NOVEL SAMPLING TOOL FOR LOW GRAVITY PLANETARY BODIES

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ABSTRACT

Surface sampling on small celestial bodies like moons, asteroids or comets require sophisticated sampling technology, that will be safe for the lander stability. On the other hand sample volume demands increases, especially in the perspective of future exploitation of e.g.. asteroids. To face such requirements the novel sampling tool was invented and developed at CBK PAN. It's based on Rotary Hammering principle, described in Seweryn et al. 2016 [1]. It's main advantage is low influence to the lander and capability to acquire relatively large samples. The paper describes the development of the device and shows the latest results obtained during tests.

1. PRINCIPLE OF OPERATION

One of the main concerns regarding sampling in reduced gravity is the stability if the lander. To prevent the lander from unexpected take-off, overturning or changing its positions different sampling solution may be applied. One is based on additional elements that hold the lander on the surface like anchors, harpoons or thrusters. Other approach is to not land at all and perform the sampling "on the fly", minimizing the contact time between the lander and the surface (or even without any contact of the spacecraft). Another possible solution is to use sampling tool that will exert minimal influence on the lander (which can be either a force or momentum transfer). Based on previous experience on Low Velocity Penetrometer (LVP) type mechanisms, where the principle of operation is to perform movement by means of hammering actions (described in [2]), novel principle Rotary Hammering was invented. Unlike the previous LVP devices which hammers itself into the soil by generating linear movement, PACKMOON is a rotary hammering device that generates rotary movement of the jaws. Sample acquisition is possible due to gradual movement of the spherical jaws. The jaws closure is enforced by hammering, where the hammers energy and momentum is transfer to the jaws in a consecutive strokes. The hammers are accelerated against connected support masses and, since the system is kinematically symmetric, direction of movement of one hammer and jaw is opposite to the other. Similarly, reaction torques from hammers acceleration and horizontal component of reaction forces are opposite and are canceled. After a number of strokes the jaws close and the sample is collected. Hammering is a highly efficient manner to penetrate the soil, therefore, the device only needs a low amount of energy for sampling. The principle of rotary hammering was proved on the breadboards developed in 2015 and also on final functional model described below.

2. SYSTEM DESCRIPTION

As it is shown on Fig. 1 and Fig. 2 the system is doubled, its main elements are two hammers, with its drives and two jaws. All those elements are mounted on common shaft called main axis. Hammers drives are connected together through the support frame. The jaws

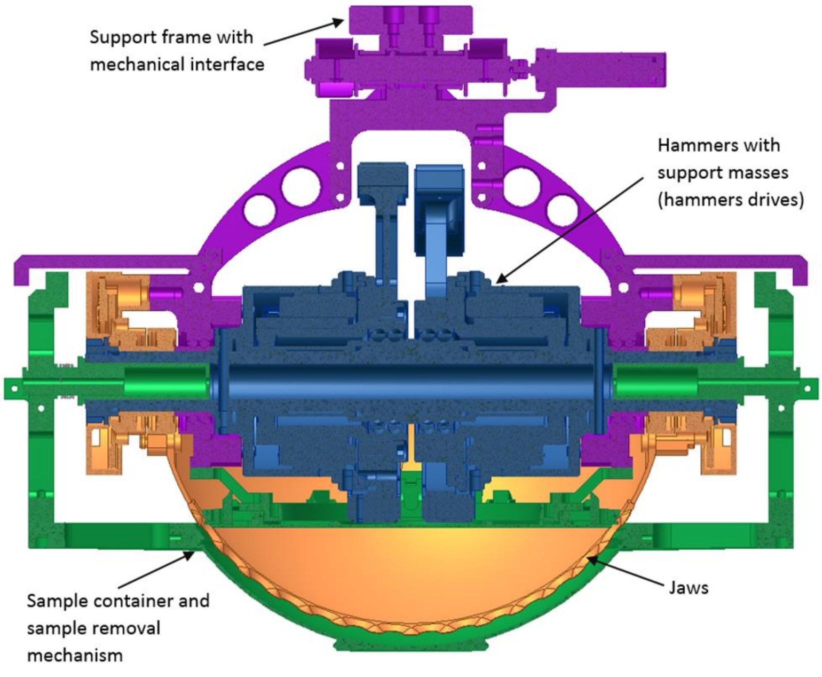

Figure 1. PACKMOON elements

can be automatically opened after sampling to provide multiple sampling attempts capability.
After successful sampling, the sample can be preserved in sample container, that later can be automatically

dismounted, enabling the container to be inserted e.g.. in Earth Reentry Capsule. Current specification of the PACKMOON sampling system is in line with ESA Mars Moon Sample Return Mission requirements. It's able to acquire samples up to 150cm3 of both lose regolith as well as consolidated material (up to 5 MPa of compressive strength).
Tab.1 below summarizes key parameters of the device.

Table 1: Key parameters of the device

Parameter	Value
Mass	2.7kg
Volume (sample container)	150 cm^3
Dimensions of sample container	Φ124mm x 40mm
Hammering energy	< 2J
Sampling Time	< 10min
Power	< 10W

The sampling procedure that covers with the ESA Mars Moon Sample Return Mission is depicted in Fig.2

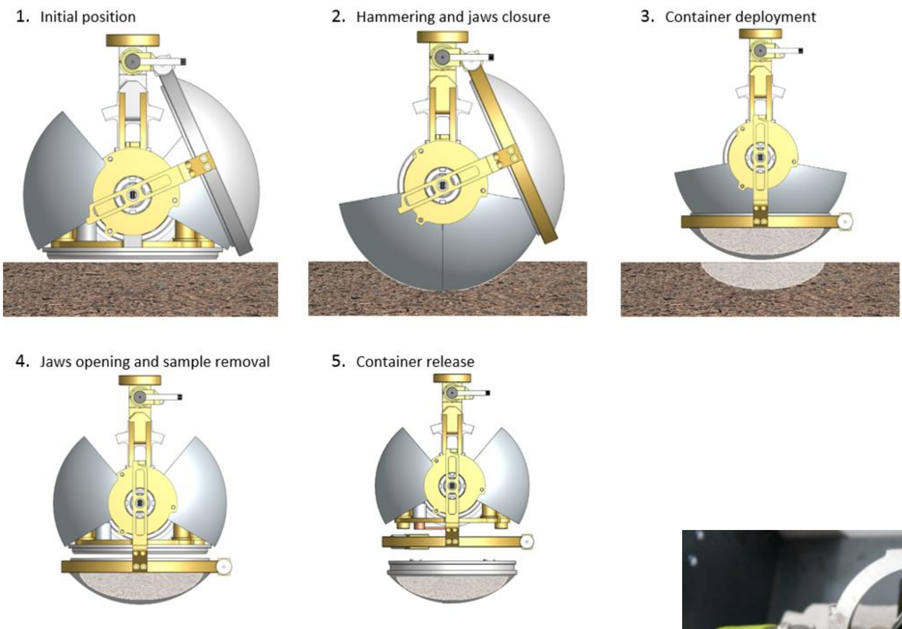

Figure 2. Sampling scenario

The sampling process starts with sampling device deployment to its initial position. After the device is delivered right above the surface, the jaws are released and the hammering process begins. After certain number of strokes, dependent on the soil properties, the jaws close and the sample is acquired. Then the sample verification occurs, when the decision is made whether to repeat the sampling process or to proceed to the next step. This stage is not done by the device itself. In case of negative verification, the jaws of the device shall be opened and the process of sample acquisition repeated. After the successful sample verification, the sample container is released, and rotated, so that it's placed below the sample. Then the jaws are opened and the sample is removed by pushing into the sample container. The pushing plate locks afterwards with the container and serves as a lid, the sample is protected. Last step is to release the sample container, it can be then placed in e.g. Earth Reentry Capsule.
Big advantage of presented sampling principle is low influence of the sampling device to the specimen. Only the outer part of the sample, which has direct contact with the jaws is affected. Additionally the structure of the sample is intact and can be preserved. Thermal coupling between the motors and the jaws is very low, furthermore the pushing plate, that is placed between the motors and the jaws serves as a radiation shield. Therefore also the thermal influence is minimized.

3. DEVELOPMENT

The breadboards of the PACKMOON sampling mechanism were developed to prove the concept of the rotary Hammering sampling method, to determine the design parameters of the mechanisms and to validate the simulation results. In the first breadboard the hammers were driven by torsional springs. It allowed to prove the concept of Rotary Hammering. Later the spring drive was replaced by BLCD motor based drive. The extensive test campaign was performed to determine the performance of the device and also to define the parameters for final model development. The second breadboard is shown in Fig. 3.

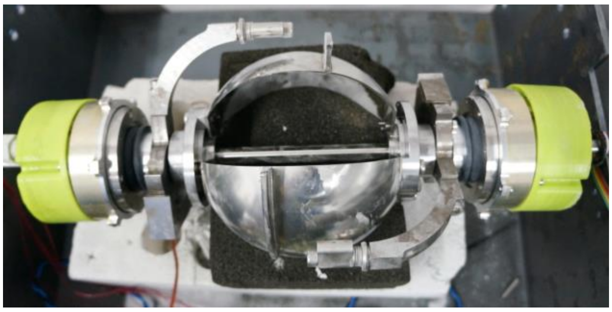

Figure 3. Second breadboard

Final, functional model of the PACKMOON device was developed in 2017. The hammers drive is based on

BLDC motor, connected directly to the hammers. Such solution allows to minimize to complexity of the mechanism. To achieve best performance motors are powered by supercapacitor battery, and controlled by level-time type PWM, which switches the current off after reaching the certain level and switches the current on after calculated time. This type of current control needs minimal amount of the additional electronic components, only one current sensor. Such control approach assures constant RMS current level, and thus keeps the torque, at desired level. Motors can generate torque up to 1.4Nm, hence the maximal energy of the single stroke for one hammer is about 2J.

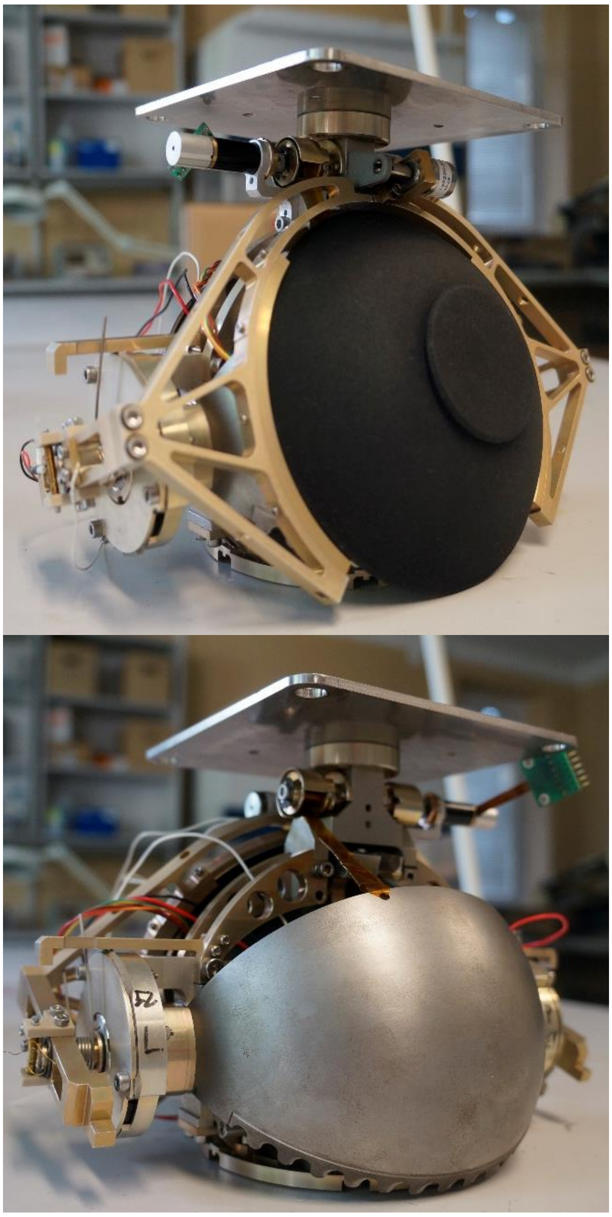

Figure 4. PACKMOON final model

4. NUMERICAL SIMULATIONS

Operation of the PACKMOON device was simulated, which allowed to determine the theoretical values of reaction forces and torques. Due to symmetric movement of the rotating 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 momentum transferred to the lander for strokes every 5 seconds is lower than the momentum 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 safe for the lander stability and is not able to permamently lift the lander from the surface of Phobos, its gravitational acceleration is sufficient to hold the lander during the sampling process. 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.

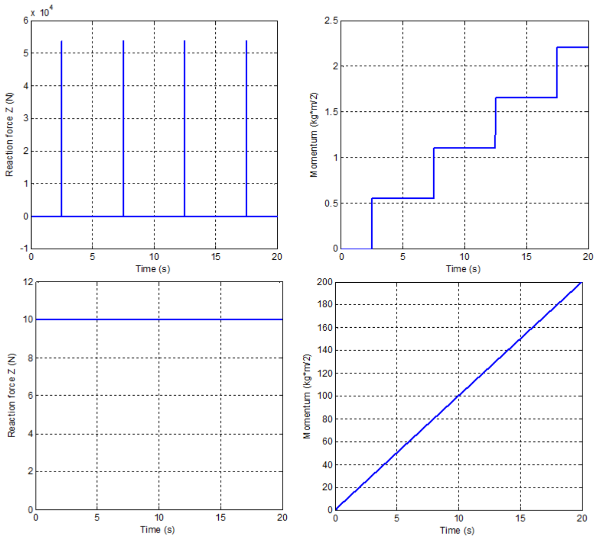

Figure 5. Reaction force for the first four strokes of the PACKMMON devicel (upper left),total momentum transferred to lander during PACKMOON operation (upper right), reaction force for the first 20 seconds of the constant-force sampling tool operation (lower left) and resulting momentum of the lander (lower right)

5. TESTS

PACKMOON breadboards have been tested for operation in various materials. Additionally to simulate the low gravity conditions off-loading spring system was used. Its principle is shown in Fig.5. So called Lander Support Force simulates the force that lander exerts on the device in low gravity conditions. Test with off-load system proved that the device is capable to collect samples even with low Lander Support force. In some cases the device is "jumping up", despite that the sample is collected. Results of the tests are shown in Tab. 2 and Tab. 3, relation between the amount of collected sample and Lander Support force can be seen. The parameters of the sampled materials are listed in Tab. 4

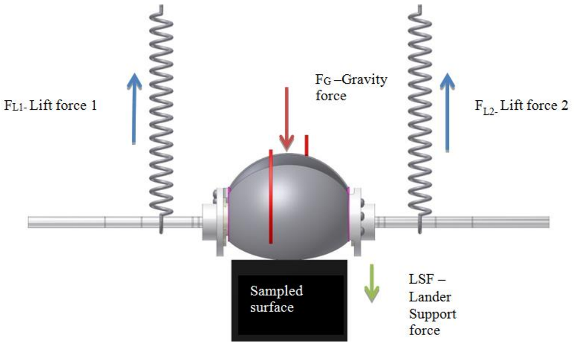

Figure 6. Off load spring system.

Table 2: Averaged results of tests in AKG 2010

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 Foamglas

Foamglas type	F1	F2	F2
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

For the purpose of final model tests the dedicated test rig was developed, which allows to measure the reaction generated by PACKMOON at the interface. The PACKMOON device was attached to the measuring unit, composed of 3 force sensors, each able to record forces in 3 directions. Force sensors are arranged in a way allowing to calculate the reaction torques. The test rig is depicted in Fig. 7.

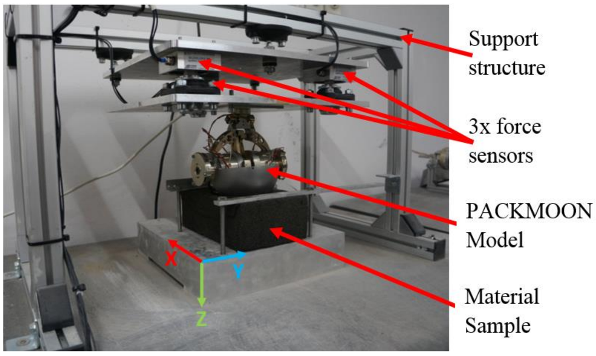

Figure 7. PACKMOON test rig

The tests were performed on four different materials:
• SAMPLER OU Soil Simulant, which is Phobos soil simulant developed in frame of SAMPLER project, further labelled M
• AGK2010, which is lunar regolith analogue, further labelled R
• Foamglass, which in past was used at CBK PAN as comet analogue, further labelled F1
• More dense variant of Foamglass, further labelled as F2

Table 4: Parameters of materials used during tests

Name	OU Soil Simulant	AGK2010 - dry	Foamglas F1	Foamglas F2
Volume density/ Bulk density [kg/m^3]	-	1414	122	172
Density [kg/m^3]	1670	2592	2633	2674
Porosity [%]	-	45.44	95.51	93.54
Friction angle [deg]	55	35.57	17.94	16.45
Cohesion [kPa]	-	3.47	378.4	122.08
Uniaxial compression strength [MPa]	-	-	4.4	2.1

In all test cases the number of impacts, reaction forces and torques at the mounting interface, sampling time and the mass of the acquired sample were recorded. The vertical components of the force and torques are considered as most relevant. Jaws are equipped with the encoder, to track their penetration progress. The encoder record from one of the tests in OU Soil Simulant is shown in Fig. 8.

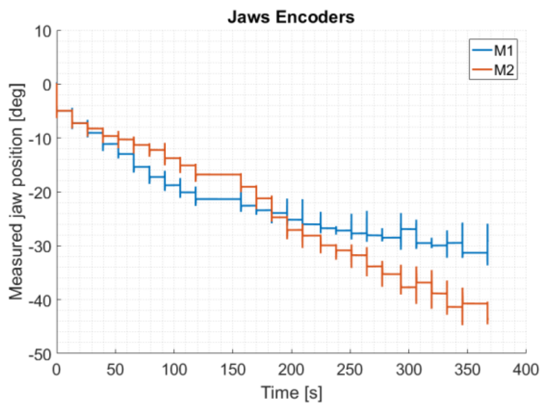

Figure 8. Jaws progress during sample acquisition.

Table 5. PACKMOON final model test results

Probe	Impacts	Vertical Force Z Peak [N]	Vertical Force Z Mean [N]	Vertical Torque Peak [Nm]	Vertical Torque Mean [Nm]	Sampling Time [s]	Sample Mass [g]	Sample volume [cm^3]
M-A1	26	89,9	59,6	19,7	12,4	208	233,1	-
M-A2	20	104,6	56,8	18,2	13,2	160	294,9	-
M-A3	19	86	61,2	17,9	12,8	152	266,3	-
M-A4	50	131,9	65	18,4	13,3	400	268,9	-
M-A5	16	86	69,2	19	13,7	128	232,8	-
M-A6	11	113,7	61	21,8	14,1	88	214,3	-
M-A7	14	105,5	61,2	18,4	15,1	112	267,8	-
M-A8	16	101,4	68,2	17,5	13,7	128	226,6	-
M-A9	35	106,3	55,3	20,3	13,3	280	266,2	-
M-A10	29	86,6	46,1	20,8	13,2	232	243,7	-
R-A1	4	73,8	60,7	13,6	11,9	32	276,5	-
R-A2	3	91	67,2	16	10,6	24	218	-
R-A3	3	71,3	57,6	18,6	11,9	24	267,9	-
F1-A1	21	108,1	67,1	19	14,7	210	20,2	~165
F1-A2	22	87,8	49,5	19,5	13	176	19,3	~158
F1-A3	21	120	76,6	24,7	15,7	168	18,27	~150
F1-A4	20	113,1	85,9	22,7	15,4	160	17,15	~141
F2-A1	55	103,2	64,6	15,5	9,9	440	32,2	~187
F2-A2	47	149,3	70,4	19,5	12,1	376	25,3	~147
F2-A3	50	105,4	76,7	19,3	10,4	420	27,2	~158
F2-A4	47	91,9	67,9	20,4	11	376	27,1	~157

As can be seen in this case the progress of indyvidual jaw` is different, which is caused by pebbles present in the simulant, thus different drag on the jaws. One of the pebble was stuck between the jaw, preventig them to fully close. Despite that the sample was succesfully colelcted.In Fig. 9 the surface after sampling is shown, the formed cavity can be observed and the pebble that is stuck between the jaws (marked by red rectangle).

Figure 9. Surface after sampling, with marked pebble stuck between the jaws.

A number of tests were performed, some of the obtained results are presented in Tab. 5. Again big dispersion of the number of inpacts for OU Soil Simulant, caused by its heterogeneity is evident. The volume of the Foamglass samples shows that in most cases required 150cm^3 was acquired. The amount of acquired sample depends on the distance between the device and the surface on its initial position. The sampling time is also below assumed at the beginning of the project 10 minutes. It can be further shorted by incresing the power of the source, the greater the power the shorter time of sampling.

Example charts of measured vertical forces and torques are depicted in Fig. 9 and Fig. 10.

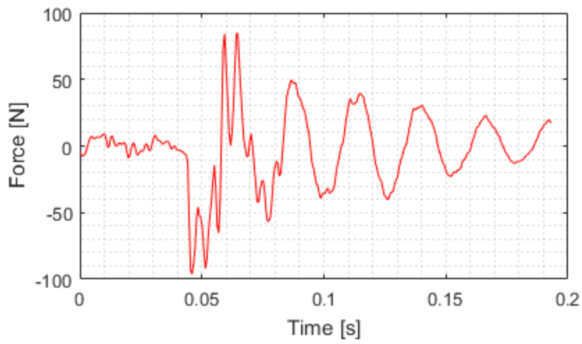

Figure 10. Vertical force

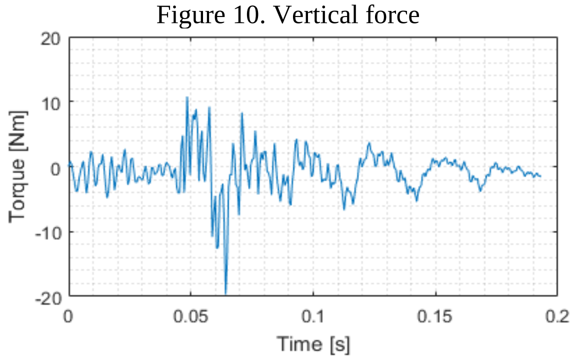

Figure 11. Vertical torque

6. CONCLUSIONS

The PACKMOON device based on innovative rotary hammering concept was successfully developed. Performed tests proved the usefulness of the device in simulated low gravity conditions. The influence of the device to the lander during sampling is not disturbing its stability. The requirements of the ESA Mars Moon Sample Return Mission were met. The device is capable to collect over 200g of the sample for the case of Phobos soil simulant, which is more than twice as required, however the amount of collected sample can be easily controlled by the initial position of the device. The device is scalable, therefore can be used in different extraterrestrial exploration missions, even those where big amounts of regolith needs to be excavated, or where ISRU needs to be applied.

7. REFERENCES

[1] Seweryn K. (2016) *The new concept of sampling device driven by rotary hammering actions*, IEEE/ASME Transactions on Mechatronic systems, 2016

[2] Seweryn, K., Grygorczuk, J., Wawrzaszek, R., Banaszkiewicz, M., Rybus, T., and Wiśniewski, Ł. (2014) *Low velocity penetrators (LVP) driven by hammering action – definition of the principle of operation based on numerical models and experimental tests*, Acta Astronautica, Volume 99;

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