Percussive augmenter of rotary drills (PARoD)

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ABSTRACT

Increasingly, NASA exploration mission objectives include sample acquisition tasks for in-situ analysis or for potential sample return to Earth. To address the requirements for samplers that could be operated at the conditions of the various bodies in the solar system, a piezoelectric actuated percussive sampling device was developed that requires low preload (as low as 10N) which is important for operation at low gravity. This device can be made as light as 400g, can be operated using low average power, and can drill rocks as hard as basalt. Significant improvement of the penetration rate was achieved by augmenting the hammering action by rotation and use of a fluted bit to provide effective cuttings removal. Generally, hammering is effective in fracturing drilled media while rotation of fluted bits is effective in cuttings removal. To benefit from these two actions, a novel configuration of a percussive mechanism was developed to produce an augmenter of rotary drills. The device was called Percussive Augmenter of Rotary Drills (PARoD). A breadboard PARoD was developed with a 6.4 mm (0.25 in) diameter bit and was demonstrated to increase the drilling rate of rotation alone by 1.5 to over 10 times. The test results of this configuration were published in a previous publication. Further, a larger PARoD breadboard with a 50.8 mm (2.0 in) diameter bit was developed and tested. This paper presents the design, analysis and test results of the large diameter bit percussive augmenter.

Keywords: Drilling, USDC, planetary sampling, piezoelectric actuation

1. INTRODUCTION

Percussion and rotation have long been identified as effective methods of penetrating solid materials and formations [Badescu et al., 2006, 2008; Bar-Cohen and Zacny, 2009]. Percussion alone is very effective at fracturing hard, brittle materials like concrete, rocks and ceramics, whereas rotation alone is more effective on soft and/or ductile materials such as wood, plastics, and ductile metals. When using only the percussion alone for drilling an additional method of removing the cuttings needs to be employed as hammering on the cuttings in the hole would use the impact energy to further fracture the cuttings and could lead to bit jamming depending on the hole depth. A key advantage of rotation is the removal of cuttings from the borehole so the end-effector of the bit continuously comes in contact with fresh surface on the drilled medium. Combining rotation and percussion produces a more effective penetration mechanism. Existing hammer-drills produce their hammering action mechanically or pneumatically. A novel rotary drill augmenter was developed by the JPL's Advanced Technology Group (under a contract with Placidus LLC) by introducing ultrasonic vibrations onto a rotating bit. The device uses a piezoelectric actuator to augment any rotary drill with high frequency percussion. There are many advantages to using piezoelectric actuators to create hammering [Bar-Cohen and Zacny, 2009; Bao et al., 2003; Bar-Cohen 2005]. They can be operated under low average power using duty cycling. They do not require high axial loading to penetrate materials, making them very easy to use particularly in planets with low gravity. They generate minimal vibration back into the mounting fixtures or the user, making their operation more convenient and less tiring. It is important to note that low power and low applied force are desirable characteristics for sample acquisition in planetary exploratory missions with very tight power budgets, particularly on low gravity planets. The ease of use and quiet operation (compared to other hammer drills) are traits that interest the construction and remodeling industry and the tested augmenter was developed as a prototype for potential commercialization. Another advantage of the PAROD is its use for rebar reinforced concrete drilling. In general, carbide teeth are used for drilling in concrete using a rotary hammer drill that besides rotation delivers high impact energy impact to the drill bit. These impacts can not be used when the teeth are in contact with the rebar as the teeth fracture. The piezoelectrically generated vibration induced in the drill bit results in lower energy impacts but at a much higher frequency in the order of tens of kHz. These lower energy impacts may be acceptable for the rebar cutting bits but the still high energy delivered to the drill cutting elements could produce an increase of the drilling rate. Moreover the same drill bit could be used for drilling in reinforced concrete without the need to change the bit when reaching a rebar.

Generally, piezoelectric materials generate a charge when under an applied stress. The converse is also true, where an applied electric field produces mechanical strain in piezoelectric materials. By driving the piezoelectric material with a sinusoidal electric field at ultrasonic frequency, vibrations with micron size amplitudes are generated. The amplitude on the vibrations is driven by the electric field generated in the piezoelectric material. Piezoelectric stacks are used for lowering the amplitude of the driving signal, produce a high power transducer and generate larger amplitude vibrations. Another significant advantage of using piezoelectric stacks as actuators is the ability to operate them at extreme temperatures. This would be particularly of interest to exploration missions to such planets and planetary satellites as Titan and Europa where the temperature is as low as -180^{o}C and Venus where it is as hot as 460^{o}C [Sherrit et al., 2005]. Constraining a piezoelectric stack between a backing and a variable cross-section horn amplifies the vibrations at the horn tip and maintains the PZTs in compression [Sherrit et al., 2001; Chang et al., 2004]. The vibrations of the horn are transferred to a drill bit that impacts the drilled media and fractures the formation. A computer program that combines LabView^{TM} and MATLAB^{TM} code was developed to control the drive frequency of the augmenter. To maintain the augmenter in resonance, a hill climb algorithm was developed [Aldrich et al., 2006]. The rotation and percussion power are supplied separately allowing the use of various power combinations to test different possibilities and determine the benefit of the augmenter over operating the drill as rotary only. The development of the augmenter was done in two phases. In the first phase a unit with a 6.4 mm diameter bit was fabricated. In the second phase a new unit was developed with a bit diameter of 50.8 mm. The design and analysis process and test results for the prototype with the large diameter bit augmenter are reported in this manuscript.

2. DESIGN AND ANALYSIS

The developed augmented drill was designed to operate as a drilling unit with two independent actuators: a rotary actuator and a piezoelectric transducer [Badescu et al., 2012]. The rotation is provided by a commercial drill and the percussion is generated by a piezoelectric stack transducer. The prototype was called "Percussive Augmenter of Rotary Drills (PARoD)" and two versions of the design were developed - a small diameter and a larger diameter bits, each with a different rotary actuator and piezoelectric transducer. The design and the tests results of the small diameter version were presented in a previous publication [Badescu et al., 2012]. The 2.0 in diameter bit version is shown in Figure 1. It consists of a rotary actuator, a piezoelectric actuator and a drill bit, where the rotary actuator and the bit are off-the-shelf components and the piezoelectric actuator was developed for this reported study. A series of intermediate components were procured or fabricated and integrated into the design including a slip ring for powering the piezoelectric actuator (Figure 1). The component details of the drill are shown in Figure 2 and they include piezoelectric actuator housing, adaptor between the rotary drill chuck and piezoelectric actuator, the slip ring collar and adaptor between the drill bit and piezoelectric actuator horn. The drill bit adaptor design parameters were adjusted such that the drill bit tip reached the largest displacements at the resonant frequency of the augmenter.

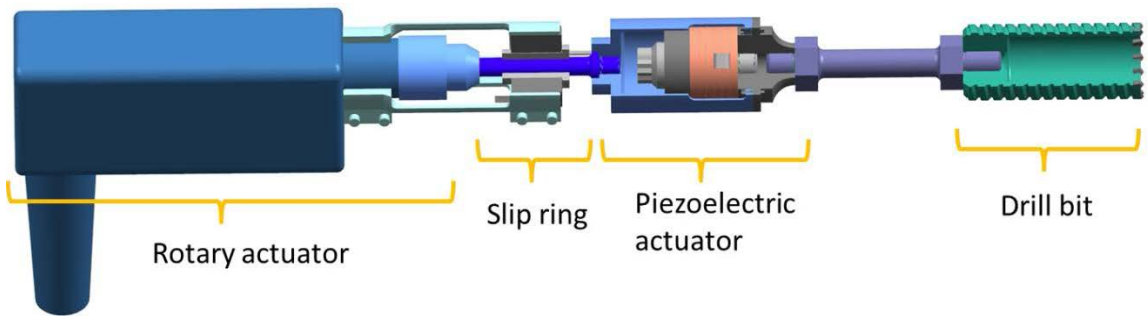

Figure 1 Drill subassemblies

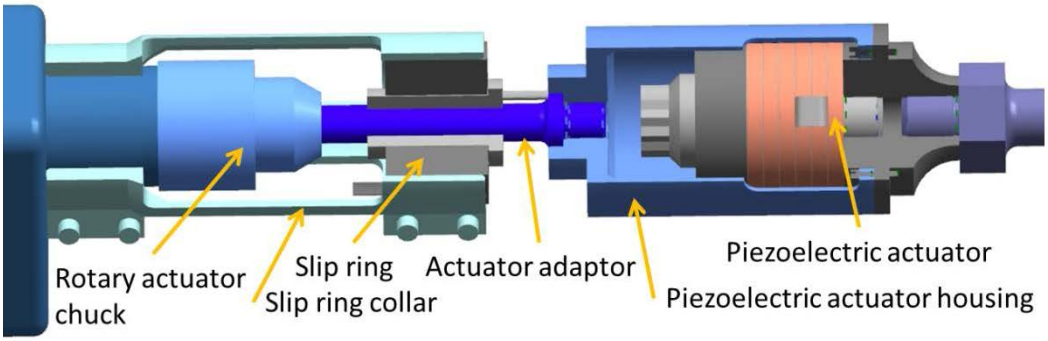

Figure 2 Details of the piezoelectric augmenter for the 2" diameter bit

To determine the PARoD design parameters and to predict its performance, finite element models were created by using the commercially available tool ANSYS^{TM}. The actuator consists of a piezoelectric stack of six PZT rings that are 50.8 mm diameter and 5 mm thick (Figure 2). The actuator design requires that the nodal plane coincides with the mounting plane, so the vibration transmitted to the rotary drill will be minimized at this location. In addition, the bit tip displacement needs to be maximized to transfer the highest impact energy to the drilled media. As the ultrasonic actuator is axisymmetric and since we are only interested in the axial modes of resonance, ANSYS axisymmetric elements were used to model half of the cross-section of the transducer. Compared to a 3D model, this 2D model using the axisymmetric elements greatly reduced the size of the FEM model and computation time. Thus, it allowed us to perform a greater number of analyses in order to optimize the design.

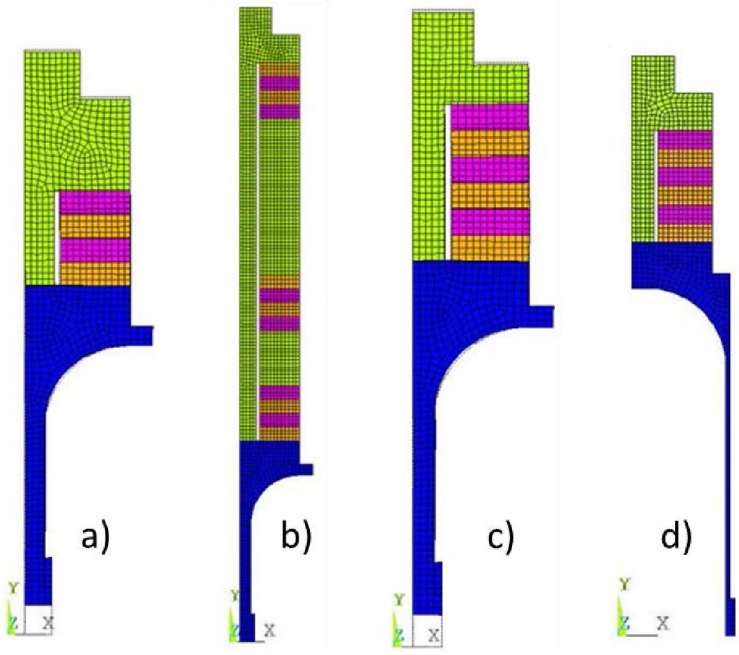

Figure 3 FEM models a) 1 stack - 4 PZT rings; b) 3 stack - 4 PZT rings each; c) 1 stack - 6 PZT rings; d) 1 stack - 6 PZT rings, inverted horn

The resonance frequencies of the actuator also needed to be predicted and a modal analysis was performed to derive the mode shapes, nodal planes, and resonance frequencies. A series of models were created and the tip displacements were compared for the same power on the transducer. The series include a 1 stack – 4 PZT rings, a 3 stack – 4 PZT rings each, a 1 stack – 6 PZT rings, and a 1 stack – 6 PZT rings with an inverted horn (the horn is tubular in shape rather than a rod). These configurations are shown in Figure 3 and a plot of the horn tip displacement around the resonance for the three stack configuration is shown in Figure 4. Table 1 shows the performance of these configurations for a 1W power.

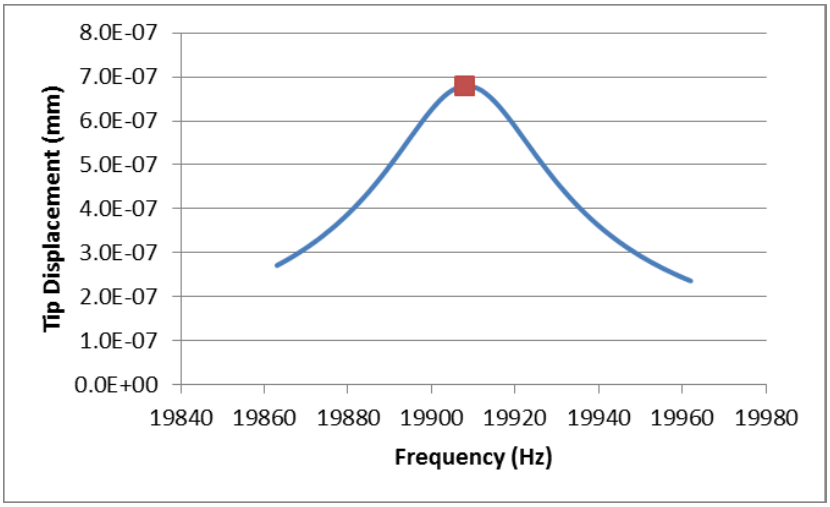

Figure 4 Tip displacement for 1 Volt drive signal

Table 1 Performance of analyzed configurations

Design	Frequency (Hz)	Mechanical Q	Power (Watt)	Tip Disp (µm)	Voltage (V)
1 stack - 4 PZT	20026	500	1.0	3.269	6.175
3 stack - 4 PZT	19912	500	1.0	3.003	4.418
1 stack - 6 PZT	19966	500	1.0	3.237	4.436
1 stack - 6 PZT, inverted	11969	500	1.0	4.601	10.602

3. FABRICATION, INTEGRATION AND TESTING

PARoD integrated the fabricated parts with commercially available rotary drills. Once they were assembled, they were mounted onto a testbed built specifically for this task that allows for the control of the weight-on-bit and maintains the alignment and feed of the drill bit during drilling. The lessons learned from testing the smaller PARoD version were integrated into developing a support stand as a 3D frame with a much sturdier sliding fixture. The bit adapter was also guided to maintain the alignment with the drill axis. The drill bit augmenter was fabricated and assembled with a rapid prototyped slip ring collar, aluminum housing for the piezoelectric transducer and a drill bit bolted into the bit adaptor (Figure 5). The piezoelectric actuator adaptor and housing were fabricated separately to reduce costs but they could be integrated into one part for better augmenter alignment. Similarly, the drill bit, the drill bit adaptor and the ultrasonic horn can be combined into one or two parts depending on the decision to make the augmenter more versatile by allowing more configurations for a given piezoelectric actuator or to increase the efficiency of the augmenter by reducing losses that each interface introduces.

The current method of drilling and coring reinforced concrete is to use two types of bits – a coring bit and a rebar cutting bit. For concrete only drilling, a coring bit is used with a rotary hammer drill. The impacts fracture the concrete and the rotation clears the cuttings from the hole. Once the rebar inside the concrete is reached, the coring bit is replaced with a rebar cutting bit. The rebar cutting bit uses higher hardness and more brittle carbide cutting teeth and can be used only with rotary drills. Although the outer diameter of the two bits used in our tests is the same, the hole size and created core are slightly different. For this reason we decided to use the volume of material removed rather than the rate of penetration for plotting the test results. For each test the weight on bit and power to the rotary drill and piezoelectric transducer were recorded, and after the test the volume of the material removed was determined by measuring the diameter of the created hole and core and the hole depth.

A set of baseline tests were performed first where the rotation only was used to drill using a power of 310W. After the baseline tests were performed we continued with another series of tests where the rotation speed was kept the same and the vibration from the transducer were added. For both the coring and rebar cutting bits the test results show up to 400% improvement in the drilling rate when adding the ultrasonic vibrations (Figure 6). In addition Copper washers were used at the bolted interfaces to test if they provide better coupling.

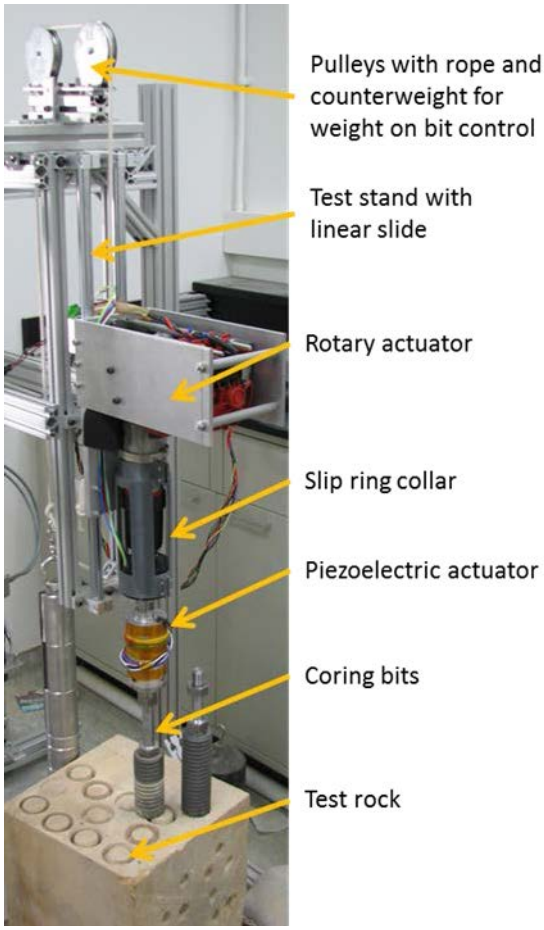

Figure 5 PARoD integrated into the testbed

Another set of tests were performed using different power levels of 300W, 450W and 600W. The Figure 7 shows the volume of the removed material for three total power levels. The horizontal axis is the power used by the ultrasonic actuator. The data points on the vertical axis represent rotation only drilling (ultrasonic power is zero). The increase in ultrasonic power was limited by the heating of the piezoelectric actuator and the power needed by the rotary actuator to overcome the friction in the system and friction from rotating the bit in the borehole. It can be seen that there is still improvement in the drill performance although not at the level obtained in previous set of tests.

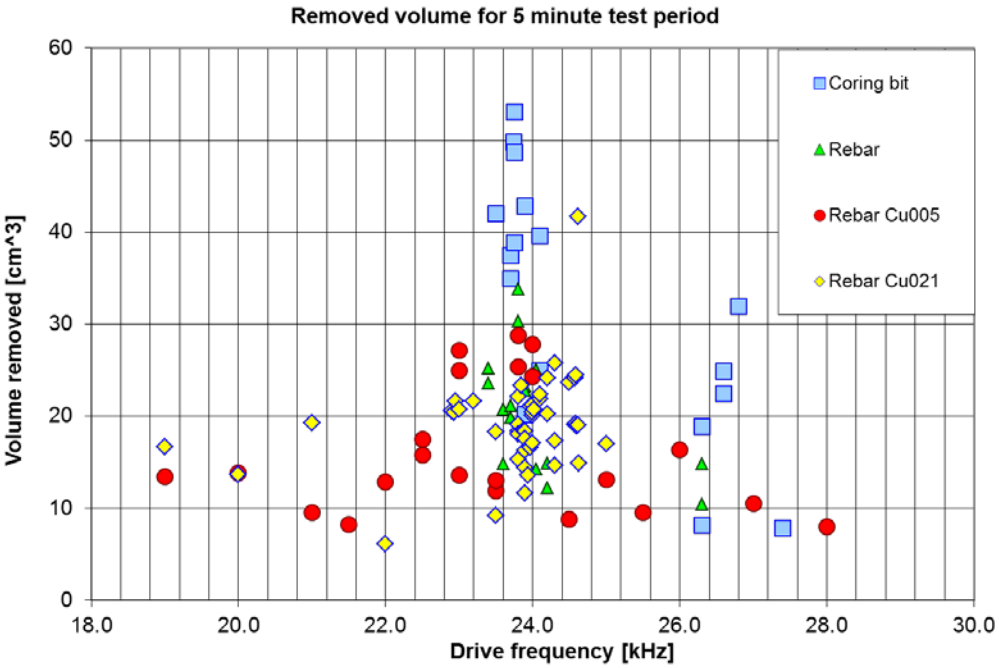

Figure 6 Removed material volume for 5 min test period

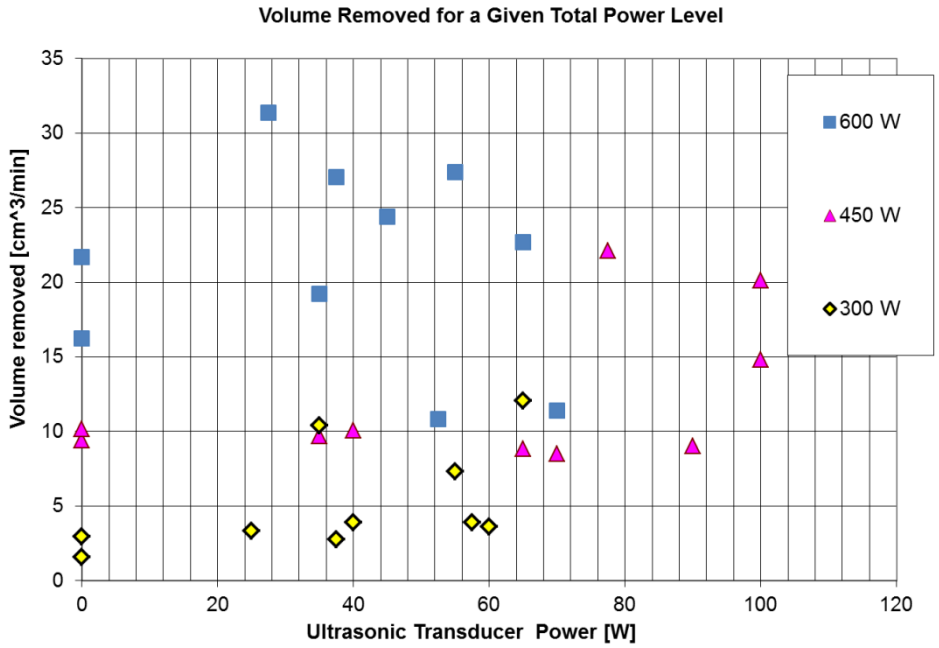

Figure 7 Removed material volume for a given total power level

4. CONCLUSIONS AND FUTURE WORK

This paper reports the development of an augmenter for rotary drills that is driven by a piezoelectric actuator to induce vibrations onto a rotary bit. The augmenter was conceived to support potential future NASA exploration missions with the objective of acquiring samples for in-situ analytical instruments. Significant improvement of the penetration rate was achieved by the introduction of the ultrasonic hammering action that is generated on fluted bits by the piezoelectric actuator. This improvement is due to the enhanced capability to fracture the rock and the fluidization of the cuttings which aids the removal process. The development was done in two steps where the first step focused on a small scale version with a 6.4 mm (0.25 in) diameter bit and the second step focused on a larger version with a 50.8mm (2.0 in) diameter bit.

The performed tests have shown that the improvement in the rate of penetration can be as high as 400% when adding vibrations generated by the piezoelectric transducer on top of the rotation only of the drill bit. Additional tests were performed where the total power consumed by the rotary actuator and the piezoelectric actuator was held constant. The results have also shown that considerable increase in the drill performance can be achieved by using a combination of rotation and piezoelectrically induced vibrations. Tests are underway in reinforced concrete with 0.375 in diameter rebar using the same 2.0 in diameter bits.

The current design of the augmenter device is made as an attachment to a rotary drill. In future modifications it can be designed and fabricated as a single unit where the augmenter is integrated into a single drill. The integrated augmenter can be mounted along a drill shaft behind the rotary motor eliminating the need for an adaptor and thus providing a more compact packaging.

ACKNOWLEDGEMENT

Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). The reported novel Percussive Augmenter of Rotary Drill (PARoD) was developed under a contract with Placidus Placid Technologies LLC, Israel-USA. The authors would like to express their appreciation of the support of Joshua Leavitt, CEO, Placidus Technologies LLC, Israel-USA.

REFERENCES

[1] Aldrich J., S. Sherrit, M. Badescu Y. Bar-Cohen, X. Bao, and Z. Chang, "Controller using extremum-seeking to drive heavily perturbed electroactive actuators at resonance" NTR Docket No. 43519, (2006).

[2] Badescu, M., Bar-Cohen, Y., Sherrit, S., Bao, X., Donnelly, C., and Aldrich, J., "Percussive Augmenter of Rotary Drills (PARoD)," SPIE Smart Structures and Materials/NDE Symposium, San Diego, CA, March 12-16, 2012.

[3] Badescu M., S. Sherrit, Y. Bar-Cohen, X. Bao, and S. Kassab, "Ultrasonic/Sonic Rotary-Hammer Drill (USRoHD)," NTR Docket No. 44765, (2006).

[4] Badescu, M., Stroescu, S., Sherrit, S., Aldrich, J., Bao, X., Bar-Cohen, Y., Chang,Z., Hernandez, W., and Ibrahim, A., "Rotary hammer ultrasonic/sonic drill system," 2008 IEEE International Conference on Robotics and Automation, ICRA-08, Pasadena, California, May 19-23, (2008).

[5] Bao X., Y. Bar-Cohen, Z. Chang, B. P. Dolgin, S. Sherrit, D. S. Pal, S. Du, and T. Peterson, IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control (UFFC), Vol. 50, No. 9, pp. 1147-1160, (2003).

[6] Bar-Cohen Y. and K. Zacny (Eds.), "Drilling in Extreme Environments - Penetration and Sampling on Earth and Other Planets," Wiley – VCH, Hoboken, NJ, ISBN-10: 3527408525, ISBN-13: 9783527408528, pp. 1-827, (2009).

[7] Bar-Cohen Y., S. Sherrit, B. Dolgin, T. Peterson, D. Pal and J. Kroh, "Smart-ultrasonic/sonic driller/corer," U.S. Patent No. 6,863,136, (2005).

[8] Chang, Z., S. Sherrit, X. Bao, and Y. Bar-Cohen, "Design and Analysis of Ultrasonic Horn for USDC (Ultrasonic/Sonic Driller/Corer)," Proceedings of the SPIE Smart Structures Conference, SPIE Vol. 5388-34, (2004).

[9] Sherrit S., S. A. Askins, M. Gradziel, B. P. Dolgin, Y. Bar-Cohen, X. Bao, and Z. Cheng, "Novel Ultrasonic Horns for power ultrasonics," NTR Docket No. 30489, (2001).

[10] Sherrit, S., "Smart Material/Actuator Needs in Extreme Environments in Space," Proceedings of the SPIE Smart Structures Conference, SPIE Vol. 5761-48, (2005).