The Auto-Gopher – A Wireline Rotary-Percussive Deep Sampler

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ABSTRACT

Accessing regions on planetary bodies that potentially preserved biosignatures or are presently habitable is vital to meeting NASA solar system "Search for Life" exploration objectives. To address these objectives, a wireline deep rotary-percussive corer called Auto-Gopher was developed. The percussive action provides effective material fracturing and the rotation provides effective cuttings removal. To increase the drill's penetration rate, the percussive and rotary motions are operated simultaneously. Initially, the corer was designed as a percussive mechanism for sampling ice and was demonstrated in 2005 in Antarctica reaching about 2 m deep. The lessons learned suggested the need to use a combination of rotation and hammering to maximize the penetration rate. This lesson was implemented into the Auto-Gopher-I deep drill which was demonstrated to reach 3-meter deep in gypsum. The average drilling power that was used has been in the range of 100-150 Watt, while the penetration rate was approximately 2.4 m/hr. Recently, a task has started with the goal to develop Auto-Gopher-II that is equipped to execute all the necessary functions in a single drilling unit. These functions also include core breaking, retention and ejection in addition drilling. In this manuscript, the Auto-Gopher-II, its predecessors and their capability 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 prioritized future exploration targets that are currently known to have or have had flowing liquid water in its past. In the latest Planetary Decadal Survey (Vision and Voyages for Planetary Science in the Decade 2013-2022), three bodies Mars, Europa, and Enceladus were specifically called out for future exploration because of the accessibility of aqueous regions. These bodies have the highest likelihood of finding either extant or extinct life in the solar system, but all require a strategy that requires sample acquisition at depths below the surface. Each body possess its own challenges in terms of drilling. On Mars, drilling would consist of drilling into dry regolith through materials have physical properties (i.e. tensor strength, hardness, etc.) whose characteristics may potentially vary many orders of magnitude though the entire drill depth. On Enceladus and Europa, drilling would be through ice of temperatures below 100 K and have to take into account the low gravitational field of Enceladus and high surface radiation of Europa. There are

enough commonalities on these bodies to progress the technology as any drilling strategy would require the use of a system to penetrate the subsurface, capture samples, and present the unaltered sample to instruments for analysis.

In developing the Auto-Gopher, the authors are seeking to demonstrate a scalable technology that makes deep drilling possible in the next two decades with current launch vehicles and power sources. The drill has been demonstrated to reach 3 m in the field, utilizing a wireline approach [Zacny et al., 2013]. The technology and concept of operation have been developed in conjunction with future mission constraints including mass, power and operation effectiveness. In the wireline approach, the drill is essentially a tube that encompasses the coring bit, drive mechanisms, actuators, and an anchor. The drill is suspended at the end of a light weight tether and, in turn, penetration depth is limited only by the packaging capability of the tether. This enables drilling to great depth without significant increase in system mass or complexity.

One of the limitations for drilling in planetary bodies is the available power. Proven power sources for landed missions are solar panels and Radioisotope Thermal Generators (RTG). In order for the Auto-Gopher to drill through ice, a few 100 Watt of power can result in 10-20 minutes of drilling (Figure 1). In contrast, an ice melt probe, would require kWs of power and this requires development of small, space-worthy nuclear reactor, something that will be very expensive and take a long time to develop.

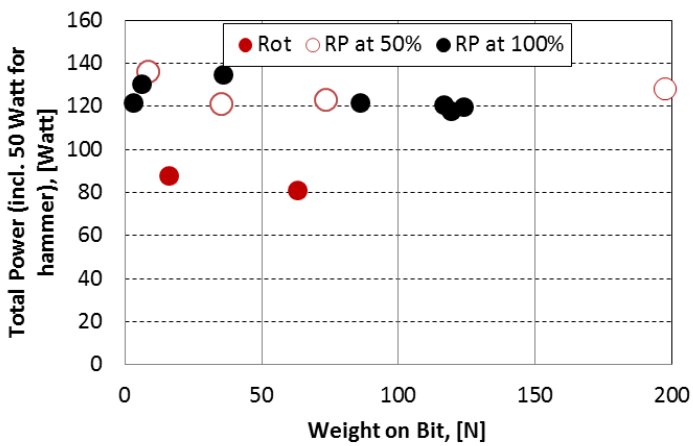

Figure 1: The Auto-Gopher-I total power (including 50 Watt for the piezo-hammer system) vs. weight-on-bit for Rotary, Rotary-Percussive with 50% duty cycle, and Rotary-Percussive drilling.

A major concern in terrestrial wireline drilling is the borehole collapse. The hole cannot only collapse above the drill trapping the drill below the collapsed point, but also the hole can get smaller through creep, and pinch the drill at a choke point. For ice drilling, this is not an issue as ice creep is a function of the ice temperature, and gravity. The low gravity and ice temperatures on bodies such as Mars and Enceladus is much lower than Antarctica, and is expected to keep the creep to a minimum as the penetration depth scales with the inverse of the gravity. The Auto-Gopher is periodically retracted out of the hole to extract a core section. During these up and

down trips, the drill could engage counter rotating reamers that, if needed, can keep the borehole open.

In the task that was completed in 2012, the first generation Auto-Gopher wireline drill was developed. This drill was demonstrated to perform semi-autonomous coring in a 40 MPa gypsum to a depth of 3 m. Building on this promising technology, recently the authors have started developing a fully autonomous Auto-Gopher-II wireline system (Figure 2). This new drill 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 drill will be tested to drill rock, permafrost and ice in an environmental chamber having simulated martian ambient environment.

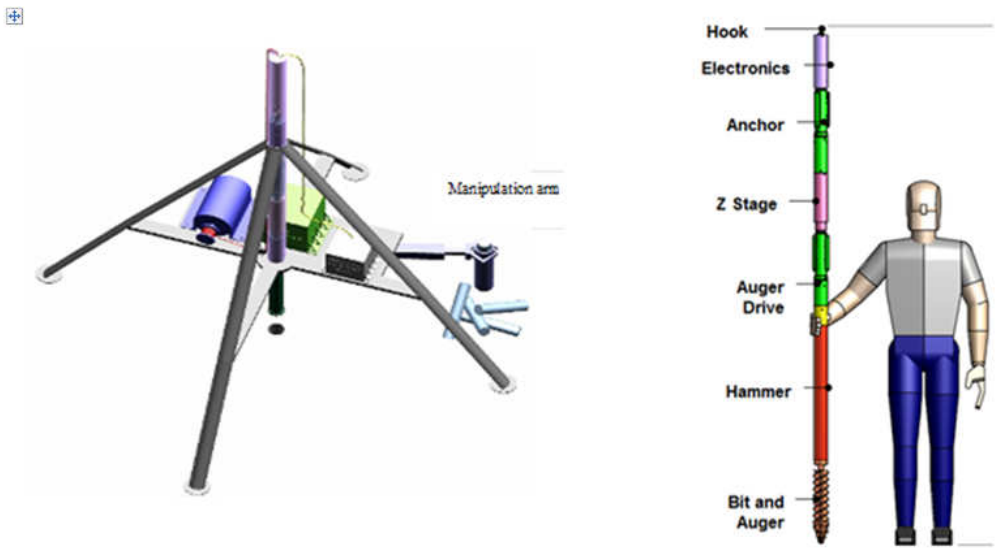

Figure 2: Notional diagram showing deployment system and core handling system (left) and the Auto-Gopher-II (right).

DEEP DRILLING OPTIONS.

Planetary drilling has many challenges that are not as much of a concern when drilling on Earth. These include limited system mass, power, and energy as well as low pressure (or vacuum) and low temperature environments. From the mass stand point, unless drill strings are made of low density material, adding drill sections to reach greater depths very quickly makes the entire system very heavy. In addition, the system needs a robotic drill string feeding mechanism such as a carousel and mating connections between each drill string. This not only increases mass but also the system complexity and, in turn, increases the risk of failure. If the drill system requires some sensors (e.g. temperature sensor) at 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 using water or mud is difficult or impossible in planetary exploration due to low pressure and low temperature conditions, drilled cuttings need to be conveyed all the way to the surface using an auger (i.e. screw). The parasitic drag of the rotating auger strings against a borehole coupled with even larger frictional drag produced by cuttings as they are moved up the hole require prohibitively large torques and power. This is the most important factor limiting the penetration depth to approximately 10 m or so when using the continuous drill string approach. A possible solution is to incorporate so called the "bite" approach, which is similar to pecking in machining [Zacny et al., 2013]. In this approach, the drill is periodically retracted to clear chips. Hence auger drag due to cuttings removal can be limited to short (e.g. 1 m) drilling "bites", however, the parasitic losses due to auger rubbings against a borehole will remain. The obvious drawback to the "bite' approach is that drill sting management has to be very robust to cope with countless drill string connections and disconnections during the course of drilling a deep hole (Figure 3).

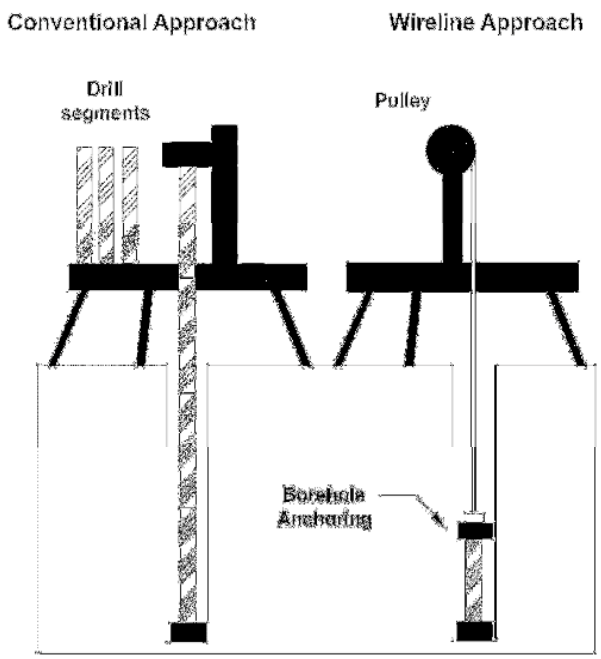

Figure 3: Conventional drill string vs. wireline drilling approach.

The approach which solves most of the problems associated with continuous drill string is the use of wireline. In this case, the drill is essentially 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. Upon reaching the target depth, 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.

Generally, wireline systems involve the mechanical complexity of packaging motors and actuators into a slim tube. In addition, as opposed to a continuous drill

string system, where the Weight on Bit (WOB) also known as a preload, is provided by a lander or a rover, the WOB in a wireline system is provided by anchoring the drill to the borehole wall (it locks the upper section of the drill) and the use of an internal screw to push on the drilling mechanism and the drill bit itself during drilling.

The main disadvantage of the wireline system is the possibility of borehole collapse. To deal with that, the drill could come with deployable (e.g. mesh type) casings but the complexity of deploying a casing would currently make the missions prohibitively risky. For this reason, the drilled environment should be restricted to stable formations such as ice or ice-cemented grounds, where the probability of finding life would be highest. In turn, plausible targets would include the Northern and the Southern Polar Regions of Mars, Enceladus, and Europa.

THE AUTO-GOPHER-II HERITAGE

The Auto-Gopher is based on three prior designs: Ultrasonic/Sonic Driller/Corer (USDC), Ultrasonic/Sonic Gopher (USG), and Auto-Gopher-I. The heart of these drills is a vibratory mechanism driven at ultrasonic frequency and its main attribute includes low axial preload required to drill various formations. The vibrations are produced by a piezoelectric stack that is sandwiched between a backing layer and the horn. The whole assembly of backing, stack, and horn is kept together by a stress bolt that holds the piezoelectric stack under compression. A free mass is used to convert high frequency vibrations into low frequency, higher momentum impacts. The free mass produces stress pulses onto the drill bit which induces impact stress onto the rock causing it to fracture [Bao et al., 2003].

High impact hammering blows are realized by the principle of the piezoelectric effect, where the input AC electrical signal on a piezoelectric transducer leads to mechanical vibrating resonant system, generating large mechanical forces on the target. The level of output mechanical forces of the ultrasonic hammer system is closely related to its vibration velocity that is proportional to the excitation frequency and displacement amplitude. Therefore, components that allow a high vibration velocity are a key enabling technology for large hammer actions. To meet the demands of high performance hammer actions, the piezoelectric stack configuration is implemented with a combination of the optimum design of ultrasonic horn. The presence of a horn amplifies the displacement induced by the piezoelectric stack by a ratio of the area of the horn tip to the base when it is driven at its fundamental half-wavelength axial mode, whereas a piezoelectric stack gives the increased piezoelectric strain that is proportional to the number of the piezoelectric layers. The energy generated by the ultrasonic horn is then transferred to a free mass, converting a high-frequency, low-amplitude excitation into a low-frequency high impact energy on the bit, realizing a relatively low voltage, and high efficiency ultrasonic hammer system. This allows for the effective conversion of high frequency, high force vibration of the horn tip into low frequency, high displacement hammering blows. These impacts create a large enough stress in the target to enable efficient drilling. A simple collision model can be applied to explain the basic mechanism of the horn/free mass interaction. If we assume that the energy loss and time duration of the impact is

negligible, the post collision velocities can be calculated using following equations based on the conservation of momentum and energy:

$$m_1 v_{i1} + m_2 v_{i2} = m_1 v_{f1} + m_2 v_{f2}$$

$$\frac{1}{2} m_1 v_{i1}^2 + \frac{1}{2} m_2 v_{i2}^2 = \frac{m_1 v_{f1}^{\ 2}}{2} + \frac{m_2 v_{f2}^2}{2}$$

The equations leads to the post collision velocities by solving for v_{f1} and v_{f2}:

$$v_{f1} = \frac{(m_1 - m_2) v_{i1} + 2 m_2 v_{i2}}{m_1 + m_2}$$

$$v_{f2} = \frac{m_1 (2 v_{i1} - v_{i2}) + m_2 v_{i2}}{m_1 + m_2}$$

where v_{f1} and v_{f2} are post collision velocities of horn and striker, and v_{i1} and v_{i2} are pre-collision velocities of horn and striker, respectively. Assuming that the mass of the horn (m_1) is much higher than the mass of striker (m_2), i.e., $m_1 >> m_2$, the post collision velocities of striker can be simplified as $v_{f2} \approx -v_{i2} + 2v_{i1}$. The equation implies that when the masses of striker are much lower than those of piezoelectric actuator or probe bit and target, the striker bounces back and forth between the horn and the probe, and its post collision velocities increase after interaction with the vibration tip. During the process, the momentum after the impact is transferred to the probe bit at each impact, delivering high impact forces on the target [Bao et al, 2003 and Sherrit et al, 2000].

Based on the USDC mechanism, the Gopher was developed, where the bit diameter was 6.4 cm. This first wireline design was built to allow the USDC mechanism to drill to depths greater than the drill length. The Gopher was tested in Mt. Hood glacier and Lake Vida, Antarctica.

The next version of the drill, the Auto-Gopher, was developed as a joint effort of the JPL's NDEAA laboratory and Honeybee Robotics Corp. The lessons learned from testing the ice gopher were implemented into the design of the Auto-Gopher by introducing a rotary motion onto the fluted coring bit [Bar-Cohen et al, 2007; Bar-Cohen and Zacny, 2009]. The most recent experiments have shown about an order of magnitude increase in drilling rate when combining the bit vibrations with rotation [Badescu et al. 2006]. AutoGopher is a stand-alone drilling system requiring no additional actuation from the surface to perform drilling except for the tether management. The drill weighs 22 kg and has a length of 150 cm. The Auto-Gopher (see **Figure 5**) consists of five subsystems. These are (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. The following sections detail each of the subsystems.

The Anchor uses a set of three compliant shoes to push against a borehole and anchor itself to the drilled hole with a force of 1600 N. This force is sufficient to provide a resistance to rotary torque from cutting bit as well as vertical force from the Weight on Bit. The Weight on Bit (WOB) Drive is provided by internally actuated ball-screw and is designed for WOB of 1000 N. An integrated load cell provides a

force feedback for WOB control. The Rotary system uses a cluster of 3 actuators with a combined electrical power up to 360 Watt for rotating a coring bit and an auger. Accounting for electrical and mechanical (e.g. gearbox) losses, the system can generate a torque of 15.5 Nm at 100 rpm. The hammer system employs a piezoelectric actuated percussive mechanism for providing impacts via free mass. The impact energy imparted to the bit is stochastic with a distribution of frequencies. Lower energy blows of the order of 0.1 J have frequencies in the hundreds of Hz range while higher energy blows of the order of 0.4 J have a frequency in the 10 Hz range. The hammering action is independent of the rotary motion and hence can be engaged when the formation becomes too hard for rotary action alone to cut through or when the tungsten carbide teeth get dull. In addition, a Percussive system allows the cuttings within the bailer bucket above the core to compact more and in turn occupy less volume.

The core bit allows acquisition of 60 mm diameter 100 mm long cores. The outside diameter of the coring bit is 71 mm. Drilled cuttings are moved up the auger flutes and fall into the cuttings chamber above the core chamber. The integrated bailer above the core chamber can accommodate all the cuttings produced during the 100 mm drilling; accounting for a cuttings volume expansion factor of 3 (i.e. as rock is being drilled, the resultant cuttings will occupy up to 3x the volume of the base rock/ice). Upon drilling the 10 cm long core, the drill is retracted and the cuttings chamber is emptied.

Figure 6 shows the photos of deployed Auto-Gopher in a gypsum quarry of the US Gypsum Company outside Borrego Springs, California (left) and drilled hole after three days drilling (right), showing a 3.07m deep drilled borehole. The purpose of the field test was to demonstrate the drilling to a depth more than the drill length, perform core recovery and obtain drilling telemetry to later extrapolate the drill time and energy required to drill at greater depth. 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 7.

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 is dissipated during off-time without leading to a temperature rise during operation. From the figure, 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.

Auto-Gopher Subsystems ***Before Assembly*** ***Assembled***

Figure 5: The subsystems of the Auto-Gopher Wireline Drill.

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

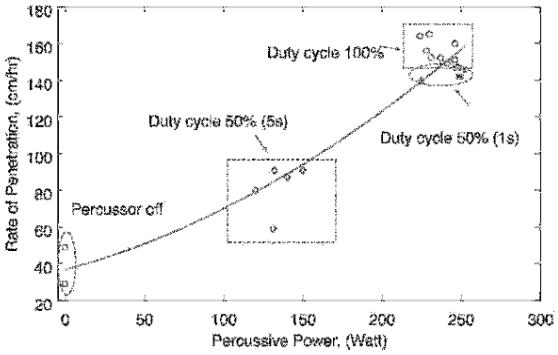

Figure 7: Penetration rate as a function the percussive power and duty cycle.

THE AUTO-GOPHER-II

The Auto-Gopher-II represents the latest generation in electro-mechanical deep drilling technology. It builds on the previous successful technology demonstrations that were enabled by the Auto-Gopher-I. The Auto-Gopher-II is being equipped with

a core breakoff system and hence the width of cutters is increased to accommodate that system. Also, core diameter is being reduced since breakoff forces are proportional to core diameter^2 (hence a small drop in core diameter has a large effect on forces).

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 allow for easy core ejection by the core handling system on the surface. There are several ways that a core can be detached from a parent rock. These include: 1) pulling (breaking the rock in tension), 2) twisting (breaking the rock in slow shear), 3) impact shear (breaking the rock by twisting it at high speed – sort of an impact twist), 4) shearing (breaking the rock by "cutting" as in pinching), or 5) bending (breaking the rock in bending at the base by applying a side force on top). The optimum method for core breaking is not necessarily going to be implemented based on the lowest required force but rather on the complexity of implementation into the current design. The Auto-Gopher-I did not include robotic core breakoff and catching capabilities since the focus of that development has been on demonstrating wireline technology alone and in turn solving anchoring. The core breakoff and capture was performed using a standalone, manually deployable system that include a tube with internal wedge and side springs (Figure 8).

For the Auto-Gopher-II, various solutions are being considered based not only on ease of core breaking but also the ease of the system packaging within the drill. An example of a solution is to employ a floating wedge that engages the core only after a certain core length has been reached. Figure 9 shows the bit with three chambers: core, cuttings and free mass. The core chamber includes at its upper end a mechanism for core break-off. The mechanism would break the core in bending as it is one of the lowest force demand core break-off solutions. In implementing the solution we are also aiming to avoid engaging the core and forcing it to rotate. During the field tests, it was observed that a broken core tends to jam the bit if it tries to rotate. This solution tries to decouple the rotation of the core break-off wedge from the bit rotation and it is a passive solution as it does not require any additional actuators or control.

As far as the drill deployment system that includes the tether management (drum), the goal is to develop a fully autonomous system that lowers the drill to the surface (initially) and then to the bottom of the hole, and upon core capture, returning the drill to the surface. The tether, in addition to the electrical conductors also includes a tensile member with a breaking strength of 10x the drill's weight to address the possibility of jamming and borehole friction. To maintain the drilling direction, a trade study will be undertaken to determine the optimal approach. A possible option that would be considered is to integrate along the Auto-Gopher two anchoring systems, each with three individually activated shoes and guide the drill gravitationally.

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 electromechanical efficiency of the

piezoelectric transducer maximizes when driven at resonant frequency, where the same amplitude of displacement can be achieved at small drive field (applied voltage) at this frequency.

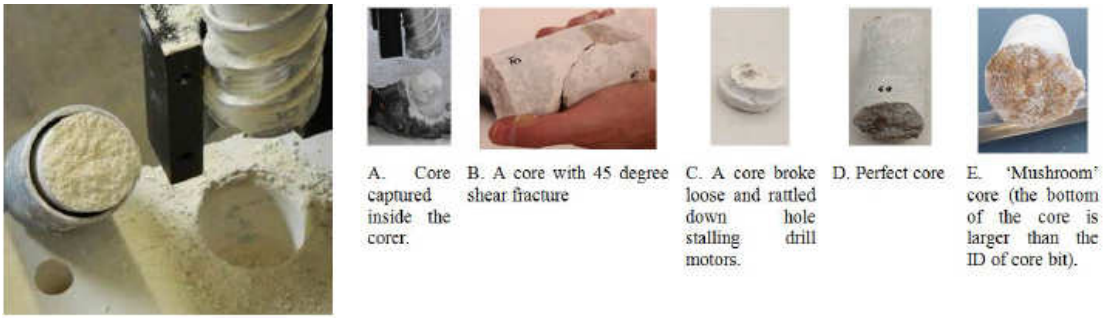

Figure 8: Left: A separate core break off system was used to break-off and capture the core, Right: Core breakoff system needs to be able to work with various cores.

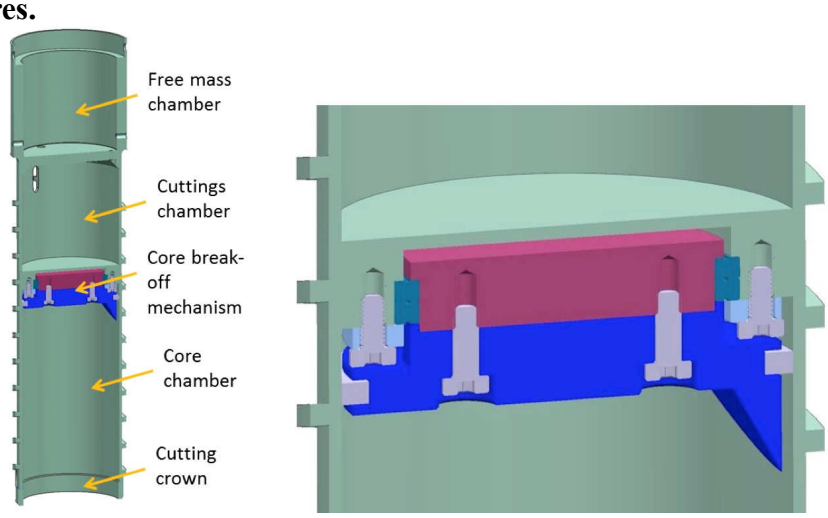

Figure 9: Bit with integrated core break-off mechanism

Extremum seeking control 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 as seeking operating set-points that maximize the vibration velocity, which occurs at its resonant frequency. The algorithm implemented to the Auto-gopher is so-called "hill-climbing", where the software determines a favorable direction in each iteration 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 device. This iterative process can be illustrated using the following formula:

$$x_{k+1} = x_k + \alpha . p$$

with

$$p = \begin{cases} 1 & if \quad dy_k / dx_k > 0 \\ -1 & if \quad dy_k / dx_k < 0 \end{cases}$$

where $dy_k = y_k - y_{k-1}$ and $dx_k = x_k - x_{k-1}$, α is the user-defined step size and p is a search direction. The variable x and y correspond to frequency and admittance, respectively. Note that a good step-size control is critical in this algorithm; although a large step size increases the convergence rate to the peak, it leads to the high oscillations around the peak, 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].

Alternatively, it is also possible to couple the same algorithm with average power as the criterion for the search of the resonance frequency. This could be done by importing the drive voltage and current readings from the oscilloscope to the computer via a GPIB-USB cable. The modified algorithm will be implemented on Auto-gopher II software so that the Auto-Gopher II system can keep a performance at its extremum value during operation.

CONCLUSION

A wireline drill called Auto-Gopher was developed and demonstrated in the field. The main feature of the Auto-Gopher is its wireline operation where the drill is suspended on a tether and the motors and mechanisms are built into a tube that ends with a coring bit. The tether provides the mechanical connection to a rover/lander on the surface as well as power and data communication. Upon penetrating a target depth, the drill is retracted from the borehole, the core is removed, and the drill is lowered back into the hole. The wireline Auto-Gopher system design allows core acquisition from depths 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-I, and currently the Auto-Gopher-II. The heart of these drills is a vibratory mechanism driven at ultrasonic frequency and its main attribute includes low axial preload required to drill various formations.

The results of the studies this far indicate that the Auto-Gopher can operate as an effective sampling tool for reaching great depths (many tens of meters). 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.

ACKNOWLEDGEMENT

Research reported in this abstract was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, jointly with Honeybee Robotics under a contract with National Aeronautics Space Administration (NASA). This research is funded by the NASA's MatISSE (Maturation of Instruments for Solar System Exploration) program.

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