto-Gopher-2

The Auto-Gopher evolved from three prior mechanisms design: Ultrasonic/Sonic Driller/Corer (USDC), Ultrasonic/Sonic Gopher (USG), and Auto-Gopher-1. These mechanisms are driven by a piezoelectric stack vibratory actuator at ultrasonic frequency and benefit from the low axial preload that is required to drill. The piezo-stack is sandwiched between a backing layer and the horn and it is held in compression by a stress bolt. A free mass is used to convert high frequency vibrations into low frequency, which result-in higher momentum impacts onto the drill bit and delivering impact stresses that fractures the drilled rock [Bao et al., 2003]. Thus, high impact hammering blows are produced by the piezoelectric effect, where input AC electrical signals are converted to resonant mechanical vibrations, generating large mechanical forces on the target.

The level of mechanical forces output of the ultrasonic hammer system is related to its vibration velocity, which is proportional to the excitation frequency and displacement amplitude. Therefore, components that generate high vibration velocity are a key enabling technology for large hammering actions and, for this purpose, a piezoelectric stack configuration is implemented with a combination

of optimal ultrasonic horn design. The generated strain from the piezoelectric stack is proportional to the number of the piezoelectric layers. The presence of a horn amplifies the displacement induced by the piezoelectric stack dictated by the ratio of the area of the horn tip to the base when it is driven at its fundamental half-wavelength axial mode resonance frequency. The impacts create a large enough stress in the target to enable efficient drilling. A simple collision model that was developed by the authors to explain the basic mechanism of the horn/free mass interaction [Bao et al, 2003]. Using the USDC mechanism, the USG was developed with a 6.4 cm diameter bit that was the first wireline design to drill to depths greater than the drill length. The USG was tested at Mt. Hood in a glacier and on Lake Vida, Antarctica.

The first generation of the Auto-Gopher mechanism, which is biologically inspired, was developed as a lessons learned from testing the USG by introducing rotary motion and a fluted coring bit [Bar-Cohen et al, 2007; Bar-Cohen and Zacny, 2009; Zacny et al., 2013; Bar-Cohen et al, 2014]. About an order of magnitude drilling rate increase has been measured in experiments augmenting the hammering with rotation [Badescu et al. 2006]. The developed Auto-Gopher-1 consisted of the following five subsystems (from top to bottom): The Anchor, The Weight on Bit (Preload) Drive, Rotary System (Auger Drive), Hammer/Percussive System, and the Bit and Auger System with Cuttings Bucket. This drill weighs 22 kg and has a length of 150 cm (**Figure 2**). It was tested in a gypsum quarry of the US Gypsum Company outside Borrego Springs, California (left). The purpose of the field test was to demonstrate the drilling to a depth more than the drill's length, perform core recovery and obtain drilling telemetry to later extrapolate the drill time and energy required to drill at great depth. The drilled hole in this field test has reached 3.07 meter deep.

The rate of penetration (ROP) of Auto-Gopher as a function of percussive power by varying the level of duty cycle is shown in **Figure 3**. 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 safe and efficient running of the drill, a 50% of duty cycle was found to be optimal as the generated heat can be dissipated during off-time without leading to a temperature rise during operation. From the graph in **Figure 3**, 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.

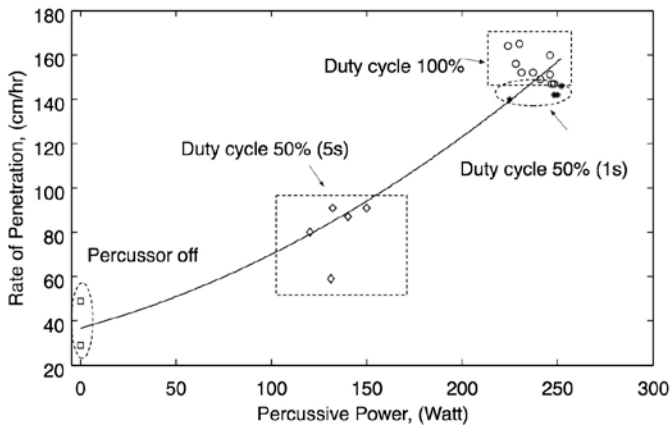

Figure 3: Penetration rate as a function the percussive power and duty cycle.

The Auto-Gopher-2 represents the latest generation in electro-mechanical deep drilling technology which includes a core breakoff system. It builds on the previous successful technology demonstrations that were enabled by the Auto-Gopher-1. The new drill diameter has been reduced since the breakoff forces are proportional to core diameter^2 and smaller forces are required. Generally, creating a core is only the first step in performing deep penetration and acquisition of samples. The second step is to break the core at its base and capture it within the coring bit. The core break-off system needs to be reusable and allows for easy core ejection by the core handling system on the surface. There are several ways that a core can be detached from the parent rock and the one that was chosen for its relative implementation simplicity is the use of bending (for breaking the rock

at the base by applying a side force on top). The testing of the mechanism was done using a standalone, manually deployable system that includes a tube with internal wedge (**Figure 4**). The wedge engages the core only after a certain core length has been reached and tests have shown successful breakoff and retention of the generated cores (**Figure 5**).

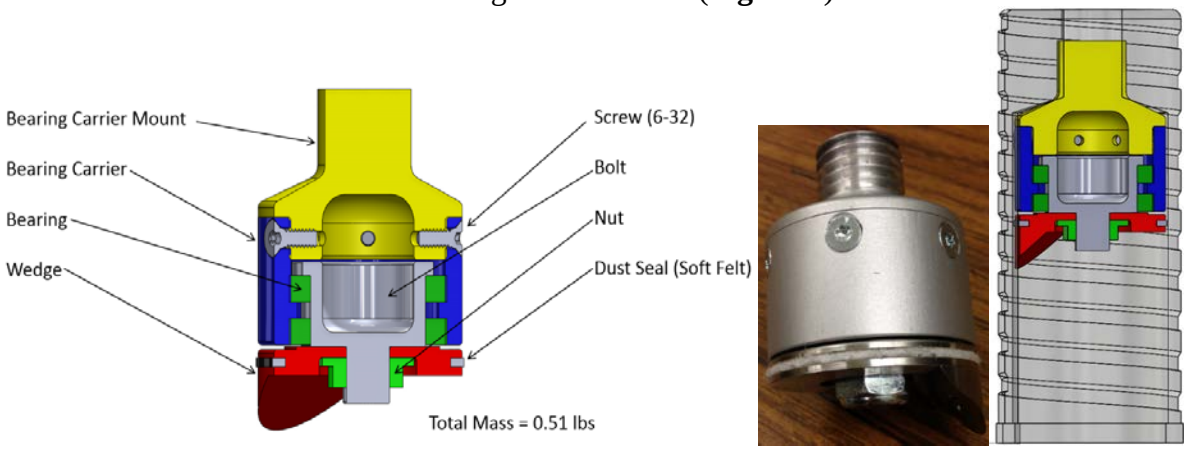

Figure 4: L: The Break-off and retrieval breadboard. Core breaker is shown inserted into a bit.

Figure 5: Successful core sample break-off and removal

The drive software that controls the operation of the piezoelectric transducer of the percussive mechanism is a critical part of the performance optimization. This requires ability to monitor the drive frequency and adjust its drifting to maintain operation at resonance. It is well known that the maximum electromechanical efficiency is obtained when driving a piezoelectric transducer at its resonant frequency leading to the same displacement amplitude but using smaller drive field (applied voltage) due to the build up at resonance. Extremum seeking is a well developed field which tracks a varying maximum or minimum of a performance function. The main advantage of this method is that the piezoelectric system can keep a performance at its extremum value while seeking operating set-points that maximize the vibration velocity. This maximum occurs at at the resonant frequency. The algorithm that was implemented to control the Auto-gopher is -called “hill-climbing". The software determines a favorable direction in each the iterations are based on the comparison between the previous and current admittance value. The control inputs continue to update in this manner until the performance output begins “climbing” up one of the resonant peaks of the piezoelectric actuator. In this algorithm it is critical to have a good step-size control; although a large step size increases the convergence rate to the peak. This leads to high oscillations around the peak and resulting in jump back and forth on both sides about the peak. In contrast, a small step-size decreases the oscillations around the peak, but it is possible to get trapped in a spurious local maximum if the step size is too small [Aldrich et al., 2006].

Conclusion

The Auto-Gopher, which biomimetically mimics a gopher, is a wireline drill that was developed and demonstrated to reach 3 m depth in gypsum. The main feature of its operation as a wireline drill is

the suspension on a tether where the motors and other components are built into a tube that ends with a bit. The tether provides the mechanical connection to a surface platform (rover or lander) as well as power and data communication. Upon penetrating a preset depth, the drill is retracted from the borehole, the core is removed, and the drill is lowered back into the hole for continuing the penetration process. The drill is capable of reaching great depths that are limited only by the length of a deployment tether. Wireline operation sidesteps one of the major drawbacks of traditional continuous drill string systems by obviating the need for multiple drill sections, which add significantly to the mass and the complexity of the system.

The development of this piezo-actuated deep drill has been done in several generations including the Ultrasonic/Sonic Driller/Corer (USDC), Ultrasonic/Sonic Gopher (USG), the Auto-Gopher-1, and currently the Auto-Gopher-II. The heart of these drills is a vibratory mechanism driven at ultrasonic or sonic frequencies by piezoelectric stack and its main attribute includes low axial preload required to drill various formations.

The results of the studies thus far indicate that the Auto-Gopher can operate as an effective sampling tool for reaching great depths. This result is significant to future NASA in-situ exploration missions that are addressing the important questions of whether life once existed or exists elsewhere in the solar system.

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