The Auto-Gopher Deep Drill

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Abstract: Subsurface penetration by coring, drilling or abrading is of great importance for a large number of space and earth applications. An Ultrasonic/Sonic Drill/Corer (USDC) has been in development at JPL's Nondestructive Evaluation and Advanced Actuators (NDEAA) lab as an adaptable tool for many of these applications [1]. The USDC uses a novel drive mechanism to transform the high frequency ultrasonic or sonic vibrations of the tip of a horn into a lower frequency sonic hammering of a drill bit through an intermediate free-flying mass. The USDC device idea has been implemented at various scales from handheld drills to large diameter coring devices. A series of computer programs that model the function and performance of the USDC device were developed [2] and were later integrated into an automated modeling package [3]. The USDC has also evolved from a purely hammering drill to a rotary hammer drill as the design requirements increased form small diameter shallow drilling to large diameter deep coring. A synthesis of the Auto-Gopher development is presented in this paper.

1. Introduction

Evidence for the presence of ice and fluids near the surface of Mars in both the distant and recent past is growing with each new mission to the Planet. One explanation for fluids forming spring-like features on Mars is the discharge of subsurface brines. Brines offer potential refugia for extant Martian life, and near surface ice could preserve a record of past life on the planet.

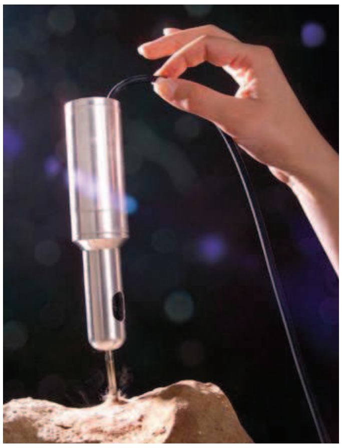
The Mars Science Laboratory Curiosity rover in its traverse in the Gale crater encountered a flat-lying, ~5.2-m-thick succession of weakly indurated clastic sedimentary rocks ranging from mudstones at the base to mainly sandstones at the top. Stratigraphic relationships and sedimentary structures indicate that this coarsening upward succession likely represents sedimentation in an ancient fluvio-lacustrine system that would have been habitable [4].

Proven techniques to get underground to sample these environments, and get below the disruptive influence of the surface oxidant and radiation regime, are critical for future astrobiology missions to Mars. A team of researchers from NASA-Jet Propulsion Laboratory (JPL) developed a USDC based ice hammer drill called the Gopher that used a wireline for deployment, gravity for determining the Weight On Bit (WOB), and compressed air for cuttings removal. Later, teams from JPL and Honeybee Robotics developed a new wireline drill version, called the Auto-Gopher [6]. The drill uses low power and low WOB to acquire cores of rocks, ice or ice cemented soil. It includes a USDC based hammering mechanism, rotation and flutes for cuttings removal, anchor for rotation prevention and a linear actuator for WOB and feed rate control. The acquired cores retain stratigraphy and volatiles to provide significant scientific information about the layered structure with inclusions and potential organisms. These wireline drills allow coring and core removal from depths limited only by the length of a deployment tether.

2. USDC description and modeling

The ultrasonic/sonic driller/corer (USDC) has been in development at NDEAA lab at JPL as an answer to the challenges raised by the need to reduce the samplers axial forces, holding torque and power consumption [1], [7]. The USDC device consists of three main parts: an ultrasonic transducer (piezoelectric stack, a backing element, a stress bolt, and a horn), a free-mass, and a drill stem. Figure 1 shows a schematic of the USDC device. The ultrasonic/sonic transducer can be designed to vibrate at a frequency from 5 to 25kHz depending on the application. The vibrations of the horn tip excite the free-mass, causing it to bounce between the horn tip and the top of the drill stem with average frequencies in the range of 100 to 1000 Hz. The free-mass transfers energy from the ultrasonic transducer to the drill stem. The shock waves caused by the impacts of the free-mass on the drill bit propagate to the bit/drilled media interface and wherever the drilled media is strained past its ultimate strain it fractures.

The functionality of the USDC was modeled to predict its performance. The developed model describes five elements involved in the drilling i.e. the electrical driver, ultrasonic transducer, free-mass, drill stem, and the rock. The main elements and the interaction between them were analyzed and modeled separately [2]. A one-dimensional model was then developed for each interaction and an integrated software program was developed to simulate the operation of all parts of the USDC. The time to run the individual components and the integrated modeling ranged from days up to a week depending on the design. In addition user input was required at many points in the calculation. The lack of autonomy and the lengthy calculation times forced us to develop an integrated package to run automatically, without human intervention, and in a shorter period of time [3]. These component programs run in ANSYS™ or MATLAB™ and require input files and transfer of information from one component program to the next. Separate C++ programs were developed to generate these input files, provide design parameters, read output files of the analysis component programs and extract useful information for the next programs. All these component programs and the new auxiliary programs are controlled by a script and can run automatically. Initial script was developed in UNIX and it was later updated to run in Windows. A diagram of this integrated package is shown in Figure 2.



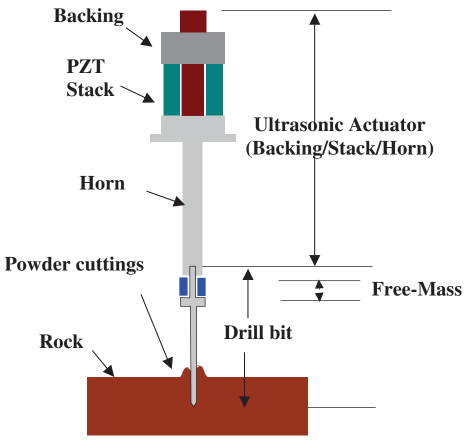


Figure 1 USDC drilling photo (left) and schematics (right)

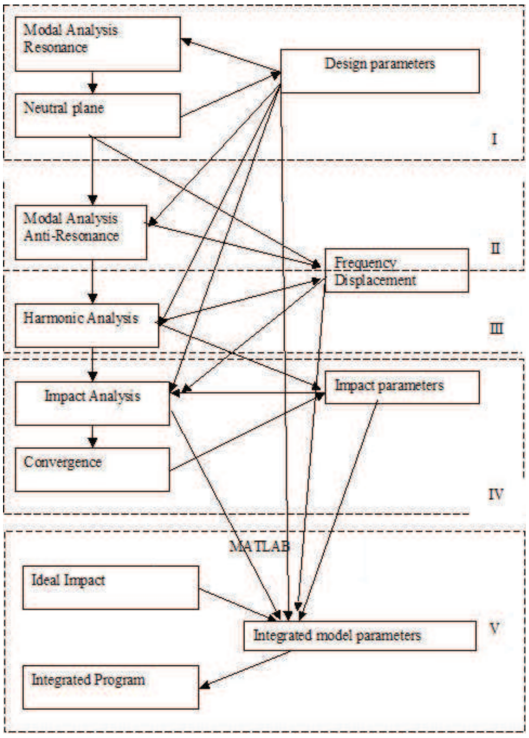


Figure 2 Integrated program package diagram

The running time of the whole package has been reduced from a period of time ranging from a few days to a week with human supervision to 8-15 hours without human intervention. It determines the design parameters for a USDC configuration. The package was used in the evaluations of 21 configurations of the Gopher actuator described in the next section and it was concluded that the best total power transmitted to the drill stem corresponds to dog bone shaped horn (see Figure 3 top) and a 250 g free mass. A dog bone shaped horn uses the enlarged tip section as a hammer that has a higher efficiency in transferring the kinetic energy to the free mass at impact. The program package can be further upgraded to include a numeric optimal design algorithm, like the Genetic Algorithm, for improved design capabilities.

3. Gopher

In an Astrobiology for Science and Technology for Exploring Planets (ASTEP) task the goal was to develop and test a novel ultrasonic corer in a Mars analog environment, the McMurdo Dry Valleys, Antarctica, and to detect and describe life in a previously unstudied extreme ecosystem, Lake Vida, an ice-sealed lake [5]. Lake Vida provided a unique opportunity to demonstrate the viability and feasibility of our Gopher as deep ice sampling drill. The combined hyper-saline, aphotic, atmospherically isolated and cold conditions in Lake Vida make it potentially among the most extreme aquatic environments on Earth. These conditions are likely to have been present during the last stages of purported lakes on Mars near the end of its water-rich past. We envisioned the Gopher being a rover “accessory” that can be added to missions that require access to ice, sediment, or fluid samples within 20 m to 30 m of planetary surfaces such as Mars and Europa. As stated above, getting samples from these depths on Mars will be critical to many future astrobiological missions focused on the search for extant and extinct life.

The Gopher system includes as main components an actuator, a drill bit, a free mass, a pump and preload weights. Figure 3 shows a rendering from the 3D model of the gopher system. The actuator includes a transducer a housing, and a housing cap. The transducer consists of a stack of piezoelectric rings maintained in compression between a backing and a horn by a stress bolt. The horn is a “dog-bone” shape design and focuses the energy of the piezoelectric stack to the tip mass. The smaller diameter neck increases the amplitude of the vibrations generated by the piezoelectric stack. The horn head, having a larger diameter than the neck, provides an interface for attaching the drill bit and acts as a hammer when impacts the free mass. The horn also provides a mounting flange for the transducer housing. It was designed such that the mounting flange coincides with the neutral plane of the transducer. The actuator allows the transmission of compressed air down to the drill bit for ice chips removal.

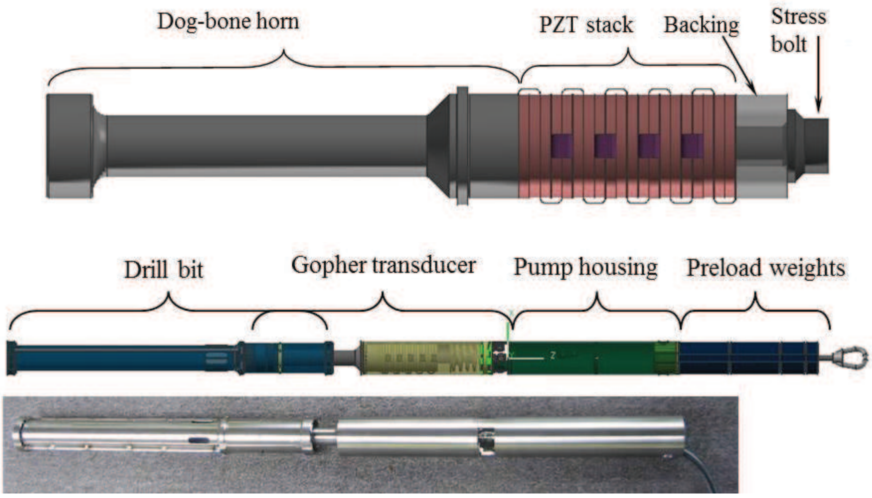


Figure 3 Gopher piezoeletric actuator (top) and CAD rendering and fabricated device (bottom)

Figure 4 Lake Vida, Antarctica test site (left) and the Gopher in the drilled hole (right)

The drill bit includes a core and cuttings cavity and a free mass cavity. The free mass cavity encloses the free mass and the horn head. To retain the free mass and the horn head in the cavity a retaining ring that is bolted to the cavity's wall is used. Additionally, for upward hammering and help with the retrieve of the gopher from the hole should it gets stuck, another free mass is added between the horn head and the retaining ring. This free mass will start working only when the system is pulled up from the hole and the transducer is activated. The cuttings cavity has at the bottom end a cutting section made out of two concentric rings connected by radial teeth. Both rings and the teeth have sharpened edges at the free end of the bit. The bit also allows the compressed air to be delivered at the cutting surface through two side air tubes. While drilling, the bit creates an ice core that remains inside the cutting cavity and ice chips between the cutting rings of the bottom section. The compressed air pushes the ice up the hole, on the outside of the bit, and they fall inside the cuttings cavity through an opening. When the cuttings cavity is full the gopher is pulled up from the holes and the cuttings removed. The two side tubes along the bit are also used to sample liquid from the bottom of the hole while drilling in wet ice.

Figure 4 shows the Lake Vida test site and the Gopher in the drilled hole. While we did not reach the proposed depth we drilled to 1.76m deep, more than the drilled length. We also concluded the deeper drilling required a better cuttings removal technique and this was the goal in our Gopher future development.

4. Auto-Gopher

The focus of next research task was on the development of a rotary-drill design that improves the capability of the Gopher by introducing flutes for cuttings removal and an anchor for WOB control, the Auto-Gopher [8]. In addition to existing features of the USDC, the Auto-Gopher incorporates a rotary actuation and an anchor. As the USDC drills and cores, it will need to periodically be removed from the produced borehole to empty an internal chamber where cuttings accumulate. This gives it the nickname Auto-Gopher. The Auto-Gopher was developed in cooperation with Honeybee Robotics. The Auto-Gopher conceptual design is shown in Figure 5.

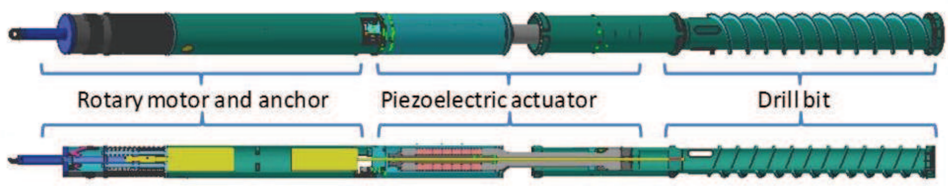


Figure 5 Auto-Gopher solid model and cross section

The wire-line Auto-Gopher operation requires that the whole body of the drill fits in the hole created by the drill head. All drill components: drill bit, percussive component, rotary component and anchor and linear feed component have to be sized and packaged to fit the cylindrical hole created by the drill bit.

All drill components were fabricated, integrated into the system and tested in the lab. The Auto-Gopher was later tested in the field. 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 6 shows the drill field test location, the extracted cores and a close-up of the drilled borehole. A total of 32 cores were extracted from a 3.07m deep drilled hole during the three days on the drill site.

Figure 6 The drill deployed in the field with the extracted cores (top) and drilled hole close-up (bottom)

An 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.

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 [9]. 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. Besides an increase in penetration rate we also observed a decrease in drilling energy per unit of depth (Figure 7).

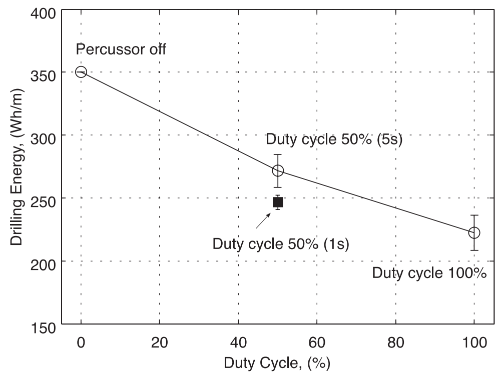


Figure 7 Drilling Energy per meter of depth as a function of duty cycle

5. Conclusions

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.

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 and the penetration rate. Future tests may include exploring additional drilling parameters and materials.

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