MOLE PENETRATOR DRIVEN BY AN ELECTROMAGNETIC DIRECT DRIVE (EMOLE)

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ABSTRACT

This paper presents a new generation of mole type penetrators driven by an electromagnetic direct drive. EMOLE is a low-speed penetrator capable of underground mobility within regolith carrying scientific instruments (such as sampling tools or thermal sensors) in planetary missions, where Mars and the Moon are the mostly foreseen destinations. EMOLE combines new ideas and earlier achievements, both of which had influence on the concept and would demonstrate the technology. In consequence, a laboratory model device was successively developed. Its principle of operation is based on the interaction of the three masses of the device between which the energy exchange is performed and, as a result, a hammering action is achieved. The major novelty of the EMOLE concept is twofold – the penetrator's drive will be much more reliable in comparison to the spring driven moles, and its new drive system will be fit to have power settings.

CONCEPTION

Space Research Centre of the Polish Academy of Sciences (CBK PAN) has been involved in the development of low-speed, hammer-driven penetrators since 1996, when the project MUPUS (MUlti PUrpose Sensor for surface and subsurface science) [1][2] for the European Space Agency's (ESAs) space mission ROSSETTA aimed at investigation of the surface and subsurface of the 67P/Churyumov–Gerasimenko comet, has begun.

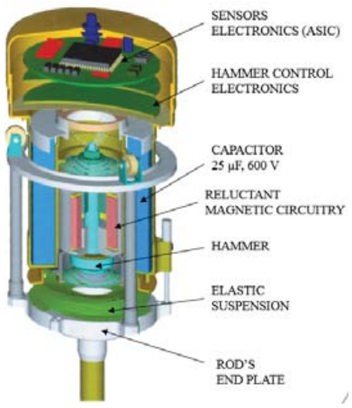

Figure 1. MUPUS insertion hammering device with an electromagnetic drive.

The aim of the experiment MUPUS was to measure the temperature profile and thermal conductivity of the comet core by insertion of the sensors up to depth of 40 cm.

For this purpose a unique electromagnetic direct drive was developed (Fig. 1). This type of solution has never been used before in space missions. Feature of this drive is that, electrical energy is accumulated in a special foil capacitor and then is discharged by a coil with moving iron stem which acts as a hammer of the penetrator.. When magnetic circuit closes, the hammer accelerates to the speed of the order of 8-9 m/s on 6 mm per hit.

The MUPUS instrument was dedicated to work in unusual environment conditions (space, comet surface, temperature up to 130K), so it has to have design features such as: ability to work in microgravity conditions, low power consumption (2W), low weight (0,48kg) as well as comparatively large striking energy (0,8J) while maintaining minimum response to impact to keep it during work of manipulator connected with lander(0-1N).

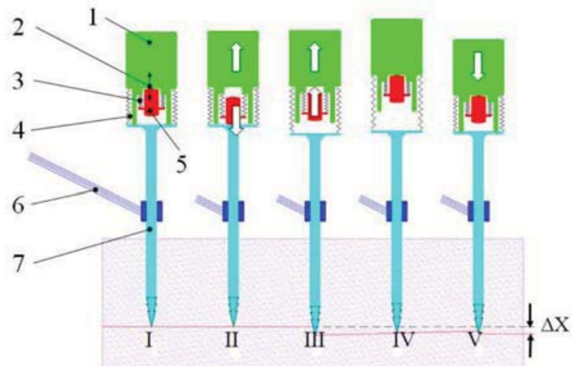

Figure 2. Principle of operation of the penetrator MUPUS (main parts: 1 - counter-mass; 2 - place to generate power; 3 & 4 - spring suspension; 5 - hammer; 6 - manipulator arm (1m) ending lead clamp (0-1N); 7 - hammered rod)

Above there is a description of the penetrator's MUPUS principle of operation. The mechanism consists of three masses interacting with each other: hammer, counter-mass, rod, where hammer with counter-mass and counter-mass with rod are connected to each other by elastic suspension.

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One cycle of work consists of the following five steps (Fig. 2.):

(I) initial configuration,

(II) acceleration of the hammer which hits the rod and causes its movement,

(III) simultaneous move of counter-mass in the opposite direction,

(IV) gradual transformation of kinetic energy of counter-mass into potential energy of flat spring that is placed between rod and counter-mass (called return spring),

(V) return of counter-mass to the initial configuration and the repeated strike by counter-mass.

Penetrator CHOMIK [3] similar to the MUPUS was developed in CBK PAN for Russian mission PHOBOS-GRUNT as a device to collect surface sample and make thermal measurements afterwards.

In 2006-2011 there were developed two elaborate mole type penetrators called KRET [3] (first prototype visible on Fig. 3.), which could entirely imbedded under regolith surface.

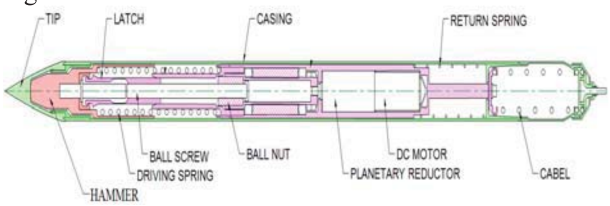


Figure 3. Mole penetrator “KRET”

It works similarly to MUPUS (cooperation of three masses), however thanks to the application of a different drive (DC engine and crossed helical gear with special grasper), it was possible to fit the whole hammering mechanism in a tube. The engine, thanks to a special grasper, pulls the spring with attached mass (hammer). At some point the grasper is released and the spring dispels hammer which at the end of movement hits the housing. Thereby, the KRET’s operating range is limited by the length of the cable supplying KRET with electrical power and by the hardness of the ground in which it is imbedded The developed Polish design solution allowed to achieve significantly more energetic hits (over 2J) and more effective work (optimization of the tip’s shape and weight distribution).

Generally, the main drawbacks of the so far existing mole solutions are:

- no regulation of hit energy, which in many cases is deadly for science sensors and sampling equipment,
- large amount of intermediate parts of mechanism type of gears, motor brushes, bearings etc. what can cause lower reliability.

According to the conception, the proposed electromagnetic direct drive is dedicated for a more reliable and secure insertion mechanism of the planetary mole penetrator. Correct operation of sensors and safety of casing are threatened by the highly energetic hammer hitting. Thus, main activities were focused on the development of a new direct drive, the most crucial part of every mole.

Newly developed penetrator should have five electromagnetic driving sections (similar to MUPUS, but downscaled and multiplied). Furthermore, its dimensions should be no larger than 25 mm in diameter and 250 mm in length.

PRELIMINARY TESTS [4]

The concept’s verification test-stand was developed and is shown in Fig. 4. A single electromagnetic drive section (one coil) is tested on this test-stand. Geometrical and mass proportions are retained in accordance with the actual full design. The velocity of hammer is measured using linear encoder and magnetic tape. For the purpose of the tests, the Counter Mass remained fixed, so as the result full stroke energy was transferred to the Hammer Assembly.

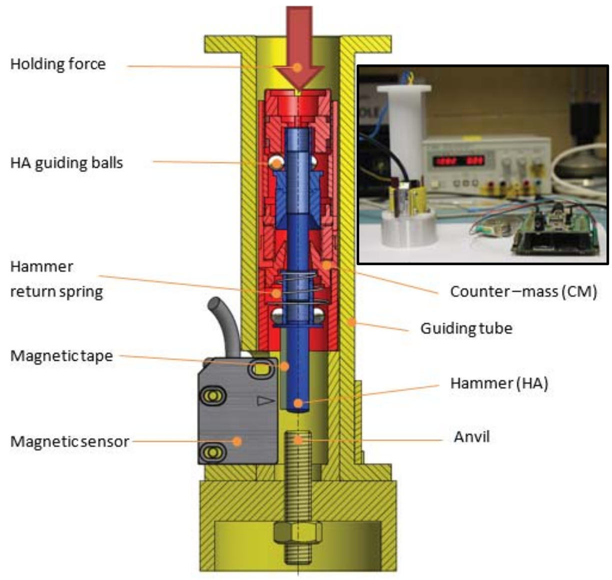


Figure 4. Verification test-stand (with ‘foot’), in the top right the actual stand with control electronics.

Goals of the test campaign on this test-stand were following:

- to see how coil material influences efficiency of the system,
- to determine the energy fit of the system (meaning: at which stored energy the system achieves highest efficiency),
- to optimize balance between pair of parameters: capacitance and voltage on the capacitor to achieve the most energetic stroke,

- to determine optimal initial gap between hammer and counter-mass for the fixed stored energy value,
- and finally to prove the concept of implementing coil with ‘foot’ to the mole type design and see the outcome of it in comparison to previously tested concepts,

For these reasons, a single coil with copper wire of 0.4mm diameter (147 coil turns) was tested to cover all the above mentioned system configurations.

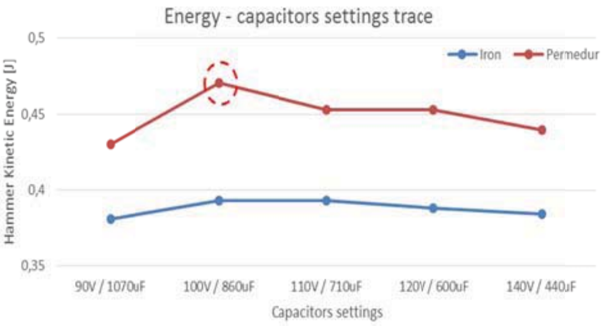


Figure. 5. Constant stored capacitor energy is maintained – 4.3J. Plot represents resulting kinetic energy of the hammer as a function of different capacitor settings for Iron and Permendur 49 coils. Dashed circle indicates optimal capacitor settings (concerning the stroke energy as the optimization criteria).

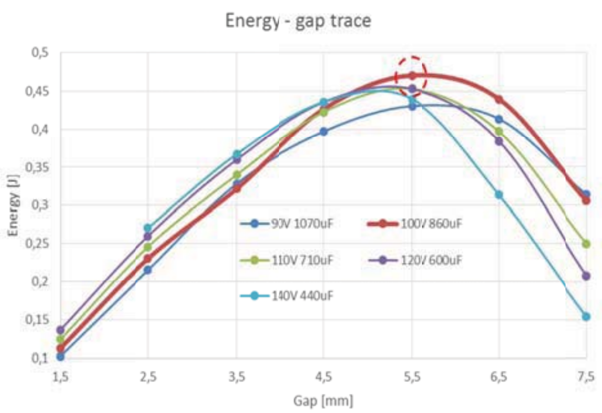


Figure 6. Optimization of Hammer travel gap. Plot represents measured kinetic energy of the hammer for Permendur 49 coil for the selected capacitor energy level (4.3J). Dashed circle indicates resulting optimal gap for the selected capacitor settings.

The results and analysis are shown and described below:

- It is clear that using Permendur 49 can increase the efficiency of the system by 13-20% with respect to the electromagnet made of Iron coil, see Fig. 5.
- Also there are no radical changes in the resulting hammer’s kinetic energy when taking into account different capacitors settings. Nevertheless, a certain optimal setting can be distinguished for Permendur 49 (see Fig. 6.), which is for 100V/860uF.
- When it comes to adjusting the energy level to achieve the most efficient system, it is clear from the test results that by lowering energy on the capacitor we get higher efficiency (at least when approaching down to energy of c.a 3.6 J). Nevertheless, it is energy of 4.3 J that is selected as the optimal since the efficiency decreases relatively slower than the energy drops. In the end, there is still a significant outcome from implementing less efficient but more energetic system. Similar situation was observed during previous penetrators tests.
- Optimal travel gap for hammer was also researched for various capacitors’ settings. Fig. 6. shows plots for constant capacitor energy of 4.3 J. For most of the cases the optimal gap is in the range of 4.5-6.5 mm (with full travel freedom of 8 mm). The selected capacitor settings (100V/860uF) have optimal travel gap of 5.5 mm and this value will probably be selected as the nominal for the final design.

DESIGN FEATURES

Mechanical design description [5]

As it was mentioned in the conceptual section, the EMOLE consist of 5 electromagnetic driving sections in which coils, ferromagnetic cores and magnetic separators are concurring to the counter-mass, while armatures of electromagnets with a connection shaft are comprising the hammer. All electromagnetic circuits elements are made of Permendur 49, whereas the magnetic separators are of a tungsten alloy and the connection shaft is made of titanium alloy. The propulsion (counter-mass + hammer) is enclosed in the outer casing assembly and consists of a long, thin wall, titanium sleeve and hardened stainless steel tip.

The hammer is guided by two sets of 3 bearing balls inside the counter-mass which provides low friction losses, while the counter-mass is sliding inside the outer-casing tube.

As in all the previous penetrators made by CBK PAN, while the hammers starting position (before hit) is set up by a hammering spring, the position of the counter-mass is determined by a brake spring designed in a way that allows the penetrator to work in a non-gravity environment without any support.

A cross-section of a CAD model of EMOLE is shown in Fig. 7.

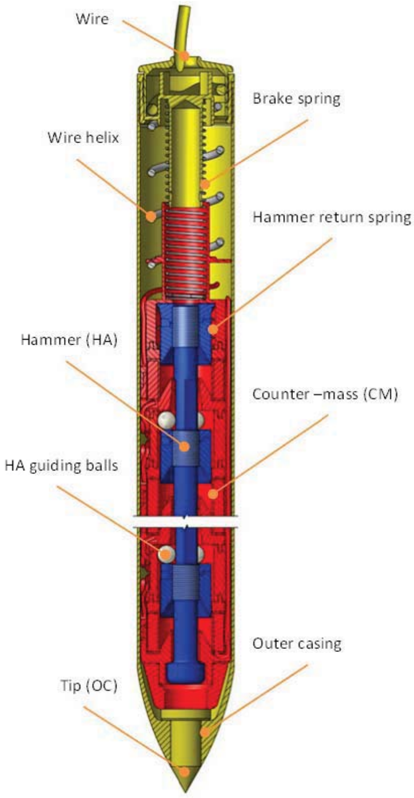


Figure 7. EMOLE CAD model cross-section.

The EMOLE has 25 mm in diameter and 250 mm length. The mass of the overall assembly is about 700 g, where the counter-mass mass has amounts to 520 g and the hammer and the outer casing are of equal weight of about 90 g.

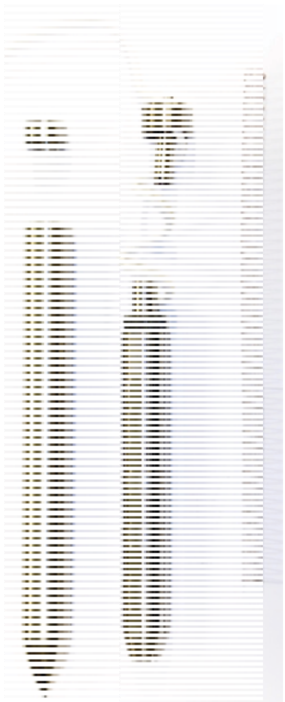


Figure 8. Outer casing, driving sections and return spring just before final assemblage.

Electrical design description [6]

EMOLE electrical system consists of three parts: control unit (controller), DC/DC converters unit and electromagnetic drive placed in penetrator. All three parts are designed to operate separately. Architectural overview of the described system is shown on Fig. 9.
Control unit, currently in form of a control panel, is used to set signals to turn on the desired mode of operation of EMOLE electronic system and therefore to control the penetrators behaviour. The control unit's interface allows to turn on and off each of the two DC/DC converters as well as to select one of several "gears" – penetrator stroke energy and actuation frequency.

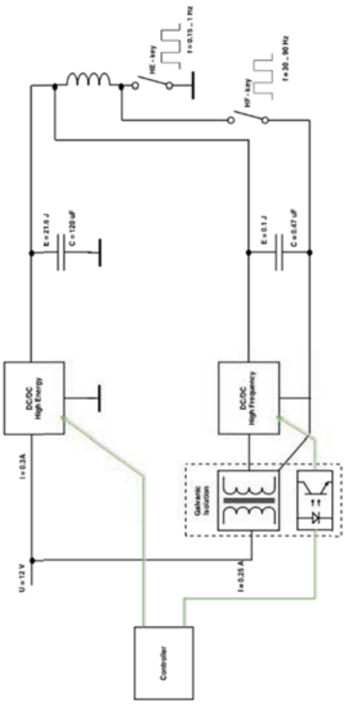


Figure 9. EMOLE electronic system architecture.

DC/DC converters unit consists of two DC/DC converters, both in flyback topology. Each DC/DC converter has an overvoltage protection mechanism ensuring safe operation of the device.
High Energy DC/DC (DC/DC HE) converter charges large capacitor, stores the energy, which is then released to the electromagnetic drive (shown as inductor in Fig. 9.) when it reaches a certain level, set by device operator. The higher the charge (the energy stored), the lower the actuation frequency.
High Frequency DC/DC (DC/DC HF) converter, operates in a similar way as latter DC/DC converter but operates on the energy level ~200 time lower and two order of magnitude higher frequency. It is galvanicaly separated from system ground to operate totally independently from the state of DC/DC HE.

TESTS

Actual velocity (and kinetic energy) speed measurements on finalized assembly

The actual velocity of the hammer with a blocked counter-mass was measured on a test stand presented in Fig. 10. For this purpose the counter-mass was clamped in the test stand (without the outer casing) and the movement of the hammer was captured on a high speed camera. An example of the hammer's displacement sequence captured on camera is presented in Fig. 11. The measurement was repeated for all five high energy power settings that the electromagnetic drive possesses.
The velocity plots for power settings 1-5 are presented adequately in Fig. 12 – 16.
The summary for the achieved velocities, resulting energies and expected efficiencies for each PS are presented in Tab. 1

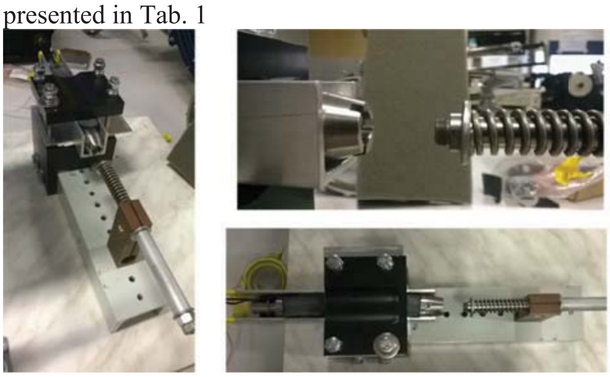


Figure 10. Velocity measurement test stand.

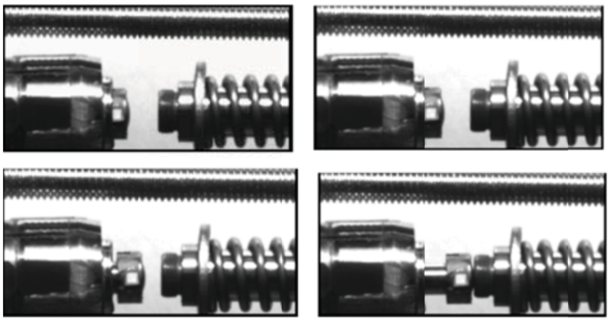


Figure 11. An example of a sequence of movements (presented: the 5th power setting; the time difference between each frame is 0.53ms). On the left: a blocked counter-mass with a protruding hammer inside; on the right: the test stand hitting rod. The thread above the scene is a scale reference – this is a standard M8 thread.

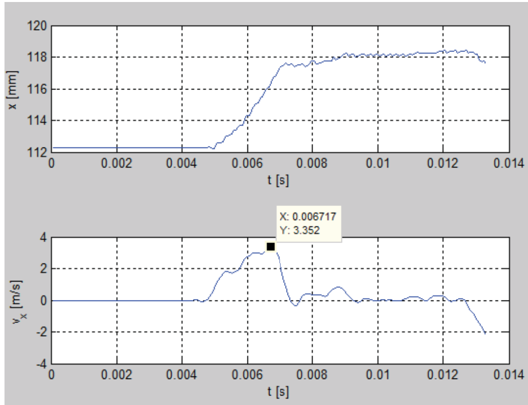


Figure 12. Velocity plot for power setting-1, measured velocity before hit.

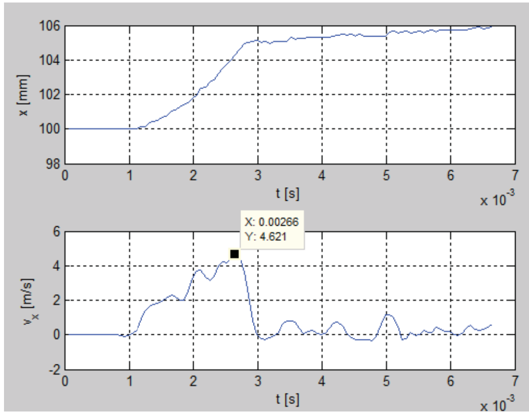


Figure 13. Velocity plot for power setting -2, measured velocity before hit.

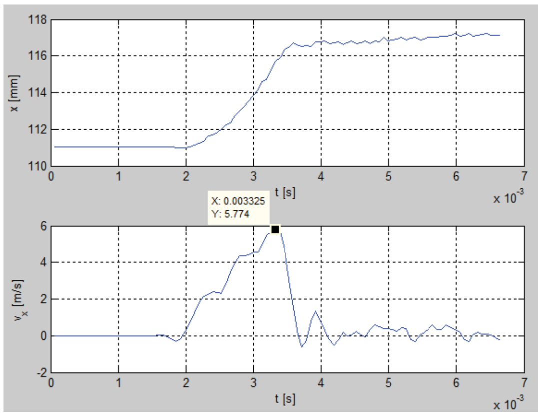


Figure 14. Velocity plot for power setting -3, measured velocity before hit.

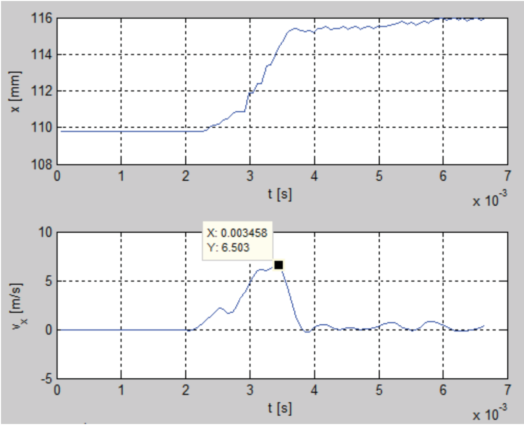


Figure 15. Velocity plot for power setting -4, measured velocity before hit.

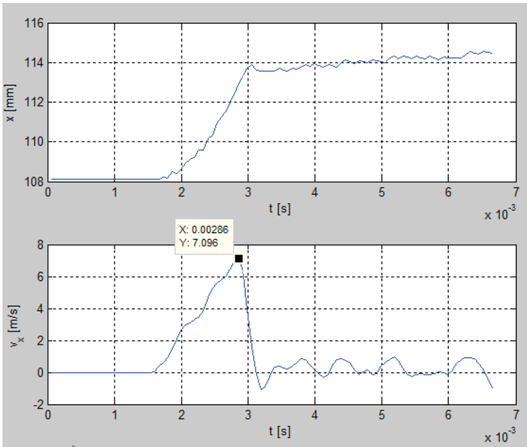


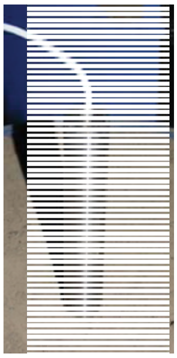
Figure 16. Velocity plot for power setting -5, measured velocity before hit.

Table 1. Summary of results.

Power setting	Hit velocity [m/s]	Hit energy [J]	Efficiency [%]
PS-1	3.352	0.49	10.72
PS-2	4.621	0.94	10.62
PS-3	5.774	1.47	11.22
PS-4	6.503	1.86	10.62
PS-5	7.096	2.22	10.28

This results show that the efficiency varies insignificantly between each power setting. The highest efficiency was achieved for the third power setting.
Furthermore, this test proved that, the stroke energy, changes quite equally with the number of the driving sections. It means, the amount of sections can be raised or decreased with respect to the direct mission mass or power requirements, and the stroke energy will raise or decrease equally.

Tests in Syar regolith analogue



After determination of the energy generated by five-coils driving system, the EMOLE was tested several times, on different power settings, in Syar regolith (Fig. 17.) up to depth of about 50 – 60 cm. The summary of this tests is presented in the next three graphs.

Figure 17. EMOLE in Syar regolith analogue.

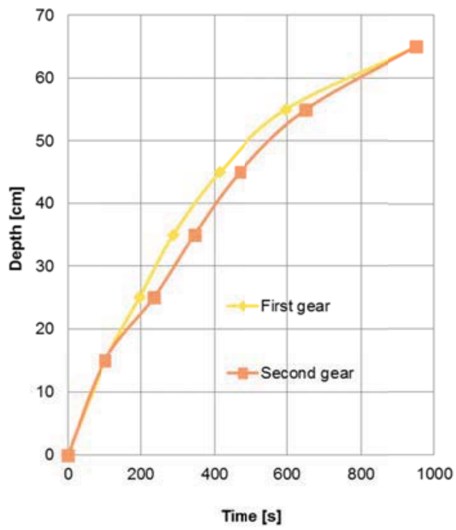


Figure 18. Dependence of time imbedded from depth in Syar regolith analogue.

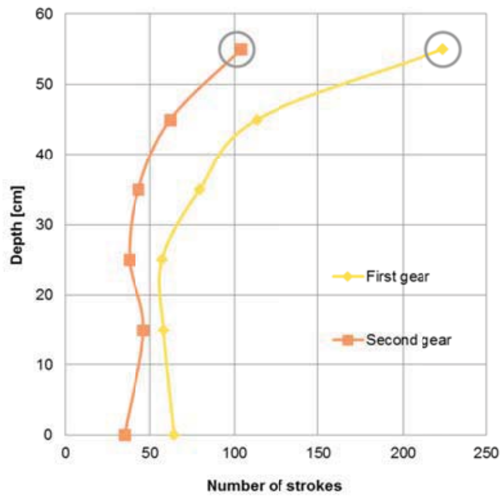


Figure 19. Dependence of number of strokes from depth in Syar regolith analogue. Numbers of strokes are presented for 10 cm depth sections and only first one is for 15 cm.

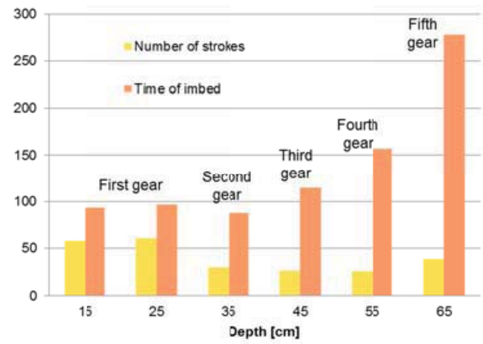


Figure 20. Dependence of number of strokes and time of imbed from depth for five power settings. EMOLE needed more stroke on higher power levels to reach the next ten centimeters because, the bottom volumes of the regolith were more much more compressed.

To date, penetrator, in all tests, made over 5000 strokes, and remains fully functional.
A full test campaign (up to TRL5, with continuing tests in different regolith types and including vibration and thermal-vacuum tests) will be duly performed during the upcoming month, concluding with the end of August 2015. Furthermore, a new test stand using magnetic sensor was developed for this purpose, which allows to make comparisons between penetrators already finalized and those planned for the future.

EMOLE ATTRIBUTES SUMMARY [5]

The table below includes all main attributes of EMOLE.

Table 2. Summary of EMOLE attributes.

Variable	Value	Comments
Diameter	**25,4mm**	1in
Length	**254mm**	10in
Overall mass	**704g**	Without power supply wire, with the outgoing wire inside the outer casing, brake spring and bearing balls.
Hammer mass	88g	
Couter-mass mass	521g	
Outer casing mass	90g	
Power consuption	**4W**	12V
Number of coils	**5**	Can be increased or reduced
Number of wire turns in each coil	147	In each coil
Capacitor parameters	1: 230V; 4,57J 2: 320V; 8,85J 3: 390V; 13,1J 4: 450V; 17,5J 5: 500V; 21,6J	Next power settings in sequence. Discharging voltage and accumulated energy.
Stroke energy,efficiency, duration	1: **0,49J**; 10,72%; **1,6s** 2: **0,94J**; 10,62%; **2,9s** 3: **1,47J**; 11,22%; **4,3s** 4: **1,86J**; 10,62%; **6s** 5: **2,22J**; 10,28%; **7,2s**	Next power settings in sequence. Generated on hammer with fixed counter-mass.

CONCLUSIONS

EMOLE is a low-speed penetrator capable of mobility within the regolith subsurface. The simplicity of the direct drive solution and its relevance to the previous flight models of MUPUS (Rosetta), CHOMIK (Fobos-Grunt) and mole penetrator "KRET" give a prospect for fast development to a high TRL in a short time (also due to the experience of CBK PAN).
Lightweight and compact EMOLE either as a whole device or only its new electromagnetic direct drive, may become flexible solution for space exploration missions providing a wide range of the possible applications, e.g.:

- carrying sensors (e.g. thermal, miniature spectrometers, cameras) underneath the granular matter of a celestial body,
- subsurface ground sampling,
- anchoring of lander in microgravity conditions,
- anchoring (better coupling with the ground) e.g. seismometers,
- may act as a special actuator for generating very high pulse force (1000-2500N).

The main structural novelty, i.e. the use of several electromagnets arranged in stock as a direct hammer propulsion, gave twofold improvements. First of all, owing to the fact that, the electromagnets do not need any drive transmissions in this case and they do not have any rotating parts as in DC motor, the whole instrument became much simpler and more reliable. Secondly, the drive has the ability to adjust hit energy during operation, which can contribute to saving the energy and to protection of the scientific instruments from damage. Furthermore, to provide an additional mode in which the typical operation is superimposed with a high frequency and low energy mode, a new electronic control was developed. Worth mentioning is the fact, that for the magnetic circuit a new material - Permendur 49 (instead of soft iron ARMCO B), was pre-tested and implemented into the final design.
What is important, EMOLE is the first mole-type penetrator which employs an electromagnetic linear drive system. Further, it is a prototype model and can be rebuild to fulfil specific mission requirements.
Space Mechatronics and Robotics Laboratory at CBK PAN is extensively involved in the development of advanced space mechanisms, where penetrators are one of the most important areas of interest. Development of the new EMOLE was expected as a natural continuation of the previous achievements (MUPUS, CHOMIK, spring driven mole penetrators) of the Lab. Actually, CBK PAN baseline policy is strongly focused on space exploration and planetary research. The proposed project fits perfectly with this policy and would strengthen the position of CBK PAN in frame of collaboration with ESA and other European space institutions.

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