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Test facility for SD2 comet sampler performance improvement

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INTRODUCTION: ROSETTA MISSION

Rosetta Mission is the third cornerstone of the European Space Agency (ESA) scientific program "Horizon 2000". This program derives from the desire to study comets, that are recognized as important objects for scientific research.
Our knowledge about comets and asteroids has improved over the last twenty years. The previous mission which tried to reveal the comet secretes were ESA's Giotto satellite and Russian Vega probes, which performed the first fly-bys of the Halley comet in 1986. In 1991, NASA's Galileo spacecraft made the first near encounter coming from the asteroids main-belt, Gaspra, on its way to Jupiter and pictured the crash of asteroid on Jupiter.
Nowadays scientists believe that comets represent the only bodies have not changed since their creation, because they have not been altered by internal heating and spend most of their time far from the Sun. Moreover scientists suppose that from these "cosmic icebergs" brought the life on Earth.

Rosetta Mission [1] is made up by two systems: the orbiter Rosetta and the lander Philae. Rosetta will be the first spacecraft to orbit around a comet nucleus and Philae [2] will be the first probe to perform a soft landing on a comet nucleus to study, in-situ, the comet composition.
Rosetta journey has started in March 2004 and it will reach, in 2014, the comet 67P/Churymov-Gerasimenko at about 450 million kilometres from the Earth.
The Rosetta orbiter will orbit around the comet for several months in order to study the nucleus as well as its evolution through its approach to the Sun, by remote sensing techniques.
The most important mission goals are: the determination of mineral and isotopic composition of the comet's surface and immediate subsurface, and of the comet soil mechanical characteristics like strength, density, texture, porosity, ice phases and thermal properties.
The in-situ analysis will be performed by several scientific instruments placed on Philae, some of them managing small samples of comet, suitably heated at different temperature levels to generate different volatiles.
To this aim it is mandatory to drill the comet soil, to collect samples and to distribute them.

SD2 SUBSYSTEM

The Sampler Drill and Distribution Subsystem (SD2) [3-4] is the multifunction device that provides in-situ operations in order to collect and distribute samples. SD2 subsystem, that is placed on the lander base plate (Fig. 1), supplies comet samples and distributes them for the following scientific analysis.

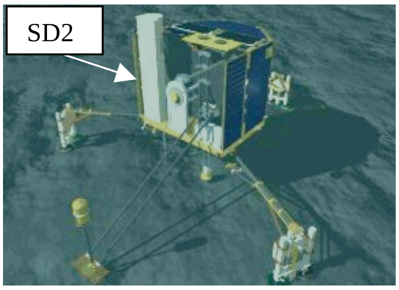

Fig. 1: SD2 accommodation on the Philae lander

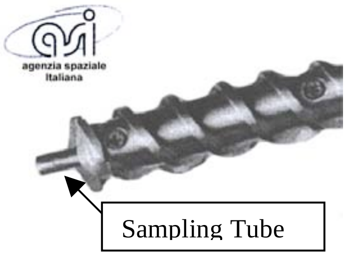

Fig. 2: SD2 drill

To this aim SD2 is equipped with a drill (Fig.2) able to collect several samples of tens of mm^3 (10-40) at different depths (the maximum depth is 230mm) from the same hole or from different holes, work in a particular environment, at very low gravity and a wide thermal excursion, and execute all the operations with a very low power consumption.

The most important environment parameters, for the design of SD2, were comet soil strength, temperature and surface pressure [5]. Parameter ranges, taken into account during the design phase, are wide in order to assure a correct functionality even in presence of a high uncertainty, as shown in Table 1. The result of the recent cometary mission Deep Impact [6] proves that physical parameters of comet Tample 1 are compatible with the Table 1.

Table 1: Environmental parameters

Comet strenght	50Pa – 50MPa
Temperature	-140°C (operation on comet) to +50°C (no-operation)
Pressure	10^{-5}mbar (space vacuum) to 1bar

SD2, with a total mass of 5100 g, is composed by three main components:

- the Mechanical Unit,
- the Electronic Unit (with embedded SD2 software),
- the Harness (for electrical connection of Mechanical and Electronic Units).

The Mechanical Unit [7] consists of the Tool Box, the Drill, the Carousel with 26 ovens and the Volume Checker.
The Tool Box, built in carbon fibre, avoids drill damages due to vibrations and shocks during launch and landing phases.
The drill, with a total length of 581,6 mm and with a 12 mm radius, is made of aluminium alloy; to reinforce the drilling bits, polycrystalline diamonds have been utilized, capable to handle also hard soil. Position, shape and geometry of the bits have been optimised by theoretical analysis, numerical simulations and experimental tests, in order to maximize the “cutting capability” with a low vertical trust (100N) and a low power consumption (14,5 W).
The Drill / Sampler Tool has two degrees of freedom: translation, to approach and penetrate the comet surface, and rotation, around the translation axis. The integrate drill sampling tube solution has been chosen for its simplicity and flexibility: the collection of the samples is performed by a pressure contact, as well as the release. It can work properly both with hard and fluffy materials.
The Carousel is a rotating platform on which some small containers, the ovens, are mounted. The material is picked up and discharged in the ovens, by the Sampling Tube, to be after analyzed by some experiments that are placed on the lander. The carousel task is to displace the filled oven under a precise experiment.
The Ovens provide interface between the collected sample and the scientific instrument. According to the scientists requests, two kinds of Ovens are onboard: 10 Medium Temperature Ovens (MTOs) with an optical sapphire prism, suited for the analysis by visible and I/R microscopes, before heating up for medium temperature experiment (+180°C), and 16 High Temperature Ovens (HTOs) suited for sample heating for high temperature experiments (+800°C).
The Volume Checker mechanism allows measurement of the volume of sample discharged into the ovens.

The Electronic Unit is installed into the warm compartment of the lander and incorporates all electronics to control the Mechanical unit. The HW platform and the SW, installed on, provide the interface between the Mechanical Unit and the lander control system, the Command Data and Management System, CDMS [8].
SD2 is supplied by the Lander's Power Subsystem with a 28V line from the Lander's Primary Bus, devoted to the Mechanical Unit, and some auxiliary power lines (+5,-5,+12,-12) from the Lander's Secondary Converters.
Once supplied, the subsystems performs self-check and then it waits for CDMS commands, a set of SW commands that can be sent separately or organised in a dedicated Mission Plan. Before execution, commands are validated by suitable checks; the next command can be accepted only when the previous one is accomplished.

Rosetta has to cover ten years long trip in the Solar System. During these ten years many activities have to be performed, in fact some passive and active checkouts are foreseen in order to evaluate the status of the system [9]. Concerning SD2, during the “link windows” it will monitor the sensor ON/OFF switching and the carousel rotation movements. All these procedures are implemented on Electronic Ground Support Equipment, EGSE (Fig. 3), located in the laboratory of the Aerospace Department at the Politecnico di Milano. The Flight Spare, FS (Fig. 4), is placed in the same laboratory. FS will be utilized for the tests described in the following chapter.
With the EGSE and with the CDMS simulator it is possible to check the Mission Plan single sequences or multi sequences, some particular procedures and eventually to organize recovery procedures.

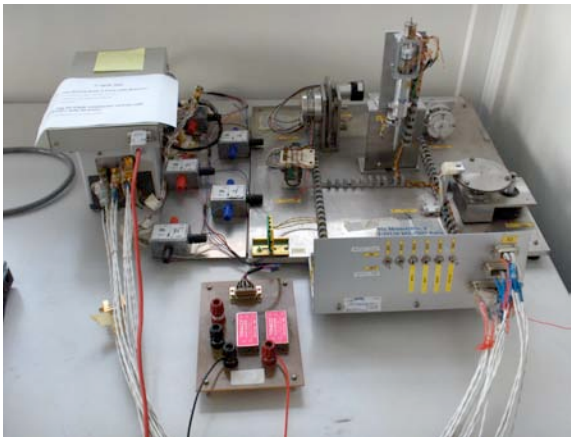

Fig. 3: SD2 EGSE

Fig. 4: SD2 FS

THE FACILITY

To operate in a more realistic way and to evaluate the SD2 behaviour in different scenarios, at the laboratory of the Aerospace Department at the Politecnico di Milano, a dedicated facility [10] has been designed and realized.
Before the realization of the laboratory tests, a requirements analysis and a study about the laboratory tasks have been performed. From this analysis all operations had been determined to be performed with the facility:

- mechanical verification of the perforation system
    - analysis of the drill structural behaviour,
    - force and torque measures transmitted by the drill to the different specimens;
- simulation of many different condition of the comet soil;
- mechanical verification of the sampling and collecting methods;
- verification of the real behaviour of the SD2 FS during the Mission Plan implementation;
- development of a drilling strategy;
- development of some procedures of not common activities (NCA);
- implementation of contingency operations, in which the operational requirements could change during the flight, as well as malfunctions and anomalies.

In order to satisfy all these requirements the facility has been equipped with:

- SD2 FS;
- a support structure thought to allow an easy inspection and to replicate the clamping system of FM
- a sensor system, to measure the drill mechanical behaviour;
- a translation system, to simulate all possible comet soil conditions like rises and depressions;
- some specimens, to verify and implement a strategy of perforation;
- an acquisition system, to measure and to elaborate, in real time, the drill kinematics behaviour.

The external support is represented by a “castle” structure realized with four planes and four beams. The first structure considered was (Fig. 5) equipped by a four prismatic beams at which four planes were coupled. Its main characteristic is the translation system that allows the SD2 FS vertical translation. This solution has been rejected after a study inspired by the terrestrial column drills. For which the plane of the specimen translates while the drill is fixed. In this way it is possible to decrease the problem of alignment between the drill and the drilled surface as well as a more efficient and compact translation system can be realized.
The final configuration is the one shown in Fig. 6.

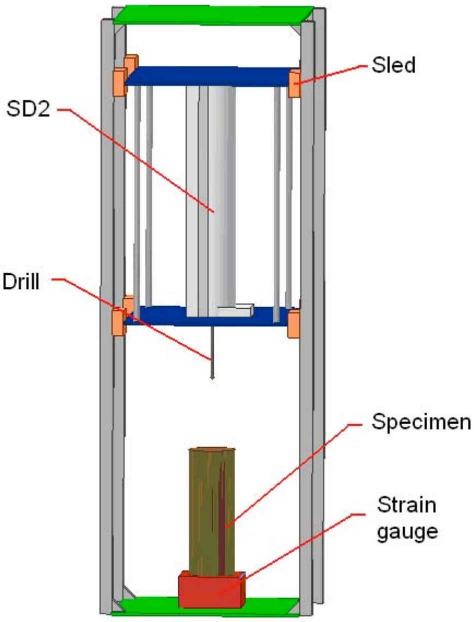

Fig. 5: First configuration

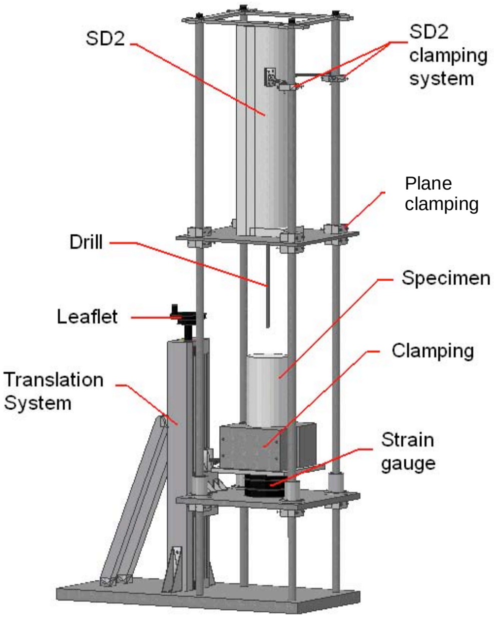

Fig. 6: Final realized configuration

The support structure is made up by: four tubular beam of 2000 mm high and 30 mm radius, three aluminium planes used as base, SD2 support and sensor system support. Four laminar beam close the structure at its top in order to reduce vibrations or distortions during the perforation phase. The planes are constrained to the tubular beam with some clamping (Fig. 7) that allow to avoid SD2 FS movement (Fig. 8) and to position the plane in a determinate heights.
The sensor system (Fig. 9) is constituted by a strain gauge that measures the normal force and the torque, both transmitted by the drill to the specimen surface during a perforation phase. The strain gauge selected has the following characteristics:

- torque FS (Full Scale) of 10 Nm (Mz),
- vertical force FS of 1000 N (Fz),
- resolution of 1N for the vertical force (Fz),
- resolution of 0,01Nm for the torque (Mz)

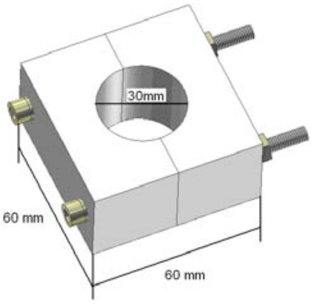

Fig. 7: Plane clamping

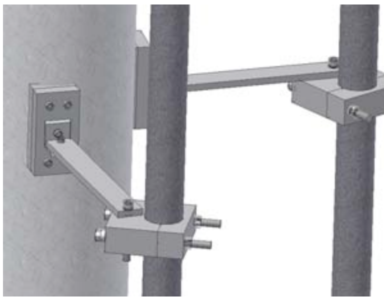

Fig. 8: SD2 clamping system

Fig. 9: Strain gauge

The strain gauge must hold a several loads at the same time given by: maximum load of 100 N performed by drill during the perforation, the load of the specimen and also the load of the specimen clamping. With this sensor, compatible with the plane dimensions, it is possible to measure force and torque in real time for a long period (e.g. two hours foreseen for a drilling campaign), to repeat the measure several times and to foreseen a fixture between the sensor and the specimen.

The sensor system furnishes a relation between the measured forces and the composition of the drilled specimens. In fact, during the oncoming tests, it will be possible to analyze, in real time and in continuum, the drilling behaviour and its connection with the mechanical characteristics of the specimens.

For a fixed scenario, *i.e.* for a fixed drill translation and rotation speed and for a fixed time range, a table like the following one can be filled.

Table 3: Analyzed variables

Material	E (Young Modulo)	ν (Poisson Coefficient)	ρ (Density)	σ (Tractive Resistance)	Fz(t)	Mz(t)
Marble						
Travertino						
Comet analogue						

The compilation of these tables, corresponding to a representative set of different scenarios, allows to correlate the nature of the drilled material with the perforation kinematics.

The translation system (Fig. 10-11) is equipped with linear aluminium guide, in which a never ending screw, with a 20 mm radius, an efficiency of 80% and a step of 5mm., is placed. On the guide there is a sled coupled with the sensor plane. The chosen never ending screw guarantees the correct translation of the plane when a marble specimen is installed on the translation plane in fact this represents the maximum load condition. Moreover, the sensor plane can easily move up and down by four cylinders equipped with sphere bearings. This solution guarantees the right plane position, during the translations, and decreases the compression work on the clamping by sopping the plane with a break. The task of translation system is to simulate all possible conditions of comet soil as eventual presence of rises or of depressions. The maximum displacement of the sled is 500 mm. In the Fig. 4 a particular of the translation system is shown.

Fig. 10: Translation System

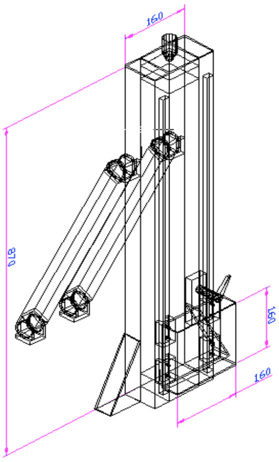

Fig. 11: Dimensions of translation system [mm]

To simulate a comet perforation, it will be utilize some several specimens that have the same mechanical characteristics of the “comet analogues” material specimen, that was built by German Air and Space Institute of Cologne, during the KOSI (Komet Simulation) experiments. To this aim it has been chosen marble, to simulate the eventual presence of small stones, and travertine, to simulate the mechanical and chemical property of comet soil.
Moreover, in order to evaluate the drilling behaviour, in the condition of soil stratification, it will realized a multi-layers specimen that will have three principal layers: one of marble, one of travertine and one of gasbeton (which has been supposed to be the most similar material to the comet soil).

A SCIENTIFIC CONTRIBUTION

As already said, the Rosetta Laboratory, making use of SD2 FS, will allow to perform, in a very realistic way on the Earth, the operations that SD2 Flight Model (FM) will perform on 67P/Churymov-Gerasimenko, simulating different sampling scenarios, according to different on comet surface conditions that can occur. Nevertheless, further studies of a new method seem to prove that also a correlation between drill movements and soil characteristics is feasible [11]. This post-processing of data can increase the possibilities of SD2 utilization. Then, future space missions for Solar System exploration requiring in situ analysis might take advantage from this. In fact, by means of a study about the relation between the telemetry data and the mechanical characteristics of the perforated material, it is possible to use SD2 not only as a tool but also as a scientific instrument.

SD2 telemetry data that should be utilized to characterize this relation, are:

- drill speed rotation,
- perforation depth,
- power consumption.

In the following table the kinematics and physical variables, measured by the EGSE and by the sensor system, are shown:

Table 2: Measured variables during a perforation

By the EGSE	By the Sensor System of the facility
Vr(t) = drill rotation speed [rpm]	Fz(t) = vertical force [N]
S(t) = perforation depth [1/100 mm]	Mz(t) = torque [Nm]
I(t) = current value [A]	

Unfortunately, among the telemetry data, for the nature of the drill rotation and translation stepper motors, it is not possible to utilize the power consumption variation as an indicator of a corresponding variation of the soil composition. In fact a stepper motor works with a fixed current value for each speed value. The Fig. 12 represents the characteristic curves of the drill rotation motor and shows that the motor presents different torque ranges (the black area) for each speed value.

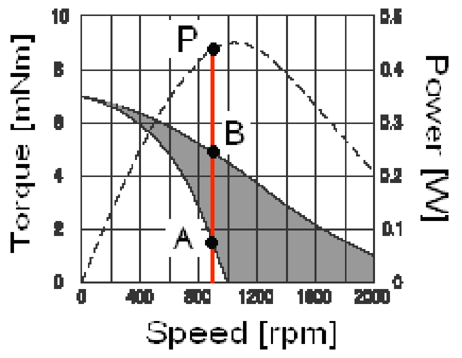

Fig. 12: Characteristic curves of the drill rotation motor

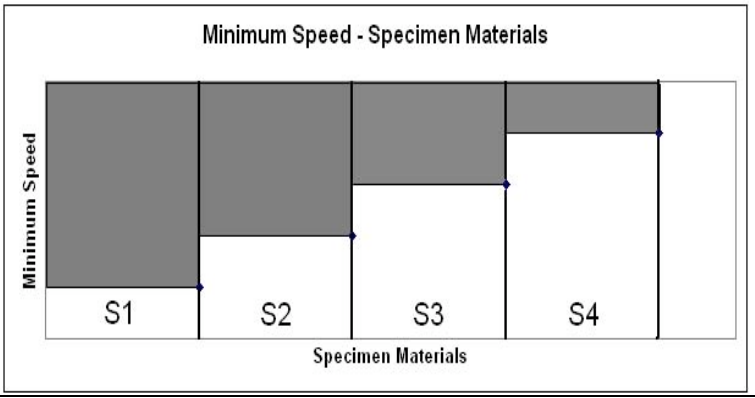

Fig. 13: Relation between Minimum Speed and the Specimen materials

If, during a perforation phase, the drill should find a small stone or a unexpected layer with high strength, one of the two following options can happen:

- if the resistance torque increase is lower than the maximum resistance torque value, Cmax (the point B in the Fig. 12), the drill can proceed the perforation with the same speed (there is no current increase);
- if the resistance torque increase is bigger than the maximum resistance torque value (Cmax) the drill can not proceed the perforation with the same speed then the motor stops.

By these considerations, a methodology, which requires only the knowledge of the speed value, has been proposed. If a proper perforation strategy is used, this method allows to calculate the minimum drill speed for different materials.
This perforation strategy consists in a command sequence imposing increasing drill speed values, discretized within a given range whose lower limit corresponds to the minimum speed required to drill a material with strength of 50Pa, while the upper limit corresponds to the speed required to drill a material with strength of 50MPa. For each type of material it exists a particular speed value below which no perforation can be performed due to the stepper motors turning-off. Therefore once the perforation has been performed and the drilling depth overcomes a given off-line fixed threshold, the current drill speed is the one used to determine, on the basis of the correlation obtained with a numerical model (shown in the next paragraph), the drilled material nature or possibly the category the material belongs to.
The dark area, in the Fig. 13, shows the range of the allowed speeds for some materials.
With this approach, SD2 can be exploited as a scientific instrument capable of identifying the material nature, a possible comet stratification [12] and in particular significant un-homogeneity in the upper layers of the comet soil.

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THE PERFORATION MODEL

One of the main goals of the planned test campaign consists in the identification of an experimental correlation between physical and mechanical parameters of the specimen materials and of the minimum rotational speed (being the translational one fixed) required to drill the sample without stepper motor turning-off.
However, due to the fact that the specimens exploitable during the ground test phase constitute a limited range of materials, not necessary completely representative of the real (unknown) comet mineralogical composition, a numerical model [13-14] is actually in development phase. Its purpose consists in the formulation of the explicit relation explaneing experimental findings. This model will be the instrument adopted to extract reliable information about the comet soil composition from on-line data gained during comet sampling. It will be then validated with the experimental results obtained with the facility tests. The selection of the parameters used to univocally identify the drilled materials, or to identify just the category the drilled materials belong to, depends on the chosen theoretical model of fracture mechanics [15]. The different available models of Linear Elastic Fracture Mechanics (LEFM) are reported in table 4.

Table 4: LEFM models

Model	Hypothesis	Input	Output
Cundall	- discontinuous material characterized by a cluster of distinct and rigid particles, that interact in contact points, where forces are transmitted in equilibrium with external loads	- x_i and θ: position and orientation (toward x axis) of single element's center of mass; - Constitutive micro-mechanics parameters: density, stiffness and friction among contacts	Fi(t) and M(t) the total force and the total moment due to the interactions among close particles
Mohr-Coulomb	- The drilling, by means of a revolving tool, induces a mixed mode (I+II) fracture - Homogeneous and isotropic soils in order to get a linear elasto-plastic behaviour towards the stress applied. - 'Intact' rocks, i.e. lithologically homogeneous and without any discontinuity.	- C [MPa]soil's effective cohesion - σ [MPa] total normal stress on movement - u [MPa] pressure on the movement surface - $\sigma_n = (\sigma\text{-}u)$ [MPa] effective normal stress on movement surface - ϕ [°] effective internal friction angle	$\lvert\tau\rvert = C + (\sigma - u)\cdot tg(\phi)$ [MPa] modulus of material's shear strength
Dugdale-Barenblatt	- Intact rocks - Biaxial loads - Linear elastic behaviour for material out of process zone	-$\sigma(w)$, w: Crack tip opening displacement -$\tau(s)$, s: Crack tip sliding displacement	$G = \int_0^{CTOD} \sigma(w)dw + \int_0^{CTSD} \tau(S)ds$ Energy Release Rate
Hillerborg	- Mode I fracture - Tensile stress (tensile breaking needs less energy dissipation than a compression breaking) - Linear elastic behaviour for material out of process zone	-$\sigma(w)$ w: Crack tip opening displacement	-$G = \int_0^{CTOD} \sigma(w)dw + \int_0^{CTSD} \tau(S)ds$ Energy Release Rate (Mode I) -$G_F = \int_0^{w_c} \sigma(w)dw$ Fracture Energy

The trade-off analysis of fragile fracture mechanics models allows us to consider the energy criteria, of the last two models, as the most appropriate to characterize the constitutive law of a brittle material (Fig. 14). In fact these two energy models have a low computational cost and they don't require the knowledge of the material characteristic parameters.

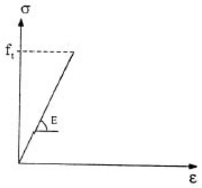

Fig. 14: Stress-Strain Curve of brittle material

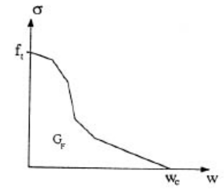

Fig.15: Softening Curve

Between the Hillerborg and the Dugdale models, the first is the best suited for our purpose. Indeed, if we assume a linear elastic behaviour of the material before breaking, and we start the analysis from the most energetically critical load-condition, the Hillerborg model provides two typical energetic parameters of the material: G and G_F (the area under the softening curve in the Fig.15). By means of these two energetic parameters, regardless of the dimensional scale of the specimens, it is possible to correlate the drill kinematics behaviour and the specimen nature.

CONCLUSIONS

The SD2 Subsystem has been designed in order to be operative even in critical thermo-vacuum environment and to meet the demanding mass/power resources limits as required by the Rosetta mission specifications. To this aim, very innovative technological solutions have been adopted: sampling tube for the drill-sampling design, composite materials, dry lubrication, stepper motors, medium temperature ovens design.

The facility, built at the Department of Aerospace Engineering of the Politecnico di Milano, allows to simulate the comet in-situ phase, and also to test several different soil materials. These tests can be performed not only on materials typically found on a comet, but also on those encountered on other celestial bodies.

This paper presents a first attempt to develop a new method able to provide a correlation between drill movements and soil characteristics. The proposed post-processing technique is sought to increase the possibilities of SD2 utilization. The availability of such a correlation between the telemetry data and the mechanical characteristics of the perforated material will make it feasible to use the SD2 as a scientific instrument, and not only as a tool.

Moreover, the numerical model of fracture mechanics could be validated by means of the facility, in order to obtain a numerical correlation between the drill kinematics characteristics and the mechanical properties of the soil.

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