PRELIMINARY STUDY ON A NOVEL CORING SYSTEM FOR PLANETARY SURFACE SAMPLING

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ABSTRACT

This paper illustrates the conceptual development of a coring system with novel geometry (Pyramidal Sampling Tool - PST) and a preliminary study for the design of its actuation system. The principle of operation is described and the main geometrical features are highlighted. Different actuator system solutions are proposed, with a particular reference to ultrasonic/piezoelectric technology, in order to obtain the requested pushing action as intermittent percussion at very high frequency with a limited energy absorption. Furthermore, the soil/tool mechanics is investigated and a sensitive analysis of the sampling process in lunar and Martian soils with respect to geometrical parameters is performed. The proposed system could be considered as a promising novel concept for the easy and non invasive sampling on different planetary surfaces. The study was manly executed during the ESA summer school 2008 in Alpbach as part of the final project on a Sample Return mission concept.

1. INTRODUCTION

The robotic Exploration Programmes of rock-solid body of the Solar System are usually articulated in different phases; the first steps were a global observation, remote sensing from the orbit orbital and the landing of scientific packages for in-situ investigation of surface, subsurface and atmosphere. For a complete and true understanding of the planet's geo-morphological features and evolution, specific tests on terrain sample are necessary; it can be done on board of planetary probes, where a dedicated sampling system makes them available after collecting from the surrounding environment. Nevertheless, extensive and specific analyses as age dating, stratigraphy, pristine chemistry require huge/heavy instruments, controlled environmental conditions and long time availability of the samples; thus, they usually can precisely be performed only on Earth. Therefore, the next cycles of planetary exploration missions will include the capability for the return of small surface/subsurface samples, stored inside reentry capsules, back to our planet.

The capability of samples collecting (by means of drilling/coring/scooping mechanical devices) and caching are actually among the most crucial technologies to be validated by the next planetary missions planned for the present decade.

2. SAMPLING IN EXTRATERRESTRIAL ENVIRONMENTS

Sampling process for planetary exploration is usually intended as surface material catching/erasing, in order to perform the subsequent analyses by dedicated instruments [1]. Several distinctive aspects are involved: the preservation of terrain physical features is one of the most important, because it affects the trustworthiness of the subsequent analyses devoted to the geological subsurface reconstruction and the chemical profile, to investigate the effect of long exposure to atmospheric conditions. Special interest is usually dedicated to evidence the existence of past or present water, because of its implications in life searching.

The most widely used sampling technique is drilling, characterized by the surface penetration of a cylindrical bit actuated by a rotary motor. Despite its simplicity, it presents not negligible limitations and it imposes severe constraints over equipments' mass and accommodation in the probe: in fact the traditional drillers require high axial forces and holding torques, together with elevated power absorption. Further restrictions in the use of drilling systems are the physical and chemical modifications induced by the penetrating action and the limited capability in mass collecting by the tip rotation.

Where the planetary target surface is mainly composed of incoherent material with small granulometry, an efficient alternative to the drill is typically the scoop, a translating open-surface tool that can acquire the material with a complex movement managed by a robotic arm. The dexterity of the arm can be also used for instruments' deployment and manipulation, but it increases the system power consumption.

Further traditional concepts for planetary sampling are the corers, the grinders for small samples capture, the penetrators/moles and the impactors/projectiles, recently included in asteroid-targeted mission.

A summary of planetary sampling techniques, adopted in past and current missions, is reported in Table 1. For the Apollo programme, the large amount of acquired material by astronauts, that was also carried back to Earth, is due to the number of missions and to the high load capability of the return module.

Table 1 – Sampling technique summary

Programme / Mission	Target	Sampling technique
Luna	Moon	Drill
Surveyor	Moon	Scoop
Apollo	Moon	Scoop
Venera	Venus	Drill
Viking	Mars	Scoop
MER	Mars	Grind
Phoenix	Mars	Dig
Hayabusa	Asteroid	Projectile
Rosetta	Comet	Drill
Exomars	Mars	Drill

The selection among them depends on the expected environmental conditions of the target and strongly affects the general architecture of the spacecraft. A significant parameter to be taken into account is the axial force: it is manly due to the resistance encountered by the driller/corer while penetrating, and is usually balanced by the local weight force acting over the entire lander/rover. If no anchoring system is foreseen to fix the structure on the ground, the maximum available force for the drilling depends on the mass of the planetary probe and on the mass of the rocky body: hence, sampling in low-gravity planetary bodies (especially comets and asteroids) by conventional equipments can be very challenging. The necessary energy affects the overall dimensions and the mass of the actuator system, together with the holding torque and equipment power consumption.

Further engineering specifications come from the environmental conditions, especially temperature and pressure; the extremely wide ranges, that are usually encountered in extraterrestrial planetary surfaces, can impose strong restrictions on the equipments and on their operational duty cycles.

The space research for future architecture missions is currently oriented both on the improvement/refinement of traditional and reliable drilling techniques, both on the investigation of new concept and technologies for resources optimization. Among these, a very promising set of novel devices are the Ultrasonic/Sonic drillers, developed by the Jet Propulsion Laboratory (Pasadena, USA), that were demonstrated to efficiently operate in extreme environmental conditions [2]. Non conventional methods are based on lasers, melting tips, electron beams or microwaves, etc.

3. THE PYRAMIDAL SAMPLING TOOL - PST

The traditional cylindrical corers usually require a dedicated additional device, placed along or at the end of the penetrating sleeve, in order to separate and incorporate the collected material. Scoops are mainly based on concave open shape, that are filled with incoherent surface material by a relative translatory motion; a dedicated robotic arm is used to distribute and cache the sample for the scientific analyses.

The new concept here proposed is a Pyramidal Sampling Tool - PST, whose geometrical main feature is the inclusion of material within a pyramidal volume through the sliding of four triangular elements along incident planes (Fig.1). These blades are properly shaped, with sharp lateral edges, in order to cut/break the soil with the minimum resistance force. The main geometrical parameters of the PST blade are described in Fig. 2; the sharp angles γ_e and γ_i are obtained on both sides in order to guarantee the balancing of flexural components of the friction forces.

The precise translational motion, that is necessary for the achievement of the closed pyramidal volume, is guaranteed by two protruded profiles in the blade's external surface; they work as guide when sliding in the complementary seats created in the support element. Moreover, they increase the bending rigidity of the triangular blade against out of plane thrusts. The top of the blades is also appropriately faceted in order to allow the penetrating force application.

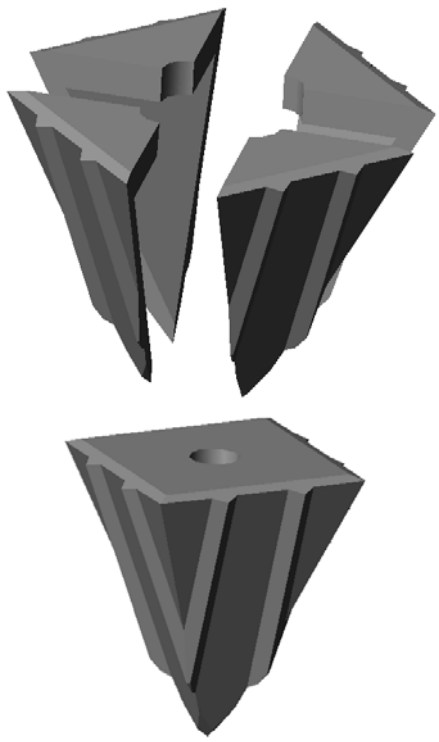

Fig. 1. The Pyramidal Sampling Tool concept

The global architecture of the tool is revealed through a cross section in Fig. 3.a, in the open configuration at the beginning of the sampling sequence. Additional mechanical devices are adopted to complete the tool and ensure the perfect closure of the blades surrounding the soil: a preload system for the axial sliding control (Fig. 3.b) and a lock ring. Sampling operations include the approach phase over the selected area (Fig. 4.a), the sampling by force on PST and locking (Fig. 4.b), then finally the extraction of the tool from the ground by vertical motion (Fig. 4.c).

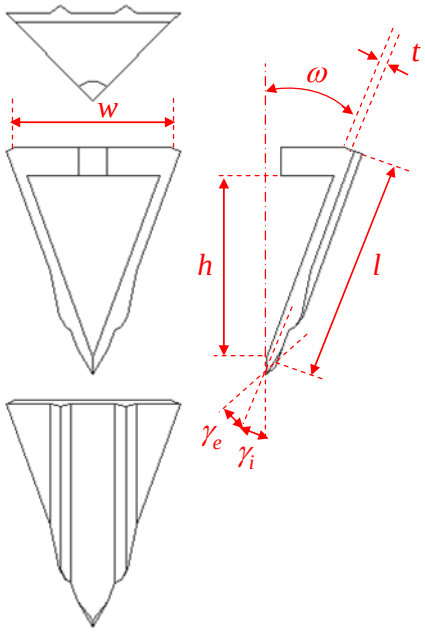

Fig. 2. PST Blade geometrical parameters

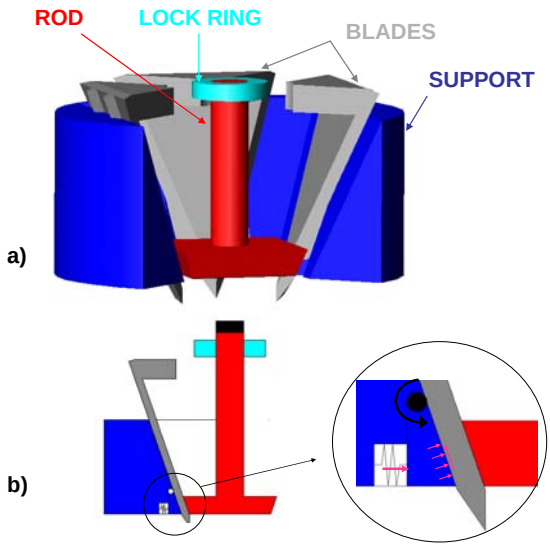

Fig. 3. PST main architecture

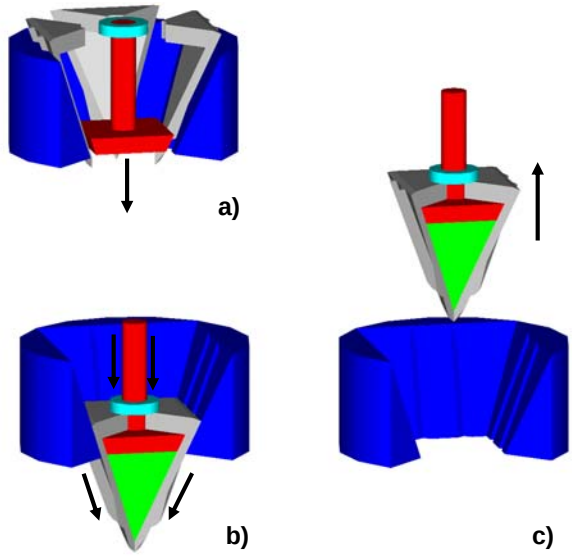

Fig. 4. Sampling sequence by PST

4. PROPOSED ACTUATOR SYSTEMS

The sliding penetration in planetary soils of the PST blades must be forced by a dedicated actuation systems. The flexibility of the tool permits to suggest different concepts of pushing forces, depending on the physical features of the encountered terrains.

For incoherent soils, a continuous force F can be applied to the blades in order to cut the agglomerate material and/or the layers and incorporate it inside the closed volume. If some reusability is requested to collect and then release the sample into distribution/cache device, a bidirectional motion of the blades can be imposed by reversible actuators (Fig. 5.a). For one-shot sampling, in order to reduce the subsystem mass excluding motor's mass, a blasting charge can be positioned over the top of the blade (Fig. 5.b). The generated impulsive force must be set according to the predicted soil resistance, hence previously tailored for the planetary selected target.

The PST penetrator can be also proposed for a mechanical coupling with the Ultrasonic actuation technology, whose advantages in planetary probe applications are consolidated [2]. Hence, the forcing action over the blades should be imposed by an impacting mass, that is excited in high frequency resonance condition by piezoelectric elements. The vibrating system could be positioned along the blade sliding axis (Fig. 5.c), or with a radial configuration of cantilever elements with natural bending modes (Fig. 5.d); their intermittent impacts on blades, reproducing the typical action of the manual hammer-chisel system, make the percussive assembly suitable also for coherent hard soils sampling. Although the blades can not able to cut hard rocks, they can erode or fracture them with an high-frequency hammering action.

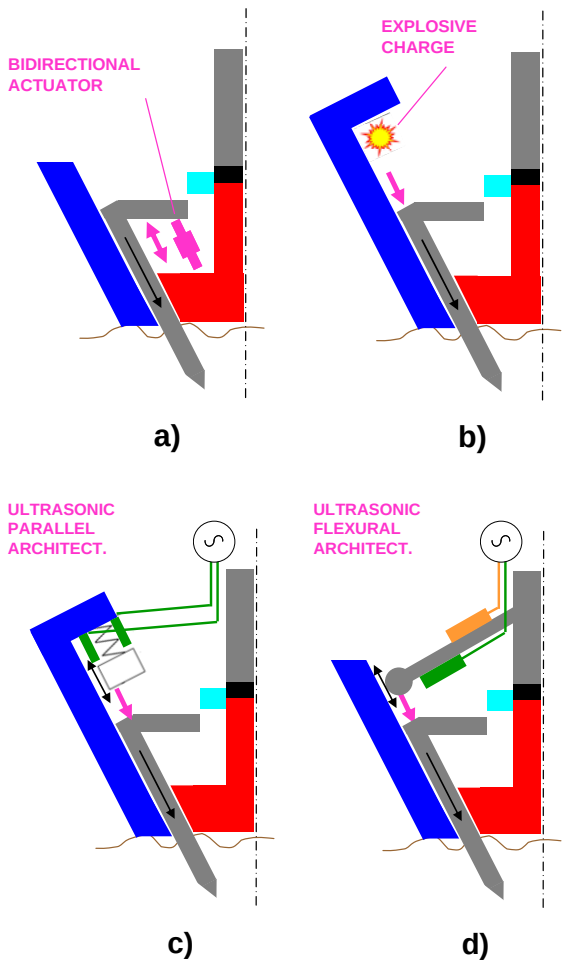

Fig. 5. Actuation concept for PST

5. SAMPLING MECHANICS

The evaluation of the penetrating force F of one PST blade through an incoherent soil is performed using the McKyes and Ali model [3], as:

$$F = \left(\rho d^2 N_p + c d N_c + q d N_q\right) w \tag{1}$$

with:

$$N_p = \frac{r}{2d}\left[1 + \frac{2rd}{3dw}\sin(\eta)\right] \cdot D_e \tag{2}$$

$$N_c = \left[1 + \cot(\beta)\cot(\beta+\varphi)\right]\left[1 + \frac{rd}{dw}\sin(\eta)\right] \cdot D_e \tag{3}$$

$$N_q = \left[1 + \frac{rd}{dw}\sin(\eta)\right] \cdot D_e \tag{4}$$

$$D_e = \left[\cot(\alpha+\delta) + \cot(\beta+\varphi)\right]^{-1} \tag{5}$$

$$r = d\left(\cot(\alpha) + \cot(\beta)\right) \tag{6}$$

$$\cos(\eta) = d\cot(\alpha) \cdot r^{-1} \tag{7}$$

where ρ is the soil bulk density, d is the blade depth, w is the blade width, c is the cohesion, q is the soil surcharge, φ is the internal friction (or repose) angle, δ is the blade-soil friction angle, α is the rake angle (Fig. 6-a). The value of β angle is calculated as minimum of the function N_p (β). For the PST triangular blades, the width w is linear function of the blade length l and d.
In case of high rake angles $(\alpha > 90° - \varphi)$ soil fracture occurs with dual failure regions (Fig. 6-b); hence, the coefficients in Eq. 1 become:

$$N_p = \frac{d'}{2d}\left[\begin{array}{l}\tan(\varphi) - \cot(\alpha) \\ + \dfrac{2d'}{d} N_p^* \cot(\theta+\varphi)\end{array}\right] \cdot D_e \tag{8}$$

$$N_c = \left[1 - \frac{2d'}{d} - \left[\begin{array}{l}\dfrac{2d'}{d}\tan(\varphi) - \cot(\alpha) \\ + \dfrac{d'}{d} N_c^*\end{array}\right]\cot(\theta+\varphi)\right] \cdot D_e \tag{9}$$

$$N_q = \left[\frac{d'}{d} N_q^* \cot(\theta+\varphi)\right] \cdot D_e \tag{10}$$

where N_p^*, N_c^*, N_q^* are evaluated through Eqs. 2-4 assuming $\alpha = 90° - \varphi$, $\delta = \varphi$, $d = d'$.

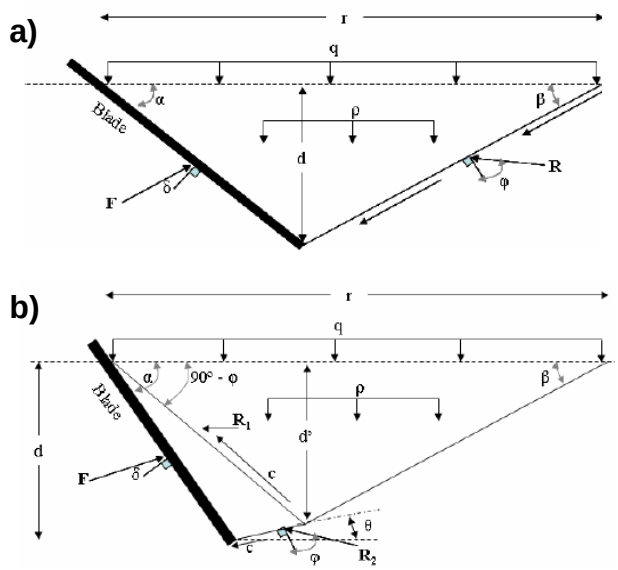

Fig. 6. Soil failure for low (a) and high (b) rake angle

6. RESULTS AND DISCUSSION

The optimization of PST geometrical parameters and the choice and design of the actuation system can be performed considering the sampling force/power requirements. For a defined PST geometry, they depend also on geotechnical soil properties of the planetary body that is the space probe's target. In order to use the McKyes and Ali model for a preliminary analysis of sampling operation on incoherent soil, the physical properties of lunar and Martian surface were collected from past missions' data and resumed in Table 2. The lunar properties are known with small uncertainty range, because the samples (especially collected from Apollo missions) were deeply analyzed by specific instruments both in situ and on Earth. On the contrary, the Mars surface geotechnical properties are derived only by in situ soil mechanical experiments, through images analysis and soil-wheel interaction for rover (when available); then, the Mohr-Coulomb failure criterion allows to relate the friction coefficient δ and the cohesion c to normal and shear stresses, hence to wheel dynamics. The repose angle φ is typically estimated by means of images analysis of the pile or tracks slope generated by lander/rover contact elements. These values are not widely available and precisely estimated; hence, the repose angle for our simulations can be assumed on the analogy of similar planetary terrain.

Table 2 – Planetary soil geotechnical properties

Soil (Mission)	Bulk density	Cohesion	Angle of friction	Repose Angle
	ρ (kg/m^3)	c (Pa)	δ (°)	φ (°)
Lunar intercrater area, 0-15 cm depth (Apollo[4])	1300	520	42	35
Lunar intercrater area, 0-30 cm depth (Apollo[4])	1580	900	46	36
Mars drift material (Viking[5])	1150	1600	18	-
Mars drift material (Pathfinder[5])	1285	210	34	-
Mars blocky material (Viking[5])	1600	5100	31	-
Mars crusty material (Viking[5])	1400	1100	35	-
Mars crusty material (Pathfinder[5])	1422	1700	37	-
Mars crater floor (Opportunity[6])	-	5000	20	-
Mars crater wall (Opportunity [6])	-	500	20	-
Mars Ares deposits (Pathfinder [7])	1285-1581	170	37	33
Mars blocky material (Pathfinder [7])	2100	5500	31	31

The geometrical parameters of the PST can be selected in order to obtain a desired amount of collected mass (choice of the volume depending of local surface density) and considering the requirements for sampling deepness d. For the PST, this value corresponds to the blade height h, because it completely penetrates the terrain. The square base side is then defined together with the blade angle ω, that for PST is 90°- α. The blades' thickness t has to be calculated by trade off process between the minimization of penetrating resistance and the adequate mechanical strength and pyramidal shape maintaining. The overall dimensions can be also considered as system constraints.

A preliminary sampling simulation is performed, by evaluating the required penetrating force for three different PST configurations thorough lunar and Martian soils. The results are shown in Fig. 7.

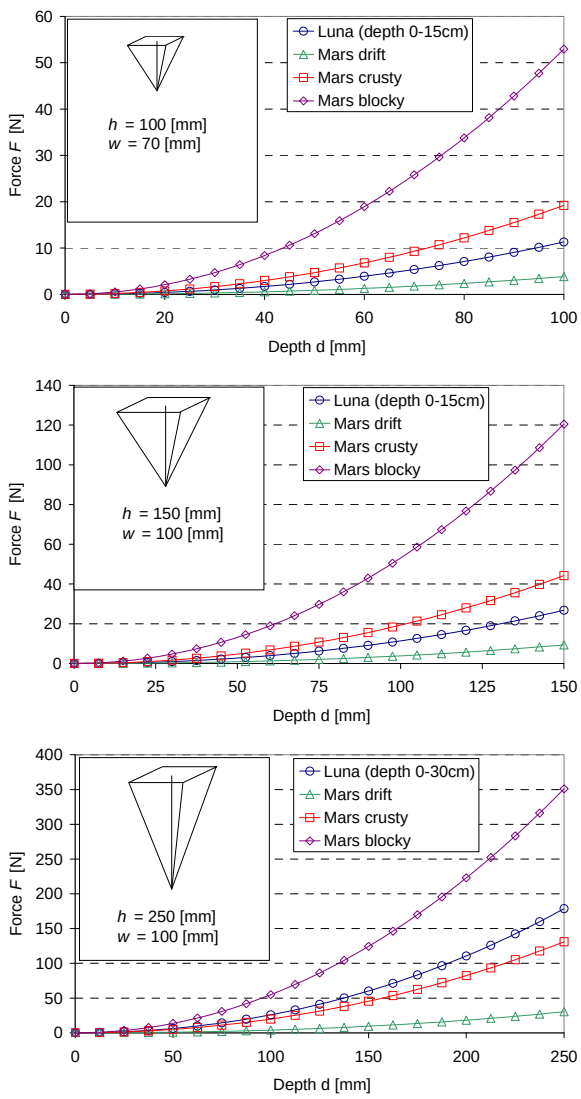

Fig. 7. Penetrating Force for PST configurations

A comparative analysis between the behaviour of the investigated geometries (h = 100 [mm], w = 70 [mm], volume V = 163 10^3 [mm] for PST1; h = 150 [mm], w = 100 [mm], volume V = 500 10^3 [mm] for PST2; h = 250 [mm], w = 100 [mm], volume V = 833 10^3 [mm] for PST3) evidences the high sensitivity of the penetrating force F with respect to soil properties. The strongest influence can be attributed to cohesion c and bulk density ρ (similarly to cylindrical tips [8]), whose variability ranges are wide in the different planetary body. The mechanical behaviour of PST1 and PST2 is similar and the required forces are equally spaced, because their geometric scale factor is the same for h and w; for PST3, the long and narrow shape increases the importance of the N_q term in Eq. 1, thus of the bulk density variability. In Fig. 8, the low influence of the slenderness, depending on α rake angle, is highlighted. The requirements for the analyzed PSTs, in terms of maximum force and required energy (calculated by numerical integration) are summarized in Tab. 3. The same sampling tool needs more than 1000% of energy for blocky material with respect to drift one. Therefore, the selected actuation system should include a capability for fine tuning of pushing force. In this sense, the one-shot explosive actuators can be considered only if the characteristics of the lading site are sufficiently known. On the contrary, the percussive action of the ultrasonic actuator could be simply regulated in intensity; this makes it suitable both for incoherent and for stony planetary surface.

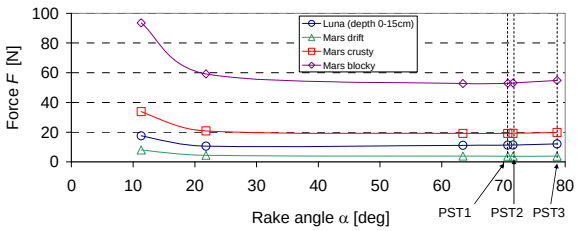

Fig. 8. Influence of rake angle α.

Table 3 – PSTs force/energy requirements

Soil	Maximum force [N]		
	PST1	PST2	PST3
Luna	11.3	26.8	178.6
Mars drift	3.8	9.3	30.3
Mars crusty	19.2	44.2	130.9
Mars blocky	52.9	120.5	351.0
	Required energy [J]		
	PST1	PST2	PST3
Luna	1.47	5.18	27.33
Mars drift	0.48	1.75	9.28
Mars crusty	2.53	8.72	42.69
Mars blocky	7.03	23.95	115.89

7. CONCLUSIONS

The analysis of terrain samples is indispensable to answer pressing questions about Solar System formation and evolution; hence, the planetary sampling technology is mandatory capability of space probes. The proposed Pyramidal Sampling Tool, here introduced at conceptual level, can be a promising device for materials collecting with low invading effects and preservation of natural soil characteristics, as the original stratigraphy and structure. Its simplicity in principle of operation makes it suitable for different kind of mechanical actuators, especially based on the ultrasonic technology; the complete assembly should be a robust and not-sensitive system to operate in extreme environmental conditions. A preliminary design and requirements evaluation by functioning simulation demonstrates the effectiveness of the concept, worthy of further investigations.

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