REGOLITH SAMPLING AND DEEP DRILLING IN LOW GRAVITY ENVIRONMENT

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ABSTRACT

In this paper two devices for celestial bodies exploration and utilization are presented. Both are specially designed to work in low gravity conditions. Moreover they are characterized by low mass and low power consumption, which makes them appropriate solutions for space missions applications. Firs device, PACKMOON is designed for regolith sampling and utilizes a novel rotary hammering principle of operation, whereas the second device is an integrated ultra-light mobile drilling system (UMDS), which in new way utilizes tubular booms to guide the drilling head and to secure the borehole.

1 INTRODUCTION

Two main goals of celestial bodies exploration may be distinguished; scientific, related to search of life signs on other planets and for better understanding of the evolution of the solar system, end economical, related to extraction of mineral resources. Further, in many cases to achieve assumed scientific goals it is required to explore subsurface regions, even deeper than 2m below the surface, where the influence of conditions on surface are minimized and the searched minerals or elements might be found. The future exploration of the solar system planets with their moons, comets and asteroids is an extremely complex challenge both in its technical meaning and due to its international context. Operation in space significantly differs from the one on Earth due to limited mass and power, extreme temperatures, low pressure, and nontrivial influence of gravity, lower than on Earth. For specific cases, like regolith sampling or drilling, the low gravity has such a strong impact that new devices with new principle of operation need to be invented. In recent years CBK PAN together with other Polish scientific institutes and universities has developed new means for extraterrestrial surface exploration, distinguished by the use of innovative technologies.

2 PACKMOON

The PACKMOON is a sample acquisition system for surface sampling in low gravity conditions. It utilizes an innovative concept of rotary hammering devices [1]. Its purpose is to collect the regolith sample from the planetary body, seal it and prepare for further transportation. The requirements for the PACKMOON device are formulated to be in line with ESA Mars Moon Sample Return Mission, but as a system PACKMOON can be adapted to other low gravity sampling missions e.g. to the Moon or an asteroid. Currently the system is designed to be able to collect up to 200cm3 of lose regolith as well as consolidated material (up to 5 MPa compressive strength).

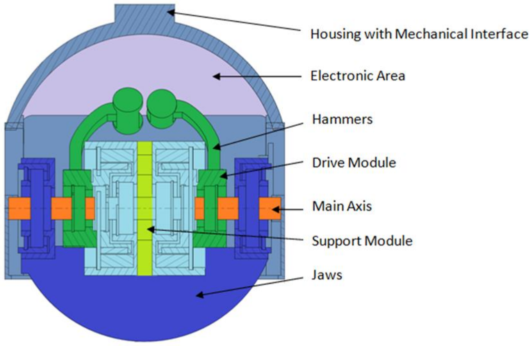

Figure 1: PACKMOON device section view

PACKMOON is a Low Velocity Penetrometer (LVP) type mechanism, where the principle of operation is to perform movement by means of hammering actions. Such actions is an energy efficient way to insert thin element into the soil. Unlike the previous LVP devices described in [2] that generate linear movement, PACKMOON is a rotary hammering device that generates rotary movement of the jaws. As shown in Figure 1 and Figure 2 the system is doubled to cancel the reaction force and torques to the lander. Collection of the sample is done by gradual rotary movement of both jaws. A finite amount of soil is closed between the jaws, which at the same time can serve as a sample container. The main advantage of using hammering action is its high efficiency in regolith penetration, therefore the device requires low energy to perform its task.

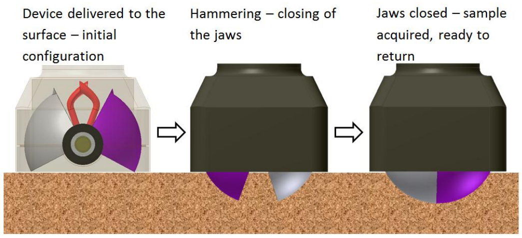

Figure 2: PACKMOON sampling phases

2.1 Characteristics and key parameters

The principle of operation of PACKMOON device as well as theoretical model which stay behind it was shown in [1]. It's based on interactions between 3 elements: hammer, jaws and support masses (Figure 1). In difference to theoretical solution presented therein, hammers in the ultimate design is driven actively by motors. Support masses consist of connected together stators of BLDC motors, which accelerate the hammers in opposite directions to certain level of energy, so that the reaction torque of the motors is canceled. Energy and momentum of the hammers is then transmitted to the jaws by short time stroke, which enforces the jaws to rotate. After certain number of strokes, dependent of the regolith parameters, the jaws close and the sample is acquired, preserving its structure, and without thermal influence. Sampling phases beginning from delivery of the device to the surface, through hammering, and final sample collection are shown in Figure 2.

Table 1: Assumed key parameters of the device

Parameter	**Value**
Mass	<5kg (goal 3.5kg)
Volume (sample container)	200cm^3
Dimensions of sample container	Φ150mmx100mmx
Required Support Force	<10N (goal 5N)
Hammering energy	2J
Sampling Time	~10 min (goal 5 min)
Power	<10W

Great benefit of such approach is the fact that the mechanism can be designed in a way where low influence on the lander is exerted, what is a key factor for mechanisms operating in low gravity conditions.

Assumed drive of the device is based on two BLDC motors. To achieve best performance motors are powered by supercapacitor battery, and controlled by hysteresis PWM modulation, which will hold the current, and thus the torque, at assumed level. It is desired to achieve 2J of hammering energy, which with current hammers moments of inertia requires to produce about 1.3Nm of constant torque at 90° path. Selected motor was simulated in order to validate assumed control approach, results are presented in Figure 3 Current varies between 11,5-10A, with RMS value 10,6A, nearly linear characteristics of the torque was achieved with RMS torque 1.4 Nm

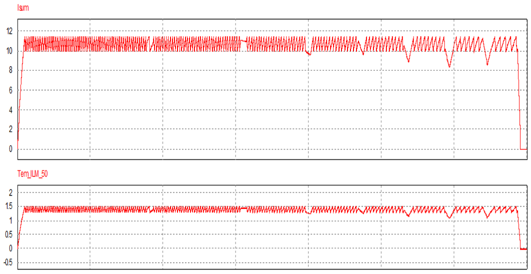

Figure 3:Chart of the simulated current (upper) and torque (lower)

2.2 Numerical simulations

Operation of the PACKMOON device was first simulated, wgat allowed to determine the theoretical values of reaction forces and torques. Due to symmetric movement of the movable parts (hammers and jaws move at the same time but in opposite direction), horizontal components of reactions cancel themselves. Generated vertical reaction last about 100ms and despite its high amplitude the impulse transferred to the lander is lower than impulse generated by gravitational acceleration of the lander (assumed mass of the lander 1600kg), even on small extraterrestrial bodies like Phobos.

Calculated total momentum transferred to the lander during sampling, assuming 200 strokes with 5s intervals is ~110kg*m/s, while total momentum transferred by device generating constant force of about 10N for 300s is 3000kg*m/s. Performed simulations of surface operations show that the PACKMOON sampling tool is not able to lift the lander off the surface of Phobos, its gravitational acceleration is sufficient to hold the lander during the hammering actions. In case of device generating constant reaction force, lander could be lifted from the Phobos surface and hold-down thrusters are required to hold the lander pressed to the surface.

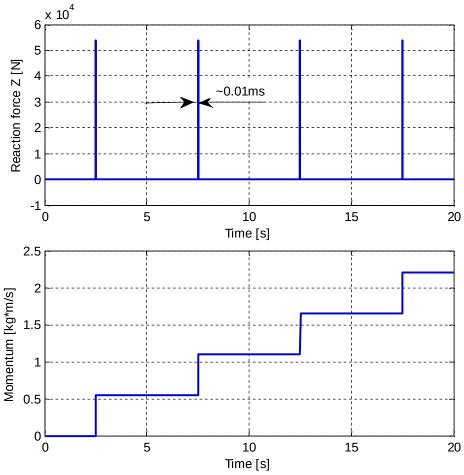

Figure 4: Reaction force for the first four strokes of the PACKMOON device (upper panel) and total momentum transferred to lander during PACKMOON operation (lower panel).

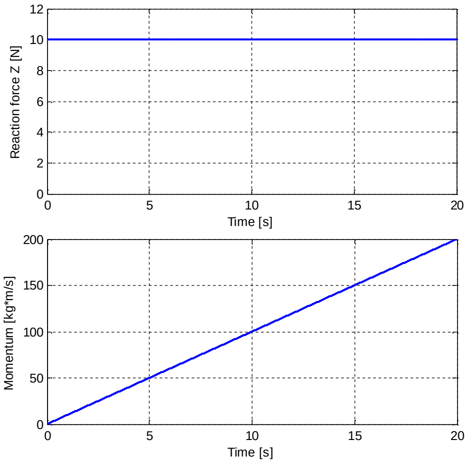

Figure 5: Reaction force for the first 20 seconds of the constant-force sampling tool operation (upper panel) and total momentum transferred to lander (lower panel).

2.3 Breadboard Test Results

In order to prove the concept of rotary hammering and to validate the simulations simplified models of the PACKMOON device where developed. Two versions where build with passive drive based on springs and with active drive based on BLDC motors, which is equivalent to target solution.

Test were performed using various materials like lunar regolith analogue and two types of foamglass (“Soft” with 2.1 MPa and “Firm” with 4.4 MPa of uniaxial compression strength).

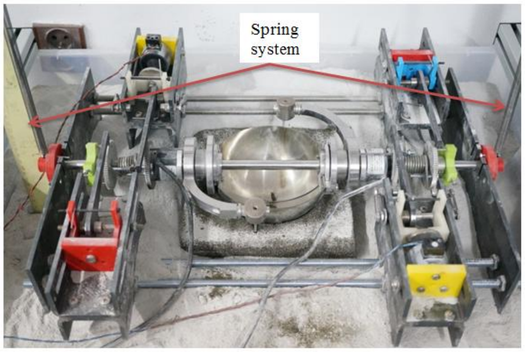

Figure 6: Breadboard with spring drive

Low gravity conditions were simulated by a set of offload springs. The spring system presented in Figure 6 and Figure 7 allows to modify the value of Lander Support Force (F_S) in Earth gravity environment. F_S is described as a difference between the Earth Gravity force (F_G) and the spring lift force (F_{L1} and F_{L2}).

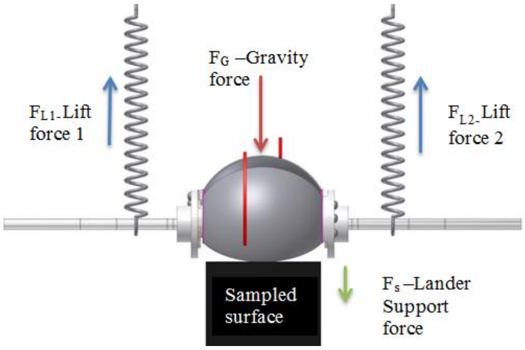

Figure 7: Offload springs explanation

Depending on the used drive springs, the energy of the hammers during impact varied from 0.4J to about 1J, in case of BLDC drive the obtained energy was at the level of 0.6J.

Figure 8: Breadboard with active BLDC drive

Both solutions proved its functionality, in total around 70 successful sampling attempts were performed. Proposed system is capable to collect samples even with Lander Support force as low as 5N. The amount of collected sample and number of strokes needed to close the jaws varies in dependence of the Lander Support force. The averaged results of tests in lunar analogue are presented in Table 1 and for foamglass in Table 2.

Table 2: Averaged results of tests in regolith

Lander Support force	5N	13N	20N
Number of hammering actions	1	2-3	9
Mass of acquired sample	120 g	300 g	450g

Table 3 Averaged results of tests in foamglass

Foamglass type	*"Soft"*	*"Firm"*	*"Firm"*
Lander Support force	11N	11N	20N
Number of hammering actions	19	51	105
Mass of acquired sample	17,2 g	16,5 g	35,6 g

As can be seen in above tables, amount of the collected sample and number of strokes is correlated with the offload. During tests the high-speed camera was used and for lower values of Lander Support force upward movement could be observed. Despite that, the device was still able to collect samples, but the amount collected material is lower, in order to fulfill required sample mass appropriate margins on the jaws volume needs to be applied. The obtained averaged hammering energy during this test was 0.4J. For comparison tests with higher energy level were performed, as expected the number of required hammering action decreases while the energy is increased.

Table 4: Number of strokes in dependence of average hammering energy

Hammering energy	0,4J	1,15 J
Number of strokes	105	34
Mass of the sample	35,6 g	36,9 g

As it was mentioned above, the assumed energy of target design of the PACKMOON device is 2J, so its performance should increase in comparison to described breadboards.

3 UMDS

The drilling technique is a well-known process that is very often used in terrestrial conditions for deep underground oil and gas production. There is a principal difference between research activities connected with drilling in terrestrial and in space conditions. In the first area the effort is focused on production optimization for maximum economic recovery. In space conditions the time of drilling is not an important factor, while minimization of mass and power consumptions has the highest priority. Therefore, the designs are focused on minimization of power which needs to be delivered to regolith or rock to allow the system to work in volume drilling regime. The important element is also necessity of the hole bottom protection and bit cleaning by efficient transport of drilling cuttings and securing the bore hole.

3.1 Characteristics

The Ultra-Light Mobile Drilling system (UMDS) is dedicated for extreme, in particular planetary environment drilling system developed in CBK PAN and AGH University of Technology [3]. Unlike conventional drill strings which are composed of screwed together pipes, UMDS system utilizes tubular boom technology to serve as a drill string. Such approach is much more mass and volume efficient. Another key feature of the UMDS is its low power consumption in all operational phases. The main subsystems of the mobile drilling system are presented in Figure 9 (mobile robot – MR, support module – SM and drilling subsystem – DR).

Figure 9:UMDS components, mobile robot - MR (blue), support module - SM (red), drilling subsystem - DR (green)

The mobile robot MR developed at The Faculty of Mechanical Engineering and Robotics of the AGH University of Science and Technology provides mobility to the system in unknown terrain. It is a light-weight (~5kg), four wheel platform intended to transport the system to the destination point of drilling, it has dedicated space for batteries, on-board computer and sampling container. Independently driven wheels and suspension system, which enables independent setting of the height of the left and right rocker provide high mobility in an unknown terrain. The suspension system provides adjustment of height of the MR platform by 100 mm or compensate roll angle of the drilling module up to 13°

Main component of support module is 3 DoF manipulator (two rotations and one translation), which main role is to set the appropriate direction for drilling operation, while the drilling head should be positioned along the gravitational vector. Moreover, the manipulator is used for insert collected samples to the vessel and for empty the DR from cuttings. SM is equipped with two sample magazines for collected cores, in total 40 cores can be stored separately in a container to reduce the possibility of contamination between the samples. Containers are equipped with linear actuators in order to position themselves beneath the working plane of the manipulator.

Third linear degree of freedom of SM is mostly used to apply the load necessary to perform the drilling process and to provide the movement of the drilling module in both directions. Specially designed linear actuator utilizes C-shape tubular boom (ϕ25mm in diameter and 330deg wrapping angle), it is capable to exert up to 400N of force in downward movement. Such high values of force can be achieved thanks to utilization of worm mechanism and spherical indentations made in the boom. Such mechanisms works in similar principle as leadscrew, and allows to omit the limited strength region of the tubular boom in the load path.

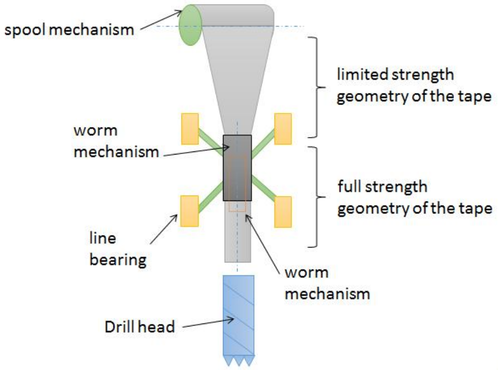

Figure 10:Schematic view of the SM linear actuator

Boom is stored on the reel in spool mechanism, located at the top of the manipulator. It allows to drill up to 2m deep, but this value can be easily expanded, with low influence on the overall mass of the system. Second tubular boom (ϕ35mm and 400deg wrapping angle) is used as cladding tape to secure the borehole, during operation in loose material, preventing from backfilling of the borehole. The operation of two c-shape systems was described in detail in [3] and its main advantage is the significant reduction of mass and volume in contrast to standard solution. In order to exert force on the drilling head in low gravity environment the whole system needs to be anchored. For this purpose two additional motors equipped with ϕ8 drills are used, linear movement is provided by passive linear spring drive. Anchors are slanted in respect to the deployed manipulator by 45°, therefore they are capable to transfer the vertical reaction force.

In fold position the SM has 720 mm to 401 mm in width and 250 mm in height, but when unfolded the height of SM is 1290 mm. The weight of the subsystem is 8.5kg (without the weight of the batteries). During the design of the mobile drilling system, it was crucial to ensure the ability to return the samples to the base in case of failure of the SM or DR. Therefore the SM is equipped with mechanical interface connecting to the rover. In case of failure of SM or DR the interface are activated and the rover could return with sample to base.

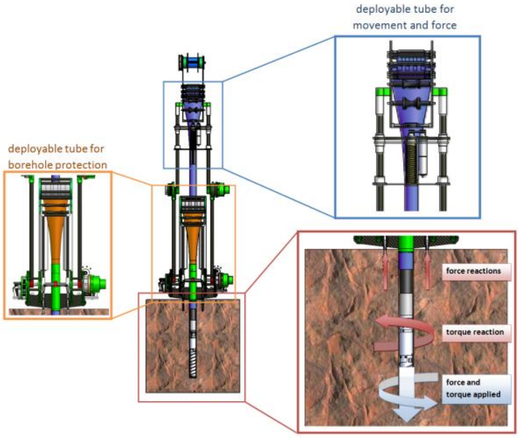

Figure 11: Key details of the drilling system:Tubular booms drill head drive, cladding tape to secure the borehole on left, actuation tape together with linear actuator to transfer the force to drill head located at the borehole bottom. The torque transfer through rotary anchor at the drill head level (bottom right)

The drilling head DR was developed The Faculty of Drilling, Oil and Gas at the AHG University of Science and Technology. It is 400 mm long and ϕ34mm in diameter cylinder which consist of dc motor with gearhead having output torque of about 7Nm, mechanical switch and titanium core barrel with two sections. In the top one the drills cuttings are collected during drive head operations and bottom one has space for collected core. Cutters of the drill head are made of sintered carbide. The feed (1 mm/s) of the driving head was chosen to assure the volume drilling which is more energetically effective than the grinding drilling.

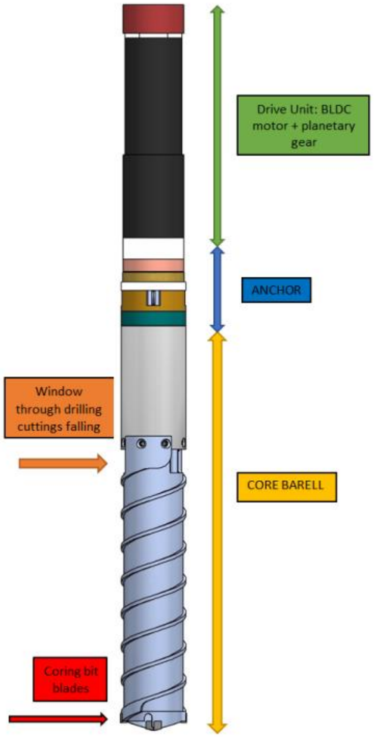

Figure 12: Main components of the drilling module.

Drilling module is capable to core both in consolidated material (rock) and unconsolidated (regolith). After acquiring of about 5cm solid material, the core is break by build in breaking mechanism. The sample is held inside the corer by set of leaf springs, which are deployed after the core is acquired. Because the drill string of the system is made of c-shaped tubular boom, which does not transfer the axial torque, the drilling module is equipped with anchor witch transfers the torque reaction to the borehole wall. Anchor is composed of steel bristles, arranged radially, so that they resist the rotation of the drill head in one direction. Before the borehole is deep enough to insert the anchor in, the whole drill head is guided by guide sleeve, which is ended with blades. Sleeve is attached to tubular boom drill string, so when it's pushed into the regolith it prevents from rotation. Such approach allows to drill into both consolidated and lose materials.

Because the drilling subsystem is dedicated to work in planetary environment, where is no possibility to use mud to remove drilling cuttings, the corer is equipped with auger coils. They transfer the cuttings from the blades to the upper part of the core barrel where they fall through the windows into the cutting reservoir. Later the cuttings are removed, after each core is returned to the sample container. All functions implemented in the drill head are driven by one 60W BLDC motor, and to switch between the functions specially designed mechanical switch is used.

Key parameters of UMLD system are summarized in table below.

Table 5: ULMD parameters.

Parameters	Values	Unit
Weight	21	kg
Dimensions: Transport phase Drilling phase	 740x512x460 740x512x1700	 mm mm
Drilling depth	2	m
Drill diameter	35	mm
Max. rover range	100	m
Maxi. power consumption	120	W
Feed	1	mm/s
Rate	50	rpm
Thrust	500	N
Special features	Possible operation with UAV	

3.2 Prototype and Tests

In 2015 all the modules of the ULMD were manufactured and integrated. Test were performed both on component and system level. Three drilling test campaigns were performed, during which over 5m were drilled, of different materials form loose sand like regolith to 30MPa compressive strength rocks.

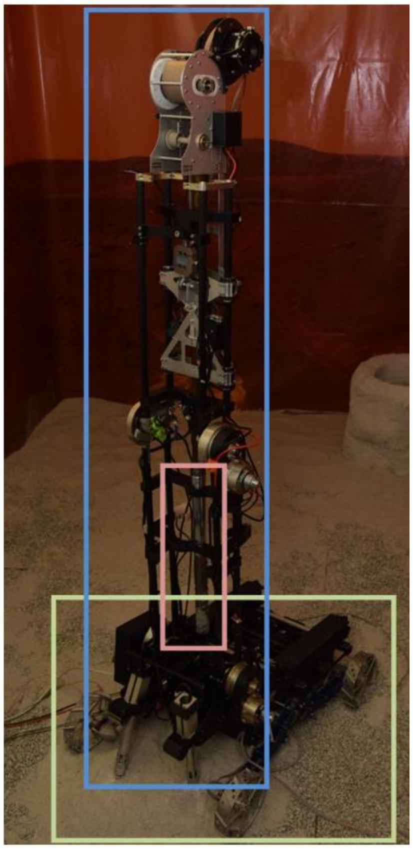

Figure 13: ULMD components, mobile robot - MR (green), support module - SM (blue), drilling subsystem - DR (red)

During first test campaign DR module was tested separately. Design of the drilling head was proved, all the mechanisms worked correctly despite high contamination. 80 cores were collected and maximal obtained depth was over 350mm.No damage to the drill head and no serious failures were observed. During test pushing force (weight on bit, WOB) and torque were measured. Results obtained for 50RPM rotational speed and different linear feed speed are shown below.

Table 6:Torque and pushing force (WOB) values, for different feed rate and 50RPM of rotational speed, in materials with compressive strength 4.6Mpa, 12.5Mpa and 30.MPa.

	4.6 MPa		12.5 MPa		30.8 MPa	
Feed mm/s	Torque Nm	WOB N	Torque Nm	WOB N	Torque Nm	WOB N
0.1	0.89	7.7	1.24	59	1.92	92
0.2	1.45	7.5	1.71	79	2.74	119
0.3	1.63	13.9	2.45	108	-	-
0.4	1.72	12	2.7	119	-	-
0.5	1.88	14.6	2.93	103	-	-

During second test campaign DR module was tested with SM's mast and tubular boom linear actuator. One full cycle composed of mast deployment, coring and drill head hoisting was performed, 3 cores were acquired. All process was controlled by SM computer. Actuator proved its ability to produce over 400N of push force, moreover under applied pressure, structure stiffens itself, providing stable guiding of the drilling head.

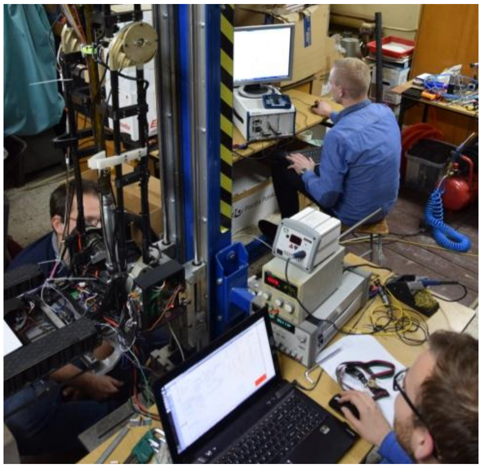

Figure 14: DR and SM tests

During last test campaign all integrated modules were tested, and whole sampling process was conducted. According to the developed operational scenario, sampling process begun with mobile robot locomotion, to the drilling destination point. Next step of the process was anchoring (Figure 15) and deployment of the drilling mast. Then MS linear actuator delivered the DR module right above the sampled material. Tests concluded by acquiring the core and returning it to the sample container (Figure 17).

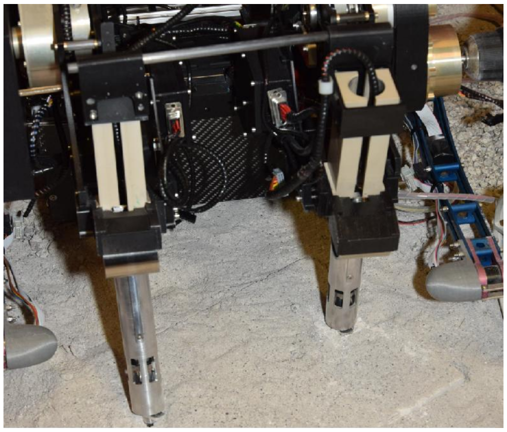

Figure 15: SM anchors

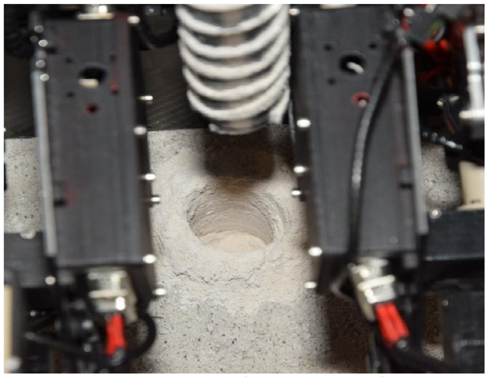

Figure 16: Bore hole after removal of the core.

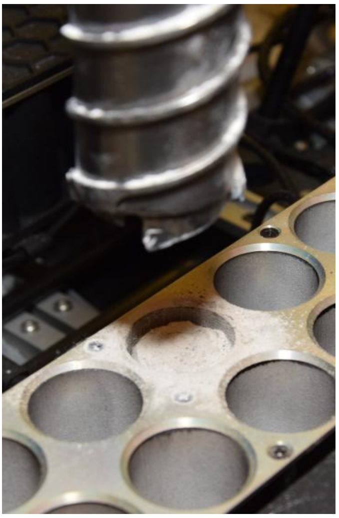

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Figure 17: Core inserted in sample container

Further test of the ULMD are envisaged in near future. Most await test is to perform 2m deep coring process which will ultimately proof usefulness of the system. Also further development is planned, where DR and tubular boom actuator are thought to be most promising.

4 CONCLUSION

Two devices intended to surface and subsurface sampling are under development. Both utilize unique technologies invented at CBK PAN, and both are able to operate in demanding low gravity conditions thanks to their features. Breadboards of the surface sampling PACKMOON device were designed, developed and tested, proving the concept of rotary hammering principle of operation. The aim of this activity is to confirm its performance with final goal to be flown on future ESA mission to Phobos or other low gravity body. Currently the PACKMOON device is under preparation for a testing campaign in the frame of ESA founded SAMPLER project together with two other sampling devices: a rotary brusher and a corer.

ULMD system, capable to core in materials up to 30MPa compressive strength, was developed and tested. The tests results bring large amount of information about whole system as well as its component. Specifically the approach to have the drill head at the borehole bottom was confirmed as well as an approach to use tubular tapes to transfer the force to the drill head. The latter once might be very useful technology in context in deep drilling missions planned for Europa.

Acknowledgement

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