Wireline Deep Drill for Exploration of Mars, Europa, and Enceladus

Kris Zacny
Honeybee Robotics
398 W Washington Blvd, Suite 200
Pasadena, CA 91103
510-207-4555
zacny@honeybeerobotics.com

Gale Paulsen
Honeybee Robotics
398 W Washington Blvd, Suite 200
Pasadena, CA 91103
626-421-7902
paulsen@honeybeerobotics.com

Yoseph Bar-Cohen
NASA JPL/Caltech
4800 Oak Grove Dr.,
Pasadena, CA 91109-8099
818-354-2610
yosi@jpl.nasa.gov

Luther Beegle
NASA JPL/Caltech
4800 Oak Grove Drive
Pasadena CA 91109-8099
(818) 642-8913
Luther.Beegle@jpl.nasa.gov

Stewart Sherrit
NASA JPL/Caltech
4800 Oak Grove Dr. MS 67-119
Pasadena, CA, 91109
(818) 354-3891
ssherrit@jpl.nasa.gov

Mircea Badescu
NASA JPL/Caltech
4800 Oak Grove Dr. MS 67-119
Pasadena, CA, 91109
818-393-5700
stewart.sherrit@jpl.nasa.gov

Bolek Mellerowicz
Honeybee Robotics
398 W Washington Blvd, Suite 200
Pasadena, CA 91103
646-239-0429
mellerowicz@honeybeerobotics.com

Ola Rzepiejewska
Honeybee Robotics
398 W Washington Blvd, Suite 200
Pasadena, CA 91103
646-239-0429
ola@honeybeerobotics.com

Jack Craft
Honeybee Robotics
460 West 34th Street
New York, NY 10001
646-459-7835
craft@honeybeerobotics.com

Shazad Sadick
Honeybee Robotics
460 West 34th Street
New York, NY 10001
646-459-7835
sadick@honeybeerobotics.com

Frank Corsetti
Department of Earth Science
University of Southern California
Los Angeles, CA 90089
213-740-6123
fcorsett@usc.edu

Yadira Ibarra
Department of Earth Science
University of Southern California
Los Angeles, CA 90089
yibarra@usc.edu

Xiaoqi Bao
NASA JPL/Caltech
4800 Oak Grove Dr.,
Pasadena, CA 91109-8099
818-354-0298
Xiaoqi.bao@jpl.nasa.gov

Hyeong Jae Lee
NASA JPL/Caltech
4800 Oak Grove Dr.,
Pasadena, CA 91109-8099
Hyeong.Jae.Lee@jpl.nasa.gov

Bill Abbey
NASA JPL/Caltech
4800 Oak Grove Dr.,
Pasadena, CA 91109-8099
william.j.abbey@jpl.nasa.gov

***Abstract* — One of the most pressing current questions in space science is whether life has ever arisen anywhere else in the universe. Water is a critical prerequisite for all life-as-we-know-it, thus the possible exploration targets for extraterrestrial life are bodies that have or had copious liquid: Mars, Europa, and Enceladus. Due to the oxidizing nature of Mars' surface, as well as subsurface liquid water reservoirs present on Europa and Enceladus, the search for evidence of existing life must likely focus on subsurface locations, at depths sufficient to support liquid water or retain biologic signatures.**

To address these questions, an Auto-Gopher sampler has been developed that is a wireline type drill. This drill is suspended on a tether and its 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 a surface as well as power and data communication. Upon penetrating to a target depth, the drill is retracted from the borehole, the core is deposited into a sample transfer system, and the drill is lowered back into the hole.

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 Auto-gopher has been successfully tested in a laboratory environment in rock to a depth of 2 m. Field testing of the drill took place in November, 2012 at the US Gypsum quarry outside Borrego Springs, CA. The drill successfully penetrated to over 3 m depth with an average penetration rate of 1 m/hr.

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1. INTRODUCTION

The main question we are posed today in space science is whether life ever arose on another planetary body. Only one body in the solar system has been shown to support life, so a universal definition of life is impossible to create. However, given what we know about terrestrial biology and chemistry, three nearly universal components that life needs to exist is organic material, an energy source and liquid water. There are three unique bodies beyond the Earth that liquid water has been shown to exist in the past, or currently is thought to exist: Mars, Europa, and Enceladus.

For Mars, it has been shown via ample geomorphological and mineral evidence that water was present for geologic time frames. If life began, it would be expected to have moved into the subsurface to follow the water, and protect itself from harmful UV and surface radiation. Hence the subsurface is the most likely place to identify extinct/extant life signatures.

For Europa, the surface is subjected to incredibly high radiation levels resulting from its location in the Jovian plasma torus, including ion bombardment from species originating on the volcanically active body of Io. The presumed subsurface ocean would bring material to the surface, which has been shown to be relatively young in geologic terms. Any biosignatures present would have to be excavated from a depth below the radiation layer, most likely on the meter scale.

For Enceladus it has been shown that a liquid ocean exists under the surface through geysers of water ice emanating from the southern hemisphere that could only come from a liquid ocean. On the surface, organic molecules would fragment quickly due to high UV radiation present. This small body requires a low weight on bit drilling platform to access the liquid water present in the subsurface, where biomolecules would exist, if they are present.

To enable deep access, Honeybee Robotics and NASA-Jet Propulsion Laboratory (JPL) developed a wireline drill, called the Auto-Gopher [1, 2]. The drill uses low power and low Weight on Bit (WOB) to acquire cores of rocks, ice or ice cemented grounds. Acquired cores retain stratigraphy and volatiles to provide significant scientific information about the layered structure with inclusions and potential organisms. This wireline drill allows coring and core removal from depths limited only by the length of a deployment tether.

This paper reports on the development and testing of the Auto-Gopher system.

2. DEEP DRILLING APPROACHES

To access great depths, there are two main approaches: continuous drill string and wireline approach as shown in Figure 1 [3].

In a continuous drill string system, as a hole gets deeper, new drill sections need to be added. This approach has been successfully used in the Oil and Gas industry for over a century. The entire drill string is normally rotated by a motor above the surface (though some downhole motors systems are also possible) and the drilled cuttings are removed by circulating water, muds, or in shallower holes even compressed air. With this approach, holes as deep as 12 000 ft. have been drilled thus far.

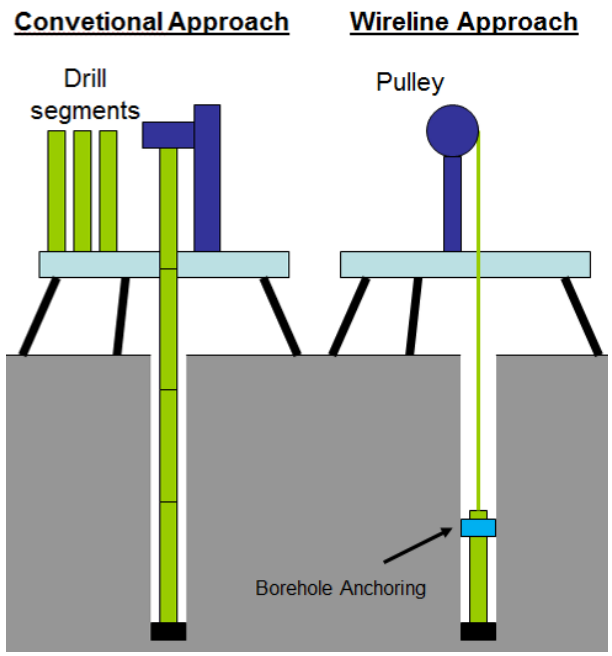


Figure 1. Conventional drill string vs. wireline drilling approach.

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 some kind of a robotic drill string feeding mechanism such as a carousel and mating connections between each drill string. This not only increases mass but also drives 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 electrical pass throughs. 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 [4].

Since using water or mud is difficult or impossible 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 single most important factor limiting the penetration depth using continuous drill string approach to approximately 10 m or so. A possible solution is to incorporate so called the "bite" approach, which is similar to pecking in machining [5]. 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.

The approach which solves most of the problems associated with continuous drill string approach is the wireline approach. In the wireline system, 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 mechanical connection to a spacecraft on a surface as well as power and data communication. Upon reaching the target depth, the drill is retracted from a hole by a 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 use of an internal screw to push on the drilling mechanism and the drill bit itself. This has an added advantage: the WOB of the continuous drill system is limited by the weight of the deployment platform (e.g. rover, hopper, or lander) and no such limitation exists for the wireline drill system.

The main disadvantage of the wireline system is a possibility of bore-hole collapse. To deal with that the drill could come with deployable (e.g. mesh type) casings but the complexity of deploying a casing would 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 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.

It should be noted that the wireline system overcomes challenges that are inherent to deep ice drills including melting or hot-water drills that are used to drill pure ice. The main disadvantage of the prior drills is their high mass and complex fixtures cannot be carried with a small spacecraft. Hot-water drills and other melt probes do not provide cores or cuttings, they require a source of large amount of ultra-clean water, they have high power requirements and they are difficult to operate in ice with sediments or permafrost, or when large rocks are present.

Other, non-traditional drilling technologies (laser, electron beam, microwave, jet, etc.) usually are competitive only in applications that are time limited and not power, energy or mass limited as is typical for space science applications. Generally, future space missions would not have enough power (or rather electrical energy) to employ these "modern" drilling technologies.

3. AUTO-GOPHER DESCRIPTION

The Auto-Gopher is a fully integrated, stand-alone drilling system requiring no additional actuation from the surface to perform drilling except for the tether management (i.e. pulley and the drum). The drill weighs 22 kg and has a length of 181 cm. The Auto-Gopher (see Figure 2) consists of five sub-systems. These are (from top to bottom):

1. The Anchor
2. The Weight on Bit (Preload) Drive
3. Rotary System (Auger Drive)
4. Hammer/Percussive System
5. Bit and Auger System with Cuttings Bucket

The Anchor

The Anchor uses a set of three compliant shoes to push against a borehole and anchor itself to a 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) System

The Weight on Bit (WOB) Drive is provided by internally actuated ballscrew and is designed for WOB of 1000 N. An integrated load cell provides a force feedback for WOB control.

The Rotary System

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/Percussive System

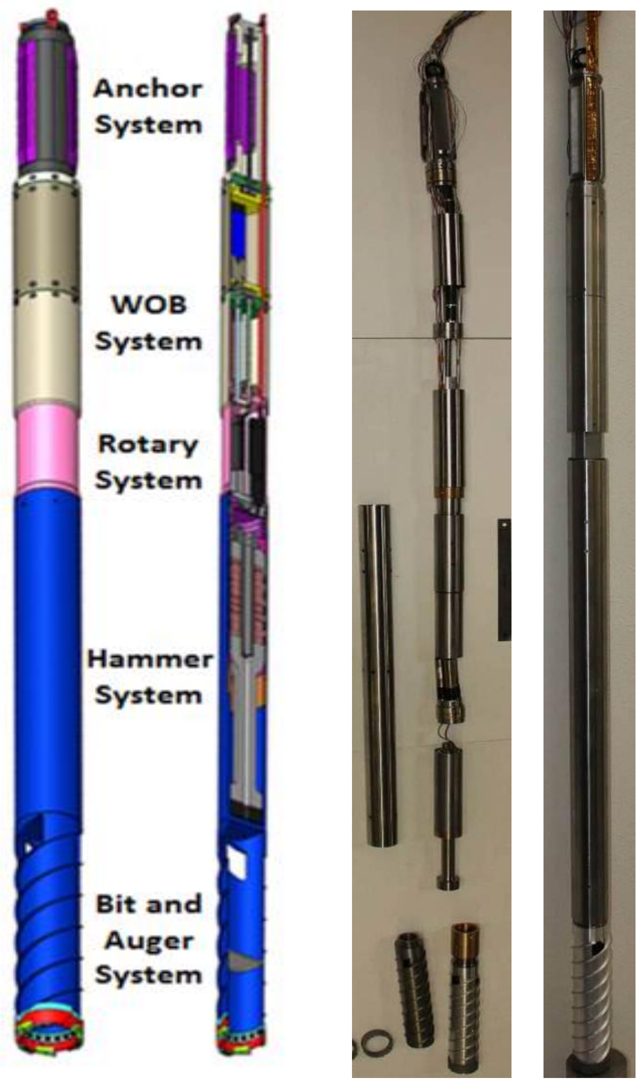
The hammer system employs a piezoelectric actuated percussive mechanism for providing impacts via free mass. The impact energy imparted to the bit is stochastic with a distribution of frequencies. Lower energy blows of the order of 0.1 J have frequencies in the hundreds of Hz range while higher energy blows of the order of 0.4 J have a frequency in the 10 Hz range.

The hammer is independent from the Rotary and hence can be engaged when the formation becomes hard for Rotary 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 Bit and Auger System

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). Upon drilling the 10 cm long core, the drill is retracted and the cuttings chamber is emptied.



Auto-Gopher Subsystems **Before Assembly** **After Assembly**

Figure 2. The subsystems of the Auto-Gopher Wireline Drill.

It should be noted that the drill diameter was driven primarily by the size of the piezo stack. In order for the piezo-based hammer system to provide more powerful impacts, the piezo stack had to be of large diameter. This made the outside diameter (OD) of the drill bit 71 mm. To minimize the drilling energy, the coring bit kerf (width) had to be made as small as possible. In the case of Auto-Gopher it was 5.5 mm making Internal Diameter (ID) of 60 mm.

Table 1 summarizes previously built wireline system from NASA-JSC and compares it with the Auto-Gopher. The main difference between the two systems is the drilling approach and in turn drill bit. The NASA-JSC drill uses pure rotary system and diamond impregnated bits for cutting (or rather grinding) through a rock, while the Auto-Gopher uses Rotary or Rotary-Percussive approach and Tungsten Carbide teeth for breaking the rock.

The diamond-impregnated bit consists of small diamonds that are embedded inside a metal matrix. The idea is that as individual diamonds wear out, so does the matrix, thus exposing fresh diamonds, while used diamonds fall out. The diamond impregnated bits have the advantage of being “self-sharpening”, and hence the penetration rate is expected to be uniform if the rock strength/hardness doesn`t change. However, since this type of bit uses a consumable (diamonds are used up and fall out) once the thickness of the diamond impregnated segment wears away, the bit stops drilling. These types of bits are suitable only for rotary drilling. The NASA-JSC drill has also used Polycrystalline Diamond Compact (PDC) type cutters but as soon as they wear out, the bit needs to be changed.

Core Break Off

Drilling a core is only the first step. The second step, which is difficult to achieve, is to break the core at its base and capture it within the core tube. The core break-off system also needs to be resettable (it cannot work just once) and also needs to allow for easy core retrieval by the core handling system on the surface.

There are a number of ways the core can be detached and 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 shear at the base by applying a side force on top). The optimum method for core breaking will not necessarily be implemented based on the lowest required force but rather on the complexity of implementation into the current design.

Table 2 shows a summary of various rock types and their physical properties. The last columns show the forces related to breaking the Auto-Gopher sized cores (60 mm diameter and 100 mm long) using different fracture modes. These forces are very large and the break off system would have to deal with the worst case scenarios. For example, if the ice core at 100K having a 1.5 MPa tensile strength was to be broken in tension, the required pull force would be 4 kN.

Table 1. Summary of planetary wireline drill systems.

	NASA JSC	Honeybee-JPL Auto Gopher	
		Rotary	Rot-Perc
Test Material (UCS, MPa)	Mansfield Sandstone (23 MPa) [6]	Cordoba Crème Limestone (25 MPa) [7]	
System Mass [kg]	7	22	22
Drill Length, [m]	2	1.8	1.8
Hole Diam, [mm]	45	71	71
Core Diam, [mm]	25	60	60
Core Length, [mm]	150	100	100
Power, [W]	50-100	80	<140
Rot. Vel., [RPM]	70	90	90
Weight on Bit, [N]	140-330	10-60	10-200
Penetration Rate [cm/hr]	9	180	240
Integrated Core Catcher	No	No	No

In its current design, the Auto-Gopher does not have core catching capabilities. This feature was removed in order to reduce drill complexity and the risk of drill getting stuck if the core cannot be sheared. Instead, a stand-alone core retrieval system was developed (Figure 3). The future generation of the Auto-Gopher will have auto-core catching feature employing core-dogs, a split ring collet or similar feature.

Figure 3. A separate core break off system was used to break-off and capture the core.

4. Laboratory Testing to 2 M Depth

The system level testing of the Auto-Gopher was performed by drilling Texas Crème Limestone also known as Cordova Crème, with an unconfined compressive strength of approximately 25 MPa. The experimental set up is shown in Figure 4 and consisted of a 2 m column of limestone rock enclosed within the >2 m tall drill stand. The drill stand included the Auto-Gopher deployment tower. All electronics for the Auto-Gopher were placed to the side of the stand.

A total of two 2-m tests were performed in the laboratory. In the first 2 m test, the Auto-Gopher was run in rotary-only mode of drilling, while during the 2nd round of 2-m tests, a rotary-percussive drilling (with percussion being piezo-driven) and rotary drilling were used interchangeably. The first test was essentially a system level check to make sure all drilling mechanisms worked as designed. The second test was a true drill performance test.

In drilling, two control approaches could be used: rate controlled (maintaining Rate of Penetration or ROP) or load control (maintaining Weight on Bit or WOB). In the rate controlled, a rotary speed (rpm), and Weight on Bit (WOB) are continuously adjusted to maintain the preset penetration rate. In the Weight on Bit control, the penetration rate (via Z-axis ballscrew), and the rotary speed are continuously adjusted to maintain the WOB.

In the case of Auto-Gopher, the algorithm used ROP based control. Initially, the auger rotary speed was set to a maximum of 90 rpm and the Weight on Bit was increased to achieve ROP of 1 mm/sec. However, to prevent the Auger motor from stalling out, the auger power was software limited to approximately 90 Watt at 90 rpm (i.e. stall torque of 10 Nm). Hence, the WOB was also controlled by the maximum Auger power. When drilling the 25 MPa Texas Crème limestone, the limit on the Auger power was reached before the limit on the ROP was reached. If another (much weaker) rock were to be drilled, most probably the limit of ROP at 1 mm/sec would have been reached at Auger power less than 90 Watt.

Figure 5 shows a drill progress into the 2 m column of rock. Note the drill progressively sinks into the drilled hole. Figure 3 shows a core captured by a stand-alone core retrieval system. As mentioned earlier, the current generation of the wireline system does not have an integrated core break-off and capture system. This mechanism will be implemented into the next generation drill. Figure 6 shows one of the 60 mm diameter and 100 mm long rock cores.

During the course of drilling a 2-m limestone rock column, a number of parameters (e.g. rpm, WOB, hammer on/off etc.) were changed in order to determine their effect on penetration rate. Since after drilling a 100 mm long core, the drill had to be pulled out to empty the core barrel of the core and cuttings, it was convenient to change drilling parameters for each of the 100 mm intervals.

Table 2. Rock Properties Table. [8, 9, 10]

Rock Type	Compressive Strength	Tensile Strength	Shear Strength	Shear Modulus	Method of Breaking a Core					
					1 Tension	2 Torsion	3 Impact Shear	4 Shear	4 Bending	5 Bending Force, 10 cm core
	[MPa]	[MPa]	[MPa]	[GPa]	kN	kNm	MPa	kN	Nm	kN
Amphibolite	278	22.8	139		64	5.9		393	966	10
Andesite	103	7.2	52		20	2.2		146	305	3
Basalt	120	14.6	60	18	41	2.5	4	170	619	6
Chert	210	23	105	17	65	4.5	4	297	975	10
Diabase	321	55.1	161	37	156	6.8	6	454	2336	23
Dolomite	90	3	45		8	1.9		127	127	1
Gabbro	186	13.8	93		39	3.9		263	585	6
Gneiss	223	15.5	112		44	4.7		315	657	7
Granite	226	11.9	113		34	4.8		319	504	5
Ice at 100K	100	1.5			4	2.1		141	64	1
Limestone	53.1	4	27	12	11	1.1	3	75	170	2
Marble	106	6.5	53		18	2.2		150	276	3
Quartzite	629	23.4	315		66	13.3		889	992	10
Salt	35.5	2.5	18		7	0.8		50	106	1
Sandstone	38.9	5.17	19	5	15	0.8	2	55	219	2
Sandstone	87	7.6	44	6	21	1.8	2	123	322	3
Schist	129	5.5	65		16	2.7		182	233	2
Shale	107	11	54		31	2.3		151	466	5
Shale	215	17	108	27	48	4.6	5	304	721	7
Siltstone	113	2.76	57		8	2.4		160	117	1
Slate	180	25.5	90	34	72	3.8	6	254	1081	11
Tuff	36	4.31	18		12	0.8		51	183	2

Figure 4. Experimental set up for the 2 m drilling tests.

Figure 5. Drilling progress into a 2 m limestone column.

Figure 6. The recovered core samples were 60 mm diameter and 100 mm long. Core recovery was 100%.

Figure 7, Figure 8, and Figure 9 compare various drilling modes Rotary to Rotary-Percussive with 50% duty cycle and Rotary-Percussive (100% duty cycle). The 50% duty cycle refer to 10 second drilling with percussive and 10 second drilling with just rotary system. In all tests, the rotary speed was kept constant at 90 rpm.

Figure 7 shows Rate of Penetration vs. Weight on Bit for Rotary, Rotary-Percussive with 50% duty cycle, and Rotary-Percussive drilling. As expected, the ROP increased with an increase in WOB (at higher WOB, the teeth would dig deeper into a rock and in turn cut greater depth each revolution). It was noticed that the hammering is engaged and works properly only when the WOB is above a set threshold (approximately 70 N). In addition, Rotary-Percussive seems to result in a slightly faster penetration rate than pure rotary drilling. There is also no great difference between 50% hammer and 100% hammer drilling. One would have expected a much larger increase in penetration rate when piezo-hammer is engaged. However, the small benefit of the hammer in this case is probably due to the low rock strength and very effective cuttings bit design. If a rock has low strength, rotary drill can easily penetrate it (cutting teeth can dig into a rock at modest Weight on Bit values) and hence the benefit of hammer is low. The benefit of a hammer system, however, could be better seen in hard rocks.

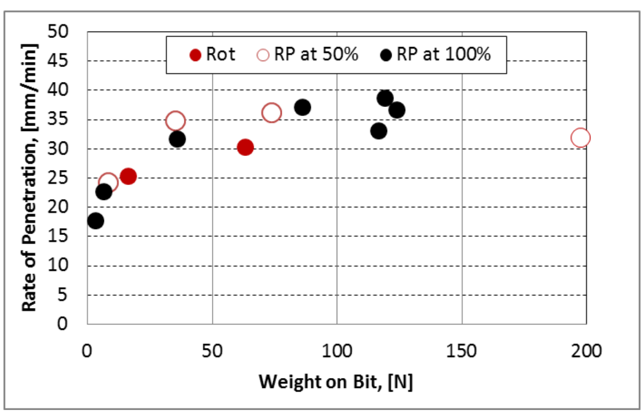


Figure 7. Rate of Penetration vs. Weight on Bit for Rotary, Rotary-Percussive with 50% duty cycle, and Rotary-Percussive drilling.

Figure 8 shows 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. The main difference in power is between rotary and rotary-percussive, since piezo-hammer required additional 50 Watt. Note that there is little difference in power as a function of Weight on Bit. Since with larger Weight on Bit cutters would dig in deeper, it has to be concluded that drilling resistance even at deeper cuts was relatively low. Another way to interpret these results is that the resistance of the rock to individual cutters was approximately the same for deep and shallow cuts. This of course is counter-intuitive because one would expect large resistance (and in turn higher torque and power) at greater depth of cuts. A plausible explanation for this anomaly is that rock was relatively weak and did not offer much resistance to the drill.

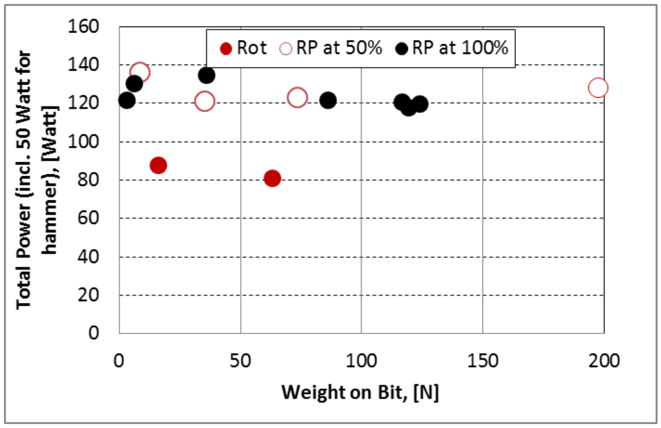


Figure 8. Total Power (including 50 Watt for the piezo-hammer system) vs. Weight on Bit for Rotary, Rotary-Percussive with 50% duty cycle, and Rotary-Percussive drilling.

Figure 9 shows Specific Energy vs. Weight on Bit for Rotary, Rotary-Percussive with 50% duty cycle, and Rotary-Percussive drilling. The figure essentially combines Power and penetration Rate (i.e. Figure 7 and Figure 8) into a single parameter: Specific Energy (SE). SE essentially is a matric used in drilling to determine efficiency of a drilling system. It is a universal metric as it eliminates the effect of diameter or hole depth. Normally, SE uses units of J/cc, however, in this case to make the data easier to understand, the units are Wh/m (i.e. energy required to drill 1 m deep hole). The SE = Power/ROP. Figure 9 shows drastic drop in SE with increase in the Weight on Bit. That is, at higher WOB, cutters dig deeper and in turn drill penetrates faster. However because the rock is relatively weak (or the drilling method is quite effective) the energy required to drill each m of hole gets lower.

Figure 10 shows Specific Energy, Rate of Penetration, and Total Power (Rotary and Percussive) vs. Weight on Bit as function of rotational speed of the drill: 90 rpm and 40 rpm. In both cases the hammer system was engaged 100% of the time. As expected, the drilling power and the penetration rate at 40 rpm are lower than at 90 rpm. In addition, specific

energy seems to be lower at 90 rpm. The penetration rate and energy at 90 rpm/120 Newton and 40rpm/250 Newton are the same. Hence doubling the rpm has the same effect on the penetration rate as doubling the WOB.

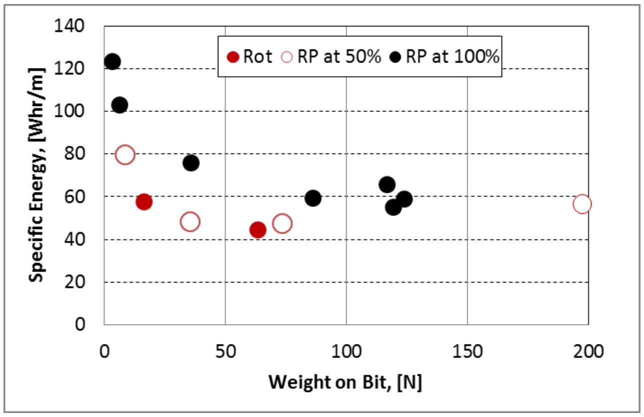


Figure 9. Specific Energy vs. Weight on Bit for Rotary, Rotary-Percussive with 50% duty cycle, and Rotary-Percussive drilling.

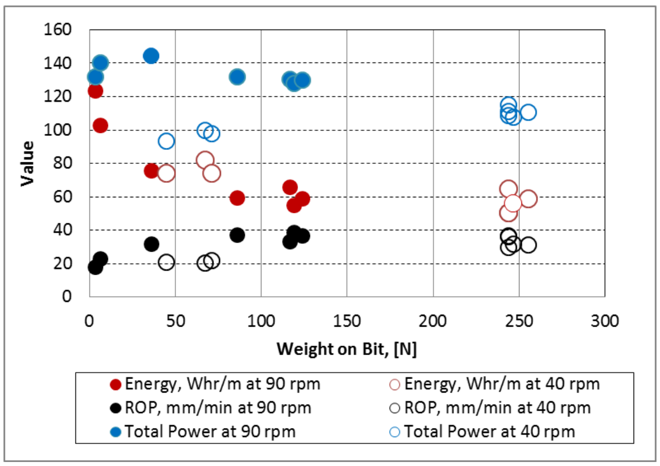


Figure 10. Specific Energy, Rate of Penetration, and Total Power (Rotary and Percussive) vs. Weight on Bit as function of rotational speed of the drill.

In general, the drill can maintain a relatively high penetration rate of 40 mm/min (2.4 m/hr) at relatively low power 120 W and Weight on Bit of 100 N. If these drilling parameters can be maintained, the drill would require 60 Whr to penetrate 1 m.

Since drilling effort is proportional to an Unconfined Compressive Strength of a material and the strength of ice at ~100K is 100 MPa (i.e. 4x the strength of the limestone rock used for testing), it is expected that the penetration rate would be 4x lower and the required energy to penetrate 1 m would be 4x higher. In addition the drill would require larger Weight on Bit, but since the drill does not rely on the mass of the lander, the issue of higher WOB is not critical.

5. Field Tests to 3 M Depth

The purpose of the field test was to demonstrate drilling and core recover to 3 m depth. The secondary goal was to obtain drilling telemetry and extrapolate the drill time, and energy to greater depths.

Location and Logistics

The field tests took place at the US Gypsum Company gypsum quarry outside Borrego Springs from 27-29 November, 2012. The exact coordinates are: 33°00'56.7786", -116°04'48.1694" and elevation: 398.8 feet.

The team is shown in Figure 11 and included engineers and scientist from Honeybee Robotics, NASA Jet Propulsion Laboratory, and University of Southern California.

Gypsum deposits are up to 200 feet thick and average 125 feet in thickness [11]. Anhydrite is found in the lower part of the evaporates.

The strength of the gypsum was measured using a Schmidt hammer and determined to be in the range of 30-40 MPa. The US Gypsum (operator of the quarry) also performed Unconfined Compressive Stress tests on 3 gypsum cores and measure the strength of 38 MPa ±2 MPa.

During the first day, the team traveled from Pasadena to the field site. The same day the camp was established and the drill unpacked and integrated. All the operations were performed within protective tent. This has been instrumental to the success of the field campaign, since the location at times was extremely windy, hot during the day and cold in the evening.

Drilling was performed over a 3 hour period till 8pm and to a depth of 70 cm. During the second day, drilling started at 9am and ended at 8pm, at the depth of 235 cm. On the third day, drilling started at 9am and ended at noon – i.e. when the depth of 3 m was reached.

Figure 11. The Field Team included (left to right): Gale Paulsen, Bolek Mellerowicz, Ola Rzepiejewska (Honeybee Robotics), Bill Abbey, Luther Beegle, Stewart Sherrit, Jae Lee (NASA JPL), Yadi Ibarra (USC), Mircea Badescu (NASA JPL), and Kris Zacny (Honeybee Robotics)

Details of the Drilling Process

The drilling process included coring to 10 cm depth, retracing the AutoGopher from the hole, cleaning out the cuttings from catch basket above the core barrel, manually breaking and capturing the core with a break-off tool

(Figure 12), followed by lowering the drill back into the hole for next 10 cm run.

Figure 12. Left to right: 1) Core bit above the hole. 2) Cuttings within the catch basket; 3) Full size core catcher; 4) Short core catcher for short cores.

It should be noted two core catchers were used: shorter and longer as shown in Figure 12. The shorter version is ideal for breaking 5 cm long cores or 10 cm cores which are in a single piece. The long core catcher was designed to house and retain the entire length of the 10 cm long and was ideally suited for cores that had mid shear planes such as one shown in Figure 14 B.

Figure 13 shows drilling progression. Since the total length of the AutoGopher was 190 cm, once the depth of 190 cm was reached, the entire drill fit within the hole. Therefore, the top anchors braced the borehole wall to provide drill stability.

Figure 15 shows the side wall and bottom of the 3 m hole. After each 10 cm, the drill operator looked down the hole to determine the state of the core (whether it broke or was intact). Out of the total of 32 cores, only 4 cores broke off downhole; 2 of them remained inside the core barrel (as shown in Figure 14 A) and another 2 remained at the bottom of the hole (which caused problems). In both of the two latter cases, a short ~3 cm thick core disks broke loose and remained at the bottom of the hole (Figure 14 C). Trying to drill around or through these disks was extremely difficult as the disk rattled in place, the cutting teeth had difficulty biting in and as a result, the drill motor kept on stalling. Note the side ring cut into the rock by the core bit. The end solution was to suction lift the loose rock disks using a long vacuum cleaner hose.

It should be noted that future field campaigns should include borehole cameras for inspecting of borehole walls and the state of the core in the hole.

The majority of cores were in a single solid piece as shown in Figure 14 D. These were very easy to break-off and capture. A couple of other cores sheared at approximately 45°, and required a full length core catcher (i.e. a core catcher extending the full length of the core as opposed to half-length as shown in Figure 14 A. An example of such as core is shown in Figure 14 B. In rare occasions, the cores would include the bottom of the hole, that is at the point of fracture, the core diameter was large than the ID of the core drill but smaller than the OD of the core drill (i.e. smaller than the borehole diameter). We refer to this as mushroom effect. A core of this type is shown in Figure 14 E.

We observed that the surfaces of the cores were covered by the fine drill cuttings, effectively obscuring the actual rock. To inspect the rock, one had to look at the fracture surface.

We also noticed that at various depths, the rock cores included iron-bearing minerals and clays. Hence, the formation was not pure gypsum.

Figure 13. Drilling progress. From left to right: 1) Anchor 190 cm above the ground (i.e. first hole); 2) Anchor 50 cm above the hole; 3) Anchor ~20 cm above the hole; 3) Anchor within the hole, 5) Anchor ~100 cm below the rim (drill at ~300 cm depth).

A. Core captured inside the corer.

B. A core with 45 degree shear fracture

C. A core broke loose and rattled down hole stalling drill motors.

D. Perfect core

E. 'Mushroom' core (the bottom of the core is larger than the ID of core bit).

Figure 14. Examples of various core types encountered during the test.

Figure 16 shows the AutoGopher drill after the completion of the field test. Shown is the drill above the 3 m hole as well as 32 cores retrieved form the hole. The cores were placed inside protective sleeves for transport to USC for analysis.

Figure 15. Looking down the 3 m hole. The future campaign should include downhole camera.

Figure 16. The AutoGopher Drill above the 3 m deep hole (note the yellow tape). The 32 rock cores are placed inside the 4 protective tubes.

Drilling Telemetry

During the course of the drill test, we acquired drilling telemetry such as power, penetration rate and Weight on Bit to estimate the resources required from a spacecraft during planetary missions. In addition, we varied percussive duration and duty cycles to optimize drilling efficiency.

We found that the average penetration rate for the 3 m hole was 1 m per hour (or 3 hours for a 3 m hole). It took approximately 20 minutes to pull the drill out of the hole, empty the catch basket of drilled cuttings, retrieve the core, and lower the drill back into the hole. For a 3 m hole, these operations totaled approximately 10 hours. In addition, we experienced approximately 4 hours of downtime due to broken wire that had to be repaired and issues related to misalignment between the anchor above the hole and the borehole itself. The latter one is of particular importance since it will have to be addressed via re-design or operational sequencing. We found that having a half of the anchor pads are above the hole and the bottom half are in the hole induces abnormally high WOB values. This is a result of small misalignment between the hole and the deployment system. Ideally, the anchors would have to be fully above the hole or in the hole – in either of the cases, the WOB was nominal.

Figure 17 shows the rate of penetration (ROP) as a function of percussive power and duty cycle. We found that the ROP is lowest if no percussion is used and increase with an increase in the duty cycle, reaching maximum at 100% duty cycle (i.e. percussion always on). However, we also found that a duty cycle of 50% with short 1 second on/off also results in high penetration rate. If the on/off periods are increased to 5 seconds, the penetration rate drops by 50% though. This implies that during the 'off' periods, penetration rate is very low.

We also found that with the percussion system on, the WOB and rotary power would decrease. In some instances, the rotary actuator would stall whenever percussive system was turned off.

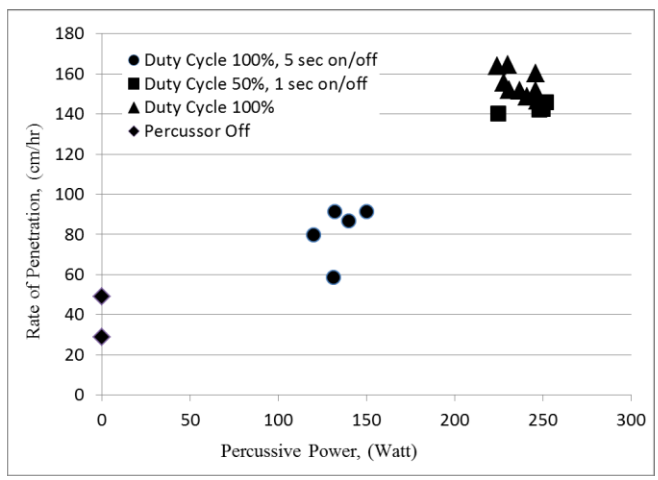


Figure 17. Penetration Rate as a function of Percussive Power and duty cycle.

Figure 18 shows the energy in Whr required to drill one meter hole (i.e. Whr per meter). To calculate the energy, total power was used (i.e. Auger power and Percussive power). The Auger power was always in the range of 90-120 Watt. The power required to actuate anchor and WOB mechanisms was negligible.

It can be concluded that the most energy efficient drilling with the AutoGopher has been when the percussive mechanisms was active at 100% duty cycle (that is continuous). In fact, it takes approximately 200 Whr to drill 1 meter. The least efficient approach is rotary drilling with no percussion.

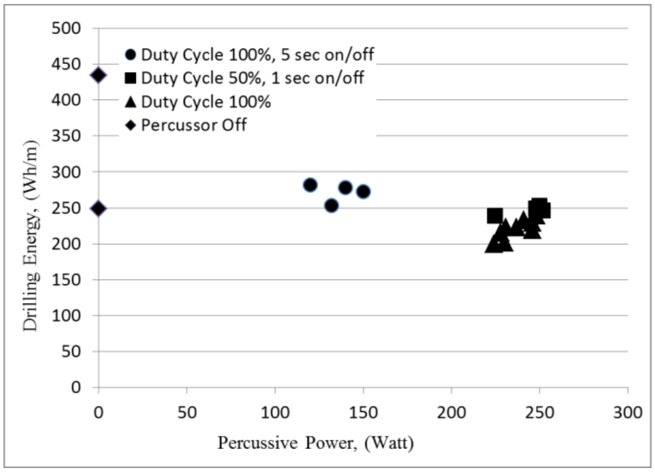


Figure 18. Drilling Energy per meter of depth as a function of Percussive Power and duty cycle.

6. CONCLUSIONS

One of the most pressing questions in space science that we are currently faced with is whether life has ever arisen anywhere else in the universe. Since water is a critical prerequisite for all Earth-based life as we know it, the nearest-known exploration targets for extraterrestrial life are Mars, Europa, and Enceladus. Due to the oxidizing nature of Mars' surface, as well as high radiation levels at the surfaces of Mars, Europa and Enceladus, the search for existing life must likely focus on subsurface locations, at depths sufficient to allow liquid water.

The main feature of the developed Auto-Gopher is its wireline operation. 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 a surface as well as power and data communication. Upon penetrating to a target depth, the drill is retracted from the borehole, the core is deposited into a sample transfer system, and the drill is lowered back into the hole.

This wireline system 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 Auto-gopher has been successfully tested in a laboratory environment in 25 MPa Texas crème limestone rock to a depth of 2 m. The average drilling power was in the range of 100-150 Watt, while penetration rate was approximately 2.5 m/hr. The energy required to penetrate 1 m depth in Texas crème limestone was measured to be 60 Whr.

The Auto-gopher has also been successfully tested in a field environment in 40 MPa Gypsum in the US Gypsum Quarry outside Borrego Springs, CA to a depth of 3 m. The average drilling power was in the range of 100-350 Watt (depending on the duty cycle of the percussive system), while penetration rate was between 30 cm/hr (no percussion) to 160 cm/hr (percussion at 100% duty cycle). The energy required to penetrate 1 m depth range from up to 20 Whr/m (percussion at 100% duty cycle) to 450 Whr/m (no percussion). Also, the Auto-Gopher was tested in the field drilling gypsum and reached 3-m depth. The most energy efficient drilling was found when the percussive mechanism was activated continuously. It required approximately 200 Whr to drill 1-meter. The rotary drilling with no percussion was found to be the least efficient approach.

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BIOGRAPHIES

Dr. Kris Zacny *Dr. Kris Zacny is Vice President and Director of Exploration Technology Group at Honeybee Robotics. His interests include robotic terrestrial and extraterrestrial drilling, excavation, sample handling and processing, and geotechnical systems. In his previous capacity as an engineer in South African mines, Dr. Zacny managed numerous mining projects and production divisions. Dr. Zacny received his PhD from UC Berkeley in Mars drilling and ME in Petroleum Engineering. He participated in several Arctic and the Antarctic drilling expeditions. Dr Zacny has over 100 publications, including an edited book titled "Drilling in Extreme Environments: Penetration and Sampling on Earth and Other Planets".*

Gale L. Paulsen *is a Systems Engineer at Honeybee Robotics. Prior to joining Honeybee in 2005, he worked with NASA's Jet Propulsion Laboratory as a graduate student for two years to develop a multi robot cliff climbing system. At Honeybee, he has performed field tests of robotic drilling systems in the Canadian High Arctic and Antarctic. Paulsen has also assisted in the development of detailed mechanical, electrical, and software designs and analyses for multiple projects such as Sample Manipulation System for the 2011 Mars Science Lab, Icy Soil Acquisition Device on the 2007 Mars Phoenix Lander, and the Rock Abrasion Tool on the Mars Exploration Rovers. He also lead mechanical, electrical, and software designs for a high precision rock grinding instrument for producing thin sections and an automated sample acquisition and analysis system for the mining industry. Gale holds a B.S and M.S. in Mechanical Engineering from the University of Nebraska.*

Yoseph Bar-Cohen *is a Senior Research Scientist and Supervisor of the Advanced Technologies Group (http://ndeaa.jpl.nasa.gov/) at Jet Propulsion Lab. In 1979, he received his Ph.D. in Physics from the Hebrew University, Jerusalem, Israel. His research is focused on electro-mechanics including planetary sample handling mechanisms, novel actuators that are driven by such materials as piezoelectric and EAP (also known as artificial muscles) and biomimetics. Using ultrasonic waves in the composite materials, he discovered the polar backscattering (1979) and leaky lamb waves (1983) phenomena. He (co)edited and (co)authored 7 books, co-authored about 360 publications, co-chaired 44 conferences, and has 22 registered patents. His notable initiatives include challenging engineers and scientists worldwide to develop a robotic arm driven by artificial muscles to wrestle with human and he held contests in 2005 and 2006. For his contributions to the field of artificial muscles, Business Week named him in April 2003 one of five technology gurus who are "Pushing Tech's Boundaries." His accomplishments earned him two NASA Honor Award Medals, two SPIE's Lifetime Achievement Awards, Fellow of two technical societies: ASNT and SPIE, as well as many other honors and awards.*

Luther Beegle *is a Research Scientist at the Jet Propulsion Laboratory where he has been employed since 2001 after spending 4 years at JPL and the California Institute of Technology as a Post-Doctoral Researcher. He received his BS in Physics from the University of Delaware in 1990, and his PhD in Physics from the University of Alabama At Birmingham in 1997. He is an experimental physicist by training and has extensive astrobiological science interests as well as experience developing instrumentation for space applications. These developments include the designing and testing of ion mobility spectrometers, charged particle optics, organic molecule extraction techniques, microwave discharge plasma sources, and cylindrical ion*

trap mass spectrometers funded under the Planetary Instrument Definition and Development Program (PIDDP), Astrobiology Instrument Development Program (ASTID) and Mars Instrument Development Program (MIDP). He is currently a Surface Sampling System (SSS) Scientist on the Mars Science Laboratory.

Dr. Stewart Sherrit *is a Senior Member of Technical Staff at JPL's Advanced Technologies Group. Dr. Sherrit received his B.Sc. in engineering physics (Nuclear-Mechanical option), M.Sc. (Solid State Physics-Thermoelectric Conversion) and PhD (Physics: Characterization of losses, dispersion and field dependence of piezoelectric materials.) from Queen's University, Kingston. Canada. He has authored 4 book chapters, over 100 papers, 45 NASA Tech Briefs and 65 New Technology Reports, 6 patents, and given numerous invited talks at international meetings. He has been involved in the development of a variety of sampling tools including the Ultrasonic Sonic Driller Corer, the Ultrasonic Rock abrasion tool, Ultrasonic powder sampler, rock crusher, Ultrasonic Gopher and Aerobot Harpoon sampler. In the course of his research he has participated in field trips to the Mojave Desert, Lake Vida, Antarctica and Mt Hood, Oregon. In 2005 he was the Task Manager for the Mars Sample Return Clean Sampling Tool. In addition to his research activities he has been involved in a variety of Missions either as a consultant or an actuator designer.*

Dr. Mircea Badescu *is a Senior Engineer at the NDE and Advanced Actuators group of the Jet Propulsion Laboratory. He received the Ph.D. degree in robotics in mechanical and aerospace engineering, from Rutgers University, in 2003 and the diploma (B.S./M.S.) in mechanical engineering from the Technical Military Academy in Bucharest, Romania, in 1992. He has experience on design of power ultrasonic piezoelectric transducers, sampling systems, instruments for planetary exploration, optical components for telescopes, optimal design of self-reconfigurable robots using parallel platforms as modules, kinematic analysis of bio-nano structures, and design of haptic devices for vehicular instruments control and automotive smart clutches. He is coauthor of 70 publications and 6 patents and recipient of 38 NASA Tech Brief and Team awards.*

Bolek Mellerowicz *is a project engineer at Honeybee Robotics since January 2010. His primary interests include electrical and motion control solutions. His master thesis project involved designing and building the Precision Sub-sampler, a mechanism used to acquire rock powder from rock cores. He recently returned from a field expedition with the Ice Breaker drill in the Canadian High Arctic. Prior to Honeybee, Bolek worked as an automation engineer in Norway for Aibel, a company engineering oil and gas production facilities. Bolek holds a B.Sc. in Applied Physics from Umea University and a M.Sc. in Mechatronics from Chalmers Institute of Technology in Sweden.*

Jack Craft *is Manager of the Exploration Technology Group at Honeybee Robotics. In that role, he has worked to ensure the success of Honeybee's efforts to develop drilling and sampling technologies. Mr. Craft is responsible for project planning and control of our several NASA ASTEP, ASTID, and SBIR R&D efforts geared towards planetary subsurface access and sampling. Mr. Craft holds a B.S. in Mechanical Engineering from the Cooper Union and an M.S. in Mechanical Engineering from Rutgers University.*

Dr. Xiaoqi Bao *is a Member of the Engineering Staff at the Advanced Actuators team of the Jet Propulsion Laboratory. He joined JPL in May 1997 after serving for about ten years as a Research Associate at Pennsylvania State University. He received his Ph. D., Physics, in 1985 and M. Sc., Physics, in 1982 from the Chinese Academy of Sciences, Beijing, China. In 1986, Dr. Bao was a Visiting Scientist at the Dept. of Electrical Engineering of Toyama University, Japan. He has research experience in piezoelectric motors, SAW sensors, piezoelectric actuators, electroactive polymers (EAP), composite materials, active vibration and sound control, and intelligent materials/structures. He has published more than 30 papers in related research areas.*

Frank Corsetti *is an Associate Professor of Earth Sciences at the University of Southern California. Frank studies the co-evolution of the Earth and its biosphere from a geobiologic perspective, searching for traces of life in deep (and not so deep) time—how has life affected*

the history of our planet, and how has the history of our planet affected the evolution of life? He is probably most noted for his studies of life during "Snowball Earth", the most severe glaciation known that occurred ~700 million years ago, but other recent projects include the origin of animals, mass extinctions, and investigations into new biosignatures for use with ancient rocks on Earth and other locales in our solar system (e.g., Mars). Frank has studied rocks as old as 3.5 billion years and as young as those forming today, and field sites are located in the US, Canada, Mexico, Peru, Australia, Namibia, and China

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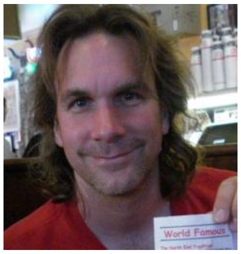
Shazad Sadick *is the Systems Engineer for the Rapid Assembly project at Honeybee Robotics. He has over eight years experience as a Project Manager, Lead Designer, and Systems Designer for Honeybee. His experience includes mechanism design and development, systems engineering, fabrication, assembly and testing. In addition to a wide range of aerospace research and development efforts, he has worked on multiple flight hardware efforts. This includes mechanical design, fabrication and assembly of the Mars Explorations Rovers Rock Abrasion Tools. Shazad was the System Engineer for the design of solar array deployment for a Bigelow Aerospace spacecraft. Through the SBIR program, he was the System Engineer for the development of a two axes gimbal system for AFRL and was later a Project Manager for development of modular gimbal in support of AFRL PowerSail Deployable Structures Experiments. Shazad holds a B.S. in Mechanical Engineering from City College of New York.*

Yadira Ibarra *is a PhD candidate and graduate student researcher at the Department of Earth Sciences at the University of Southern California.*

Hyeong Jae Lee *was born in South Korea and received the B.S., M.S. and Ph.D. degrees from the Pennsylvania State University, University Park, Pa, in 2007, 2010 and 2012, respectively, in Materials Science and Engineering. In August 2012, he joined Advanced Technologies Group at the Jet Propulsion Laboratory as a Caltech Postdoctoral Scholar.*

His research interests focus on piezoelectric materials and devices, with applications in biomedical imaging, therapeutic ultrasound, underwater sonar, ultrasonic drilling and non-destructive testing.



Bill Abbey *is a Member of the Technical Staff with JPL's Planetary Chemistry and Astrobiology Group. He assists in a wide variety of NASA efforts under the MFRP, ASTEP, ASTID & NAI programs, and currently provides technical support to the Surface Sampling System scientists on MSL. A field geologist by training, he also has provided logistical planning and on-site geologic expertise for investigations in the U.S., Chile and Arctic Circle. He holds a B.S. and M.S. in Geology from George Washington University.*