SAMPLING MECHANISM FOR LOW GRAVITY BODIES

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1 ABSTRACT

In future exploration missions to low gravity bodies (e.g. a Mars moon or a near-Earth asteroid) it is planned to collect more than 100 grams of soil and return them to Earth. In previous studies several sampling tools have been proposed but there is no single sampling technology for low-gravity bodies that has been specifically conceived to provide the ability to collect material in any envisaged situation. Low gravity bodies present indeed peculiar conditions which need to be taken into account during the design and test of sampling and sample handling systems. Primarily, the very reduced gravity limits the thrust reaction capability in support to drilling operations; and, although reactions can be achieved by spacecraft anchoring or by thrust reversal, these operative conditions could limit the effectiveness of the sampling action.

An alternative solution is the exploitation of the forces naturally arising from Spacecraft momentum inversion, which can be achieved by ‘touch and go’ techniques (as e.g. performed in Hayabusa mission). Although the small duration of the contact with the soil would anyhow limit the sampling depth and the collectable soil types, a properly designed sampling system would require to conclude the operation with a great effectiveness.

In the last three years an ESA founded study has been carried on and a fully functional sampling mechanism for "touch and go" sampling on a low-gravity body has been selected, designed and breadboarded. Based on the results of several Proof-Of-Principle models tested on different types of specimen and after the analysis performed on a dynamic simulation model for the sampling action, a device implementing the most promising sampling technique has been designed and manufactured. It has been then tested under ambient conditions using various kinds of asteroid soil stimulants.

The proposed paper will resume the key aspects and the main achievements of the study.

2 CONTEXT OF THE STUDY

As the sampling technology is strictly related to some system/mission key choices, the context of the study was specified by the ESA's Statement of Work:

> "*After an orbital mapping phase with sampling site selection the S/C performs a touch and go sample acquisition. The S/C descends to the surface with limited residual vertical and lateral velocities to the largest extent. During a very short period (~2 s) the sampling mechanism touches the surfaces and collects regolith. After lift-off the successful acquisition of material shall be verified by means of a dedicated measurement device or other method. After positive confirmation the sample canister will be inserted by means of a transfer system, as simple as possible, into the Earth Re-entry Capsule. Eventually the S/C leaves the orbit and returns to Earth.*"

The aim of this study was thus to select, design and breadboard a fully functional sampling mechanism for touch and go (~ 3 seconds) sampling on a low-gravity body.

3 REQUIREMENTS DEFINITION

At the beginning of the study a review of the sampling technologies capable to cope with above defined sampling procedure was done, together with the review of the main requirements, which were finally consolidated as follows:

- Soil: mainly loose material (grain size from some µm), but considering also the potential presence of some pebbles. Bulk density of 1 - 2.2 g/cm^3. Sample grain size from some µm to 3 cm. Intra-particle cohesion of 0.1 - 5 kPa and angle of friction of 20° - 40°, which implies that the Tool should be sized to cope with about 500 kPa (a.k.a. "soil bearing capacity").
- Collection performances: 100 cm^3 of material (assuming to collect 100 g in a single attempt in a material with density of 1 g/cm^3) in few seconds (~ 2 - 3 s). Implementation of a system to verify the successful sampling. Side speed of 5 cm/s max during collection. Possibility to performs at least 3 collecting attempts for failure mitigation. Sample mechanism or parts of it to serve as sample containment and be returned to Earth.
- System characteristics: Overall mass within 3 kg (target). Part of the sampling system inserted into the Earth re-entry capsule not exceeding 200 mm dia. x 130 mm height.
- Environment: asteroid or Martian moon scenario. Soil temperature: 120 K to 470 K. Low gravity environment (<0.0084 m/s^2 at equator for a body of 11 km mean radius). Vacuum conditions.

An assessment was also done to select the best soil simulants for the test campaign to be conducted at the end of the study. Based on spectral similitudes of the Asteroid 2008 EV5 with the Orgueil meteorite, which is dominated by serpentine and magnetite, the selection was targeted to a material similar to Carbonaceous chondrites, thus including minerals are phyllosilicate, serpentine, magnetite, and olivine. However asteroid surfaces may include also sands and gravels, and the test campaign shall take into account a variety of surface conditions. Finally, three sample types were selected:

- type P "powder": 50% regolith + 50% sand + some pebbles
- type G "gravel": grains and pebbles of various sizes
- type M: montmorillonite + serpentine + olivine + magnetite in equal parts, plus some sand and small grains

4 SELECTION OF SAMPLING MECHANISM

4.1 Proof-of-Principle tests

After a review of concepts compatible with the short sampling time, several sampling tools have been proposed, such as rotating corers, rotating stingers, push tubes, bucket types, brushes, rotary augers. To support tools evaluation and trade-off, several Proof-Of-Principle models were developed representing the different sampling technologies and a test campaign conducted to gain practical experience.

The identified PoP models were manufactured by means of commercial items and/or fast manufacturing techniques. A total of 30 tool models were therefore developed and tested in 6 different types of specimen (mixtures of sand, olivine and gravel, both stirred and compacted forms). Some of them are shown in Figure 4-1.

Figure 4-1: Some of the Proof-of-Principle models and Test Equipment

4.2 Dynamic modelling of sampling strategy

The sampling strategy was also simulated through a computerized model of a cylindrical container randomly filled with particles of a given distribution (93.94% of 5 mm, 6% of 10 mm, and 0.06% of 25 mm of main size). Simulation were done on Push Tube, Rotating Stinger, and Grab Bucket tools. Results allowed to estimate the performance in low gravity of sampling with these tools when sampling time is 1.5 s and 3 s.

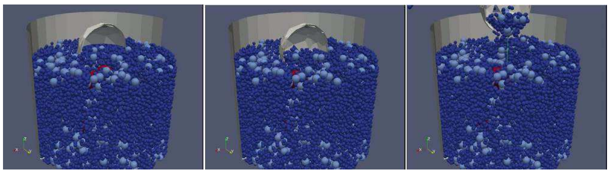

Figure 4-2: Example of sample collection simulation by Grab Bucket

4.3 Candidate solutions and trade-off

The preliminary data allowed to perform a selection and reduce the number of solutions which could be potential candidate for the final breadboarding activity.

Among them a trade-off was conducted which put in evidence that the grab bucket family is in general well suited to the purpose, especially wide opening and spherical grab bucket. They work in stirred material with negligible thrust, can collect very large pebbles due to the large front opening, and can be used without tool rotation to collect samples from loose soil with pebbles with low power.

5 SAMPLING MECHANISM DESIGN

5.1 Architectural design

Once selected the Grab Bucket as the baseline solution, a set of possible implementation were conceived to build the actual device, which should be made by two units: the Sampling Tool and the Tool Drive.

The Sampling Tool is the parts which actually comes in contact with the soil and collects the sample. Because it is used also as sample container for the return flight towards Earth, its mass and sizes shall be kept as minimum as possible (within the compatibility with the mission requirements). It shall thus include only the buckets and part of their actuation mechanism, while the actuator shall be hosted inside the other part, the Tool Drive, which remains on the planetary body.

The Tool Drive will include also the actuator performing the rotation of the Sampling Tool during the collection, and the detachment mechanism to disconnect the Sampling Tool once it is inserted into the Earth Return Capsule.

Particularly, the selection was based on two aspects:

1. the mechanical interfacing between the Tool Drive and the Sampling Tool about the way to transfer the actuation action for the buckets: linear or rotational coupling?
2. the decoupling of the actuation of the bucket from the rotation of the Tool: mechanical or electronical decoupling?

Furthermore, a trade-off was conducted among various solution (here shown in based on aspects like the simplicity and reliability of the kinematism and its risk in harsh environment, the internal forces developed in the tool, and the overall physics parameters (mass, volume, power).

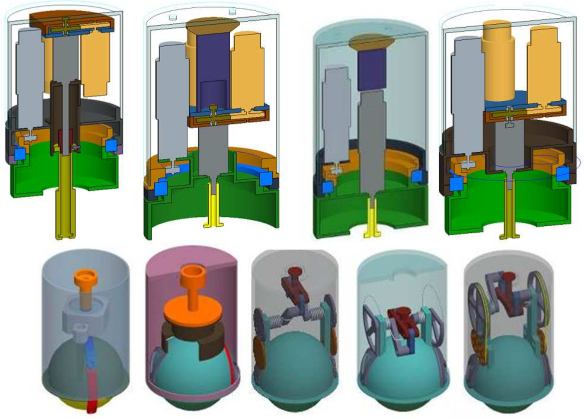

Figure 5-1: Conceived architectures

At the end an architecture has been selected in which:

- the actuation to operate the buckets is transmitted by a rotational coupling positioned in the central axis of the device;
- buckets actuation and Tool rotation are mechanically decoupled.

5.2 Detailed design

The selected architecture was thus preliminary designed in its essential elements. particularly, motorization margins were evaluated according to the applicable space standards. Then, for the Breadboarding activity, a detailed design was performed including structural verification and FEM modelling of the main elements (sustaining parts, buckets joints, gears, ...).

The Tool Detachment Mechanism (which allows to disconnect the Tool from the Tool Drive when the Tool is inserted within the Earth Re-entry Capsule) was instead not included in the detailed design; in the breadboard model it was substituted by a screwed interface between the Tool and the Tool Drive.

The resulting breadboard hardware is shown in Figure 5-2. Its main features are:

- Motorization: maxon brushless motor EC22 100W with 1:119 reduction for Tool rotation, maxon brushed motor DCX22L + 1:270 reduction for bucket closure
- Mass: 303 g Tool + 2012 g Tool Drive (exlc. any margin and sample); 260 g estimated for detachment mechanism for a flight unit.
- Sizes: 76 mm dia. x 92 mm height the Tool, while 100 mm dia. x 258 mm height for the Tool Drive
- Sensors: one accelerometers on 3 axes and a camera to check proper sample collection

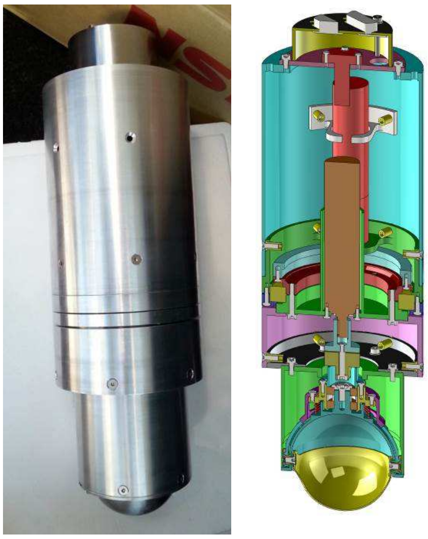

Figure 5-2: Sampling Tool final design

6 GROUND TEST EQUIPMENT

The designed breadboard was used to validate the concept by a test campaign. Considering the reference scenario (a touch-and-go sampling with the sampling tool at the tip of a robotic arm) a Ground test Equipment was designed and manufactured to simulate the movement imposed to the Sampling Device by the robotic arm itself.

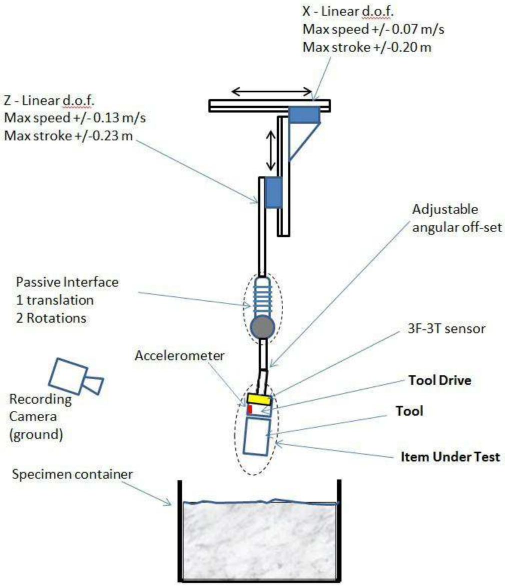

Figure 6-1: Ground Test Equipment concept

Figure 6-2: Final Test Equipment hardware

The main features of the Test Equipment are:

- Motorization: two linear DoFs, plus the possibility to set an approach angle towards the soil within the range ±10°.
- Compliance: passive compliant device to simulate the robotic arm's elasticity during touch-and-go sampling.
- Mass: 294 kg
- Sizes: 2160 mm x 1297 mm x 510 mm
- Sensors: 6 axis FTS sensor, position sensors along actuation axes.

7 TESTS

The test campaign was aimed to verify the performance of the breadboard tool against test conditions such as:

- Type of soil
- Vertical speed (30 mm/s, 70 mm/s, and 130 mm/s)
- Horizontal speed (40 mm/s and 70 mm/s)
- Tool-soil initial angle of inclination (perpendicular or 10° towards the motion)
- Sampling action trigger means and timing (FTS data, accelerometer data)

For each test the touch-and-go impact was simulated by operating the 2-DoFs motorization of the Test Equipment according to the profile given in Figure 7-1.

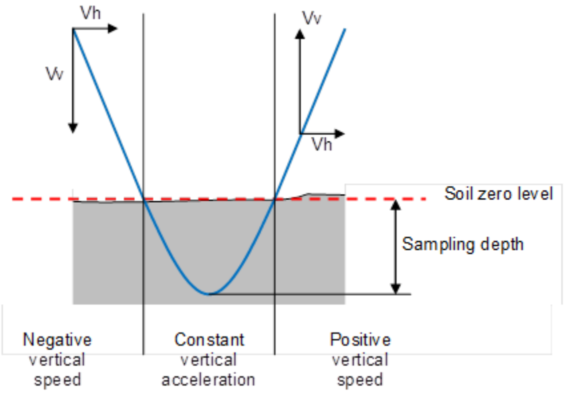

Figure 7-1: Impact trajectory profile

Some initial tests were conducted, aimed to determine the best strategy to detect the contact with the soil and trig the buckets closure (trading-off between force threshold and acceleration threshold). Finally, it was decided to use only the force of the impact perpendicular to the soil, and make the trigger to occur when the moving average over 100 readings overrides the threshold value of 10 N for the 5th time.

Some tests were also conducted to determine whether, after the contact detection, a certain delay should be waited before actuating the bucket closure. Finally, the best collection performance was achieved without any delay.

After these initial and preparatory tests (~130 tests) a set of 135 tests were conducted, 45 test for each of the soil types.

8 RESULTS

The main results of the entire test campaign are:

- Impact speed: the most efficient strategy to collect the highest quantity of soil is limiting the vertical speed to values lower than 70 mm/s and maintaining the horizontal speed around 40 mm/s. By using this strategy, the average collection performance, equal to 53% of the collecting chamber volume, can be increased to 66%.
- Tool rotation: the rotation of the tool helps the collection performance by a 12%.
- Tool attitude: no appreciable improvement of the collection performance is achieved by inclination the tool towards the direction of horizontal motion;
- Force level: no correlation can be seen between the push force towards the soil and the collection performance.

Figure 8-1: Some images taken during the test campaign with M soil (top) and G soil (bottom)

9 CONCLUSIONS AND FUTURE WORK

Along the study a solution capable to collect the required amount of soil sample during a fast touch-and-go manoeuvre has been designed. Based on it, a breadboard model has been developed, manufactured and successfully tested.

Test results have allowed to confirm the sampling capabilities. Furthermore, the execution of an entire test campaign with variation of some parameters allowed to assess the best usage conditions.

The potential next step are the development of a fully functional breadboard, to include also the Tool detachment mechanism, and the possible execution of some tests in simulated micro-gravity environment (parabolic flight).