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ROSETTA MISSION

MISSION PLAN GENERATOR FOR THE SCIENTIFIC USE OF THE SAMPLER, DRILL, AND DISTRIBUTION SUBSYSTEM

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Abstract

This work focuses on two main activities both concerning the Sampler, Drill, and Distribution (SD2) subsystem, currently flying onboard the Rosetta mission.

The first activity concerns the development of a software tool to combine different telecommands into mission plans. The tool is a support for engineers to operate the drill in a more simple way and to monitor its energy consumption.

The second activity, on the other hand, is the design and execution of an experimental campaign that involves the use of SD2 to characterize the compressive behavior of a selection of sample materials. The results are than integrated with those of a new set of tests carried out in the laboratory of the Department of Aerospace Science and Technology of Politecnico di Milano, using both an exact copy of SD2 drill bit provided by SelexEs and a penetration testing tool designed and manufactured at the Politecnico di Milano. The final goal is to confirm that SD2 can be actually used as a scientific tool to measure the mechanical properties of the materials on the comet's surface.

Introduction

The Rosetta mission, decided by the European Space Agency (ESA) in 1993, is one of the most ambitious endeavors in European spaceflight's history [1]. Its goal is to reach a comet, to enter its orbit and to send a probe on its surface to study its composition. As a matter of facts, comets are widely considered to contain the least processed material in our solar system and, since their condensation from the proto-solar nebula, it is most likely that even pre-solar grains have been preserved inside them. The physical and compositional properties of comets may therefore be a key to their formation and evolution, hence to the formation of the solar system.

The target

The original goal for the Rosetta mission was the comet 46P/Wirtanen but, due to technical problems with the launcher Ariane 5, the mission was delayed and the target was changed in favor of 67P/Churyumov-Gerasimenko [2]. This target variation will have a non negligible effect on the landing device which, due to the different physical properties of the comet, will have to face a higher touchdown velocity than the one expected for Wirtanen implying a higher level of risk. However, the flexibilities in the mission design will provide high confidence for a successful landing [3].

An interesting fact about 67P/Churyumov-Gerasimenko is that, up until 1840 it was invisible from Earth. Then, due to the gravitational effect of the planet Jupiter, its perihelion distance changed from 4 AU to 1.29 AU becoming visible [2].

Its origins, like all the other comets from the class of the Jupiter Family (JPC), come from the Kuiper belt where it was produced from one of the many collisions happening in that region [2].

Another important characteristic of 67P/Churyumov-Gerasimenkois that its nucleus presents some active regions which will be observed in detail during the comet's perihelion passage [2].

More features can be found in Table 1:

Diameter of nucleus	3x5 [km]
Rotation period	~12 [h]
Orbital period	6.57 [years]
Perihelion distance	194 [10^6 km] (1.29 AU)
Aphelion distance	858 [10^6 km] (5.74 AU)
Orbital eccentricity	0.632
Orbital inclination	7.12 [Deg]
Surface temperature (day)	-80 +20 [°C]
Surface temperature (night)	>-200 [°C]
Year of discovery	1969
Discoverers	Klim Churyumov & Svetlana Gerasimenko

Table 1 - 67P/Churyumov-Gerasimenko comet features [2].

The journey

Launched in March2, 2004, Rosetta will reach the comet in May 2014 after a ten years journey through the solar system [1].

During its travel, in order to acquire enough energy to reach the target, the probe exploited four gravity assist maneuvers: Earth - Mars - Earth - Earth. In between the last two Earth swing-bys, Rosetta flew by the main belt asteroid 2867 Stains and, after the last gravity assist maneuver it travelled by another important asteroid known as Lutetia [2].

For what concerns the power generation, Rosetta will rely completely on solar panels becoming the first mission ever to travel beyond the main asteroids belt using only this technology instead of the traditional radio-isotope thermal generators. This new solar-cell technology, composed of two 32 m wide solar panels allows Rosetta to operate over 800 million kilometers from the Sun where solar radiation is only 4% of the amount available on Earth. This means that even with such a wide surface and with hundreds of thousands of specially developed non-reflective silicon cells mounted on it, in deep space, the amount of power generated is around 400 W which is a very small amount to perform the foreseen experimental activity [5].

Due to the very long time spent in deep space it was important to have a constant status update on the mounted payloads. For this reason, between the commissioning until the beginning of the hibernation phase, a total of 13 Payload Checkouts were carried on. During each one of them, instruments had the opportunity to activate their units, exercise mechanisms, refresh EEPROM memories, and perform calibrations and software updates.

All of the above activities required the developing of dedicated procedures. For each operation, a specific list of commands is generated to optimize data return [4].

Once the comet will be reached, after a rendezvous maneuver, Rosetta will start orbiting its target to perform the first measurements and to look for a place suitable for landing. Then, Philae, a landing device, will be released from the orbiter to land on the comet's surface. The name "Philae" was chosen prior to launch to remember an inscription on an obelisk from an island near Aswan, Egypt called Philae which confirmed the decipherment of the Rosetta stone [3].

The separation between Rosetta and Philae will provide the landing device with a relative velocity of 0.05 m/s up to 0.52 m/s. Its descent to the comet's surface will be stabilized by an internal flywheel and supported if required by a cold gas system. The descent time will be in the range of about 30 min, depending strongly on the actual comet properties and the selected delivery orbit [2].

Table 2 shows the main phases of the mission:

Phase description	Date
Launch	2 March 2004
First Earth gravity assist	4 March 2005
Mars gravity assist	25 February 2007
Second Earth gravity assist	13 November 2007
Asteroid Steins flyby	5 September 2008
Third Earth gravity assist	13 November 2009
Asteroid Lutetia flyby	10 July 2011
Begin hibernation phase	July 2011
End hibernation phase	January 2014
Entering comet's orbit	May 2014
Mapping the comet's surface	August 2014

Phase description	Date
Philae landing	November 2014
Perihelion passage	August 2015
Mission end	December 2015

Table 2 - Rosetta mission main phases [1].

During the comet's long journey to its perihelion, both Rosetta and Philae will travel alongside. As this phase approaches, Rosetta will continue to orbit the celestial body, while the Philae lander will remain attached to its surface where it will be able to precisely monitor how the formerly cold and inactive chunk of dust and ice will "awake" [1]. Figure 1 shows an artistic impression of Philae after the landing with Rosetta orbiting the comet.
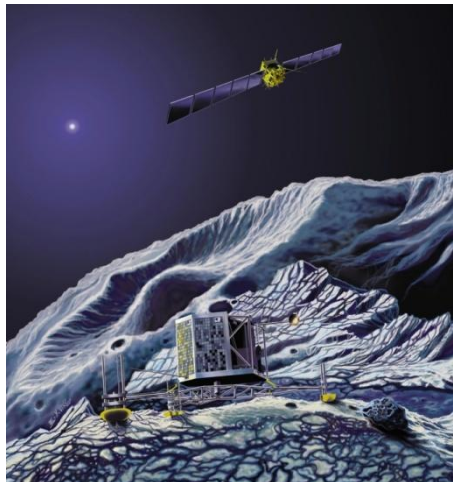
Figure 1 - Artistic impression of the Philae lander with Rosetta orbiting the comet [1].

Rosetta and Philae

Rosetta's design is based on an almost cubic central frame, 2.8 m × 2.1 m × 2.0 m, with an aluminum honeycomb main platform. The total launch mass, including the 100 kg lander and 165 kg of scientific instruments is 2900 kg. The spacecraft is made of two primary modules: the Payload Support Module, which holds the scientific instrumentation and two payload boom deployment mechanisms in the top part of the frame. Then there is the Bus Support Module, which holds the spacecraft subsystems in the lower part and a steerable 2.2 m

diameter high-gain parabolic dish antenna attached to one side. Finally, the lander Philae is mounted on the opposite side (see Figure 2) [1].

The science instrument panel is mounted on the top and it is designed to be facing the comet continuously during orbit while the antenna and solar panels face the Earth and Sun, respectively. Radiators and louvers are mounted on the back and side panels facing away from the Sun and comet. In the center of the spacecraft, protruding from the bottom, there is a vertical thrust tube made of corrugated aluminum with strengthening rings. This subsystem provides the propulsion for primary maneuvers and contains two 1106 liter propellant tanks [2].

The spacecraft is three-axis stabilized and the orientation is controlled by 24 thrusters of 10 N each. Attitude is maintained by four reaction wheels as well as two star trackers, Sun sensors, navigation cameras, and three laser gyro packages [2].
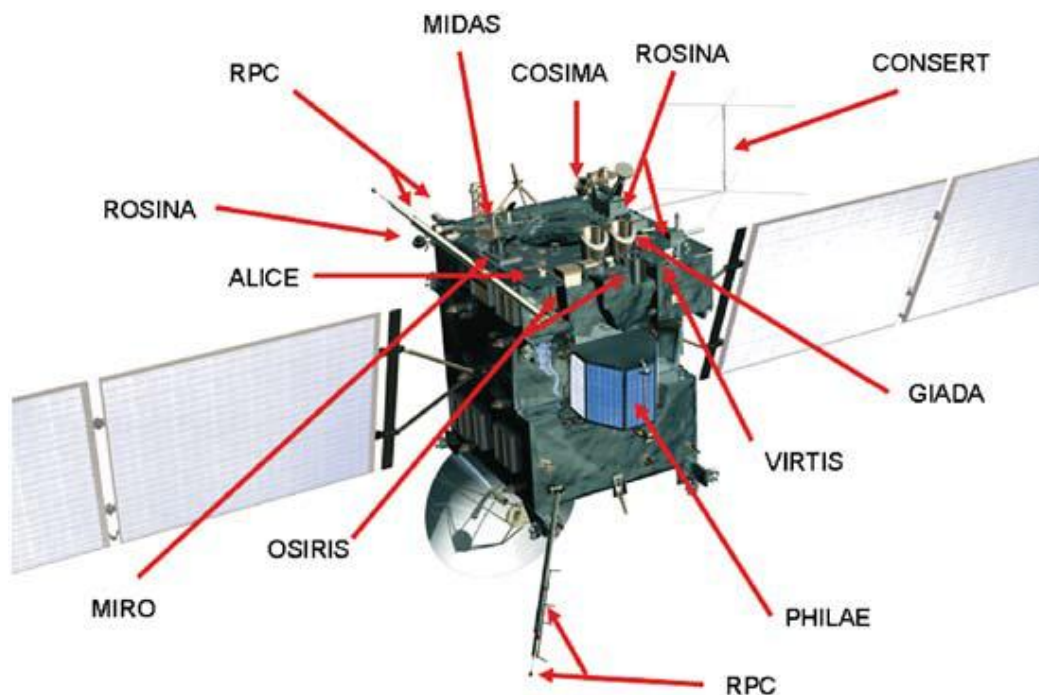
Figure 2 - Rosetta spacecraft and its scientific payloads [2].

In addition to the lander, Rosetta's scientific payload includes 12 experiments.

ALICE - it will analyze gases in the coma and the tail, and it will measure the comet's production rates of water and carbon monoxide or dioxide. It will also provide information on the surface composition of the nucleus.

COSIMA – it will analyze the composition of dust grains emitted by the comet and it will tell whether they are organic or inorganic.

GIADA – it will measure number, mass, momentum and velocity distribution of dust grains coming from the comet nucleus.

MIDAS – it will study the dust environment around the comet and provide information on particle population, size, volume and shape.

MIRO– it will determine the abundances of selected major gases, the surface outgassing rate and the nucleus sub-surface temperature.

OSIRIS – consists of a wide-angle and a narrow-angle camera to obtain high-resolution images of the comet's nucleus.

ROSINA – will determine the composition of the comet's atmosphere and ionosphere, the velocities of ionized gas particles and reactions in which they take part [2].

The five instruments and the plasma interface unit of ROSETTA's plasma consortium – RPC – are designed to study structure and dynamics of the comet-solar wind interaction during the comet's approach to the Sun. RPC will also examine the physical properties of the nucleus. And during the cruise phase the RPC instruments also provide scientific measurements about possible encounters of cometary ion tails and dust trails. A radio science investigation –RSI – uses shifts in the spacecraft's radio signals to measure e.g. the mass, density, and gravity of the nucleus [2].

VIRTIS – it will map and study the nature of the solids and the temperature on the surface of the nucleus. VIRTIS will also identify comet gases, characterize the physical conditions of the coma and help to identify the best landing sites.

In addition to these scientific experiments the orbiter is also equipped with a standard radiation environment monitor – SREM – to monitor the high energetic, ionizing particle environment aboard the spacecraft. The objective of SREM is to provide a continuous, almost uninterrupted measurement of the high energetic particles encountered by Rosetta and provide this information for mission analysis purposes [2].

The Rosetta lander, Philae can be considered as a scientific spacecraft of its own carried and delivered by Rosetta to the comet. After the landing, Philae will investigate the comet's nucleus in detail. With the images and the results from chemical, physical and mineralogical analyses that will be radioed back to Earth, scientists hope to better understand both the origin of comets, and the earliest times of the solar system [2].

Table 3 shows the experiments which will be carried outby the Philae lander:

Name	Scientific purpose
APXS (Alpha Particle X-ray Spectrometer)	Analyzes the distribution of chemical elements on the surface.
ÇIVA (Comet Infrared and Visible Analyzer)	Analyzes the core samples gained from SD2 with a microscope.
CONSERT (Comet Nucleus Sounding Experiment by Radio-wave Transmission)	Investigates the inner structure of the comet by propagating radio waves through the core.
COSAC (Cometary Sampling and Composition)	Analyzes the chemical composition of the frozen surface down to 30 centimeter's depth.
MUPUS (Multi-Purpose Sensors for Surface and Sub-Surface Science)	Measures the temperature near the surface and the thermal conductivity of the ground.
PTOLEMY	Analyzes the isotopic composition of the drill cores with a mass spectrometer and a gas chromatograph.
ROLIS (Rosetta Lander Imaging System)	Images the landing site and the surrounding areas during the descending phase and landing.
ROMAP (Rosetta Lander Magnetometer and Plasma Monitor)	Determines the strength of the magnetic field at the landing site and during descent.
SD2 (Sample, Drill and Distribution)	Drills cores up to 20 centimeter's depth.
SESAME (Surface Electrical, Seismic and Acoustic Monitoring Experiments)	Contains sensors to measure mechanical and electrical properties of the comet's surface and a dust-particle impact monitor.

Table 3 - Scientific experiments on board of the Philae lander [1].

The scientific phase

After Philae's landing, scheduled for November 2014, the scientific activity carried out by its instruments will be divided into two main phases: FSS (First Scientific Sequence) and LTS (Long Term Science).

The FSS will have a limited duration of approximately five days during which the power will be provided by the lander's 1 kWh primary battery. In this period, many instruments will operate simultaneously. In particular, SD2, the sampler, drill and distribution subsystem will sample the cometary soil and distribute the collected materials to the proper scientific port. These operations must be optimized in order to respond to the requirements imposed by the three scientific instruments: ÇIVA, COSAC and PTOLEMY.

To obtain these goals, a set of three drilling activities has been developed. These three operations will be carried out in the same spot changing only the depth at which the sample will be taken from and the instruments used to study their composition. The first one will be extracted from a depth of 440 mm, the second one from 470 mm and the third one from 500 mm [4].

Each one of this operation requires the development of specific mission plans which will be explained in the following of this work.

Another important issue, other than the short amount of time and power available, will be the communication of data between the lander and the orbiter which may suffer delays due to the relative visibility of the two elements. This problem will limit the possibility of uploading telecommands to SD2 requiring the automatic execution of all the scientific tasks with minimal ground support [4].

The First Scientific Sequence will then be followed by the Long Term Science phase during which Philae will rely on the power from the solar generator and from its secondary battery. The instruments onboard the lander will continue to operate for a few months. In this period of time, SD2 will continue to provide material to the scientific ports. On the other hand, recent studies and experiments have proven the existence of a correlation between the drill behavior during perforation and the mechanical characteristics of the soil. Therefore, SD2 was recently proposed to be also used as a scientific instrument. This, however,

requires the development of a dedicated strategy to be sure to understand correctly the results coming from the comet [4].

The initial idea investigated in previous works was to perform multiple perforations at different torque and speed levels using both translation and rotation to identify the drill working zones. Information about the mechanical characteristics of the terrain could be obtained by comparing the working zones measured on the comets with a database of test materials available on the ground. Since this kind of procedure required a very large number of perforations, a new experimental strategy had to be developed [5].

This new concept is to use SD2 as a quasi-static penetrator to estimate the resistance of the soil to the drill penetration. Therefore, the drill was used to perform only translations to a given depth at increasing values of torque level. The cometary soil penetration resistance was then estimated by finding the minimum value of torque level for which the translation succeeds.

In order to minimize the power consumption and to develop the best telecommand sequence for these operations, an activity planner program was also developed.

Thesis layout

The following of this thesis has been divided in three parts. Chapter 1 contains a detailed description of the SD2 subsystem, an overview on the DAST test facility and how to operate it.

The second chapter, presents the Mission Plan generator tool including a practical example to demonstrate some of its features.

Chapter 3 contains the description of the experiments carried out to create the new scientific strategy for the scientific use of SD2.

Chapter 1

The SD2 subsystem

As introduced in the first chapter, SD2, the Sampler, Drill and Distribution subsystem is able to drill more than 20 cm into the comet's surface, collect samples (10 ÷ 40 mm^3) and deliver them to different ovens or for microscope inspections.

To do so, SD2 has two degrees of freedom: translation, to reach the comet soil, and rotation around its axis to penetrate into the surface. This solution allows the possibility to play with different combinations of the two movements to overcome the different conditions that may be found on site.

Both the translational and the rotational degrees of freedom are maneuvered by two electrical stepper motors. Depending on the level of power required they can work separately or together. Also, for each degree of freedom it is possible to control the motors behavior by selecting at which speed level and at which torque level they should operate. For the velocity, there are 32 levels which goes from 0 up to 31 while, for the torque, there are only 8 possibilities: from 0 to 7.

On the other hand, the sample collecting/discharging mechanism is actuated independently.

All the procedures to operate the drill are performed through a list of commands that can be sent directly by the user [9].

For the design of SD2, the parameters taken into account were: the comet soil strength (50 Pa ÷ 50 MPa), the temperature (-140˚ C ÷ +50˚ C) and the external pressure along the different mission phases (10-5 mbar in space ÷ 1 bar on Earth) [9].

1.1 Technical overview

SD2, with a total mass of 5.1 kg, is composed by a mechanical unit (3.7 kg), an electronic unit (1.0 kg), and the harness for the electrical connections between them (0.4 kg) [6].
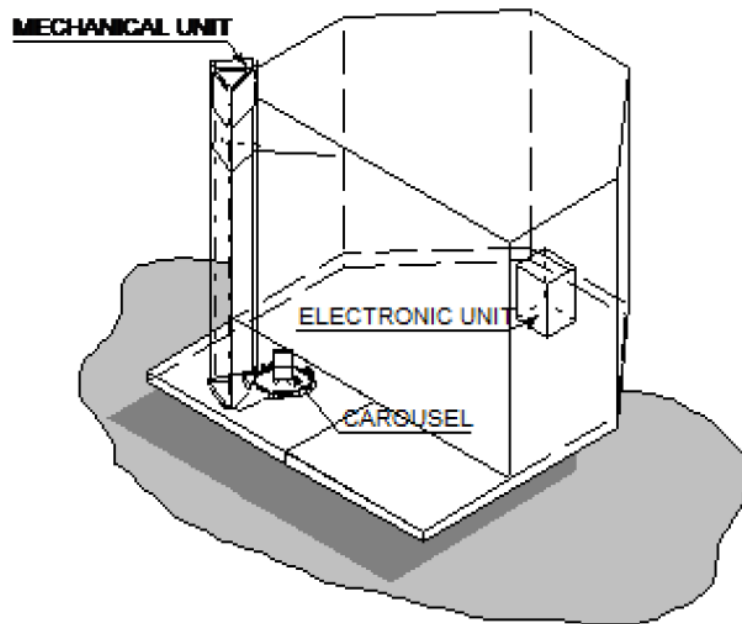
Figure3 - Schematic of SD2 on the Philae lander [5].

The mechanical unit is mounted on the lander balcony in the location dedicated to the drilling and sampling activities. This unit consists of the tool box, the drill, and the carousel [6].

- The tool box is the drill external protection which avoids any contamination from the external environment. It is built in carbon fiber and it also preserves the drill from damages due to vibrations and shocks during the launch and the landing phases [6].

- The drill, with a total length of 581.6 mm and a radius of 12 mm, is made of aluminum alloy while the drilling bit, in order to perforate hard materials, is made of polycrystalline diamonds. Position, shape and geometry of the bit have been optimized by theoretical analysis,

numerical simulations and experimental tests in order to maximize the "cutting capability" with a low vertical thrust (100 N) and a low power consumption (14.5 W). The sampling tube (diameter: 3.5 mm; length: 10 mm) is embedded into the Drill bit and it can be extracted to pick up the sample from the soil. The collection and release of the samples are performed by pressure contact [6].

- The carousel is a rotating platform on which some small containers, the ovens, are mounted. The material, picked up by the drill is discharged inside these ovens which are then positioned by the carousel itself below the required instrument. In order to satisfy the different scientific requirements of the mission, the ovens are divided in two categories: MTOs (Medium Temperature Oven) and HTOs (High Temperature Oven). MTOs can reach up to 180° C andthey are suited for the analysis by visible and I/R microscopes. The High Temperature Ovens, on the other hand, can reach 800° C. The carousel contains also a "Dummy Oven" which is a tool required to pull the sampling tube back inside the drill bit after every sampling operation [6].

The electronic unit, installed into the warm compartment of the lander incorporates all the electronics to provide the interface between the mechanical unit and the Command Data and Management System (CDMS).
The energy required to operate SD2 is supplied by Philae's power subsystem with a 28 V line from the lander primary bus, dedicated to the mechanical unit and with auxiliary power lines at ±5 V and ±12 V from the lander secondary converters [9].

The Command Data and Management System (CDMS) is the data control interface unit which is responsible, together with the electronic unit, for transmitting the commands to SD2 and for handling the telemetry data sent by SD2 during its activity. Also, the CDMS, during each mission phase can decide if the system and all its parts must be turned on or off and the duration of the activation period for each subsystem. From this definition, it is possible to define SD2 as a smart unit capable of self controlling itself thanks to another specific subsystem called C-DPU (Common Digital Processing Unit). This universal processor was designed, build and tested to control and regulate every experiment mounted on Philae [9].

The last element required to control the behavior of SD2 is the flight software known as SD2_FSW (SD2 Flight Software) [9].

The main tasks performed by SD2_SFW are:

- Receive commands from CDMS;
- Control SD2 operations;
- Transmit gathered data back to CDMS.

1.2 The DAST test facility

To operate in a realistic and accurate way and to evaluate the SD2 behavior in different scenarios, at the DAST (Department of Aerospace Science and Technology) at the Politecnico di Milano, a dedicated facility has been designed and realized [9].
In particular, the operations that can be carried out in this facility are the following:

- Analysis of the drill structural behavior and evaluation of the force and torque transmitted by the drill to the specimen;
- Simulation of different comet-like soils and drilling scenarios;
- Mechanical and functional verification of the sampling and collecting system;
- Evaluation of SD2 behavior during mission plan execution;
- Definition of the optimal perforation strategies;
- Design of the recovery procedures in case of SD2 non-nominal behavior;
- Assessment of SD2 power consumption during drilling/sampling activities.

The final configuration of the flight spare model of SD2 in the test facility is shown in Figure 4.
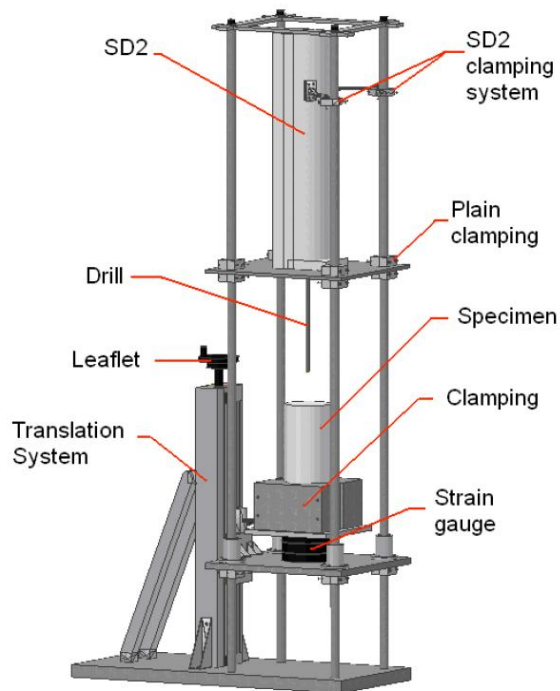
Figure 4 - Final configuration of the SD2 facility at DAST [6].

As shown in Figure 4, SD2 FS model is fixed to an external support structure made by four aluminum planes, four beams and a clamping system. The four tubular beams are 2000 mm long with a 30 mm radius. In order to reduce vibrations or distortions during the perforation phase, four laminar beams close the structure at its top.

Also, this test facility includes a sensor system constituted by a strain gauge that measures the normal force and the torque transmitted by the drill to the specimen surface during the perforation phase. The strain gauge has the following characteristics:

- Torque full scale of 10 Nm (M_Z)
- Vertical force full scale of 1000 N (F_Z)
- Resolution of 1N for the vertical force (F_Z)
- Resolution of 0.01 Nm for the torque (M_Z)

These sensors are only available in the test facility while, on the comet, the only available measurements will be related to the position of the drill bit which is automatically recorded by SD2's software. Therefore it is highly important to precisely estimate the level of force applied to the drill in order to avoid damage which could jeopardize the success of the mission.

Since the spare model of SD2 was designed to work in space, some modifications were made to operate in a terrestrial environment. For example, the motor-transmission unit was characterized by a dry lubrication unsuitable for the conditions inside the laboratory.

1.3 Operating SD2

The main unit responsible to operate SD2 as well as all the other experiments on board Philae is the CDMS (Command Data and Management System; see Chapter 1.1). All the commands required by the CDMS to guarantee the achievement of every goal during each phase must be generated on Earth and then sent to the lander or they can be previously uploaded inside the onboard computer and then activated from Earth.

The procedure to send the instructions from the test facility at the Politecnico di Milano to Philae is the following:

1. The list of commands is sent from the DAST test facility to the Science Operation and Navigation Centre (SONC) located in France.
2. After testing, SONC, sends the commands to the Rosetta Science Operations Centre in Germany.
3. RSOC provides for the link to the space segment through the ground station.
4. After the command's execution, the opposite path is followed by the resulting telemetry data.
5. Telemetry data are checked at the DAST test facility.

CDMS communicates only "word by word". Each word is made of 16 bits producing a four digits hexadecimal number. The structure of the specific commands which allow SD2 to complete every task is made of a set of words. The first one of them is the address of the reference unit for the CDMS and the

others are specific parameters, with the exception of the final one which is a checksum. Table 4 contains a list of every command required to operate every part of SD2. As an example, some of them contain also the hexadecimal coding [9].

Command	Operation	#of words	Code
ZERO	Perform zero condition and switch all action sections.	3	
ONOF	Switch On/Off the electronic actuation sections.	2	
ACRE	Acquire values of resolvers.	2	
CAPO	Perform carousel rotation.	4	
CASI	Move an oven to a scientific port.	4	
DRTR	Perform drill translation.	3	
DRGO	Perform drill rotation.	3	
DRST	Perform drill rotation stop.	2	3955 3955
MVCK	Move volume checker.	3	
VCAC	Activate volume checker.	4	
ABRT	Abort command.	2	5122 5122
EMST	Emergency stop.	2	5F66 5F66
EHEN	Enable/Disable error handling procedure.	2	
SARE	Release sampling tube.	2	6BB8 6BB8
RDAD	Read the contents of a specific board address and put it into a scien_dat.	3	
WRAD	Write the specified word in the specified address.	4	
ENEM	End of emergency.	2	8366 8366
MHIT	Manage HIBT acquisition.	2	
LDMP	Load a SD2 command sequence from CDMS memory to SD2 internal buffer.	6	
STARTOP	Notify that the specific command is starting.	2	
STOPOP	Notify that the specific command has been completed.	2	

Command	Operation	#of words	Code
DELAY	Perform the required delay before executing the next operation.	3	
LANDG	Load the data relevant to the landing gear.	10	
DRTT	Perform drill translation with timeout.	4	
DRTC	Check drill translation, main or redundant.	4	

Table 4 - Complete list of commands to control SD2 [9].

These commands can be divided in two categories: normal commands, which are executed when the sequence of activated operations is finished, and instantaneous commands which are executed in the same moment when they are sent. This second category contains DRST, ABRT, EMST, SARE and ENEM, which are also the ones with the hexadecimal code next to their descriptions. On the other hand, the number of words for the normal commands depends on the specific inputs for each specific operation [9].

A list of commands, appropriately listed to permit the system to achieve a specific goal is called **Mission Plan**. When different mission plans are gathered to complete a set of operations in a given order, a **Mission Program** is obtained [9].

In order to easily assemble all the different commands into Mission Plans and to keep an eye on the time required for each operation and its energy consumption, a software tool has been developed and tested in this work. A detailed description of this tool can be found in the next chapter [9].

Chapter 2

The Mission Plan Generator

Created using the Guide function of Matlab, the Mission Plan Generator is a program which gives the user the possibility to build a new personalized Mission Plan from scratches or to use previously saved Mission Plans to generate a Mission Program. Once the Mission Program is created, the program automatically produces two tables: one with the power and memory consumption for each operation and one with the data concerning the overall mission plans. These data output can also, if requested, be saved as Excel tables. For this reason it is important to point out that Matlab works with an American format for numbers while Excel follows the system setups. Therefore, in case an Excel table is required, it is highly suggested to check the system settings before launching the program.

2.1 Get started

The Mission Plan Generator is a Matlab based software tool, therefore, it can only be operated using Matlab.
To get started, these steps must be followed:

1. Download the Mission Plan Generator folder on your hard drive.
2. Open Matlab.
3. Go to File --> Set Path...
4. Click on the Add Folder... button.
5. Find and select the MPG_Matlab folder then press OK.
6. Save the new path and close the window.
7. Type "Mission_Plan_Generator" in the Matlab Command Window.
8. Press ENTER.

Once the main window appears, the user can select a folder where the files will be saved by clicking on the "Browse" button or leave the default Matlab directory as it is.
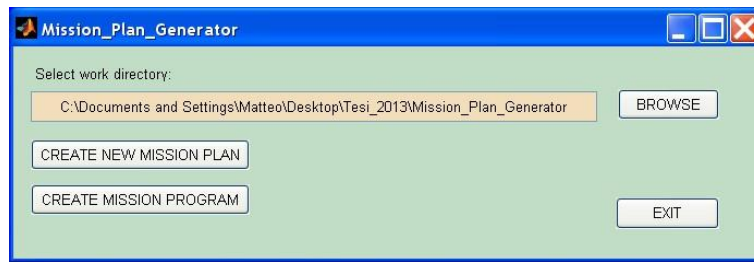
Figure 5 - Mission Plan Generator main window.

At this point, from the window displayed in Figure 5, it is possible to select one of the two options identified by the two buttons on the left: Create a new Mission Plan or Create a Mission Program.

2.2 Create a new mission plan

If the option "Create a new Mission Plan" was chosen, a new window is presented to the user (see Figure 6). From here it is possible to create a new Mission Plan selecting from the scroll down menu, one by one the single operations which must be performed.
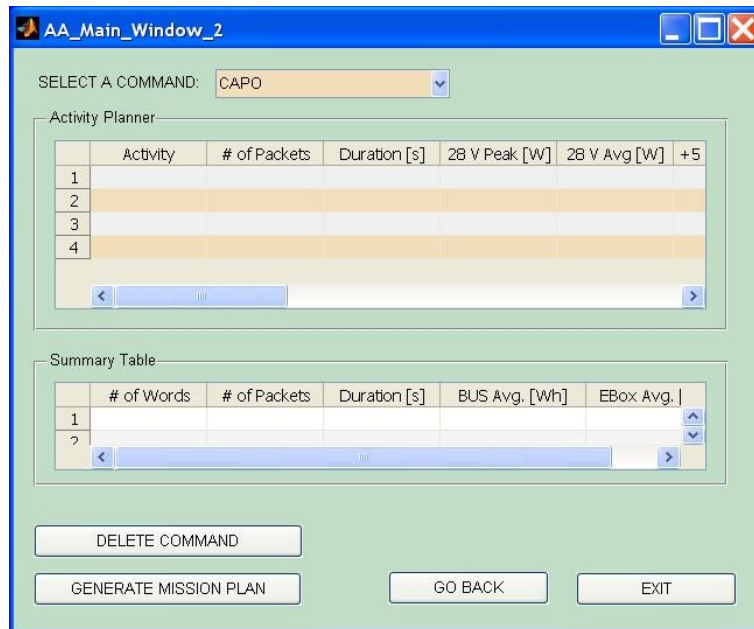
Figure 6 - Create a new mission plan window.

As visible in Figure 6, there are two tables. The first one is the Activity Planner, it has 15 columns and it contains all the values of power and energy consumption needed for each operation as well as the time required to complete them and the number of data packets produced. This value, unlike all the other entries, is not displayed for every command but it appears only when the command MHIT is called to download the scientific results on the hard drive (see Chapter 2.3). The second table, called Summary Table, contains the overall values for the mission plan and is constantly updated when a new command is added. On this table, the only new parameter is the number of words, which represents the amount of space on the TC Buffer required to contain the whole mission plan.

If any mistake was made in the process or if some parameters were set to the wrong value, it is always possible to delete the last introduced operation using the "Delete Command" button.

As introduced in Chapter 1.3, in order to operate SD2, there is a wide list of commands that can be used. Since only a limited number of operations were considered, it was decided, for this version of the Mission Plan Generator, to make a selection of the most relevant ones. The list of the available commands can be seen in Table 5.

Command	Operation
CAPO	Perform carousel rotation to a defined position
DELAY	Perform the requested delay
DRGO	Perform drill rotation for a defined time
DRST	Stop drill rotation
DRTC	Perform drill translation to a defined position
EHEN	Enable/disable error handling procedure
LANDG	Load data relevant to the landing gear
MHIT	Manage HITB acquisition
ONOF	Switch On/Off electronic actuation sections
SARE	Release sampling tube
STARTOP	Notify that the specified operation is starting
STOPOP	Notify that the specified operation has been completed

Table 5 - Available commands.

For most of them it is possible to set specific parameters which become available in a new window once it gets selected. When the choices are confirmed, the command will automatically appear in the first empty line of the Activity Planner table.

2.3 Specific Command Parameters

Before moving on to see how to save a Mission Plan and how to create a Mission Program, it is important to see for each available command which parameters can be set and how these choices may affect the rest of the activities.

CAPO
This command controls the rotation of the carousel containing the ovens and, when activated, it places a specific oven under the drill or under one of the instruments.

The control window for this command is shown in Figure 7.
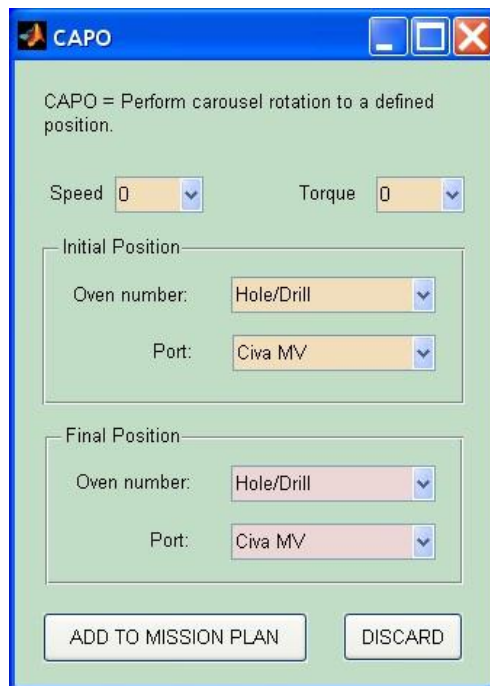
Figure 7 - CAPO control window.

From the window displayed in Figure 7, it is possible to select the rotation speed of the carousel (from 0 up to 31), the torque applied (from 0 up to 7), the initial position and the final position. The starting and finishing point of the rotation are set by selecting which oven is currently under which instrument and where a certain oven must be placed after the rotation. The direction of the rotation is then automatically selected by SD2 to minimize the displacement angle.

In order to have a better idea on how this program works, it is important to have a look on how the ovens and the scientific ports are placed around the carousel.

A schematic representation of the carousel including the number of each oven and the location of the scientific instruments can be seen in Figure 8. This representation is also the reference to the angular position of each oven and instrument in Table 6.
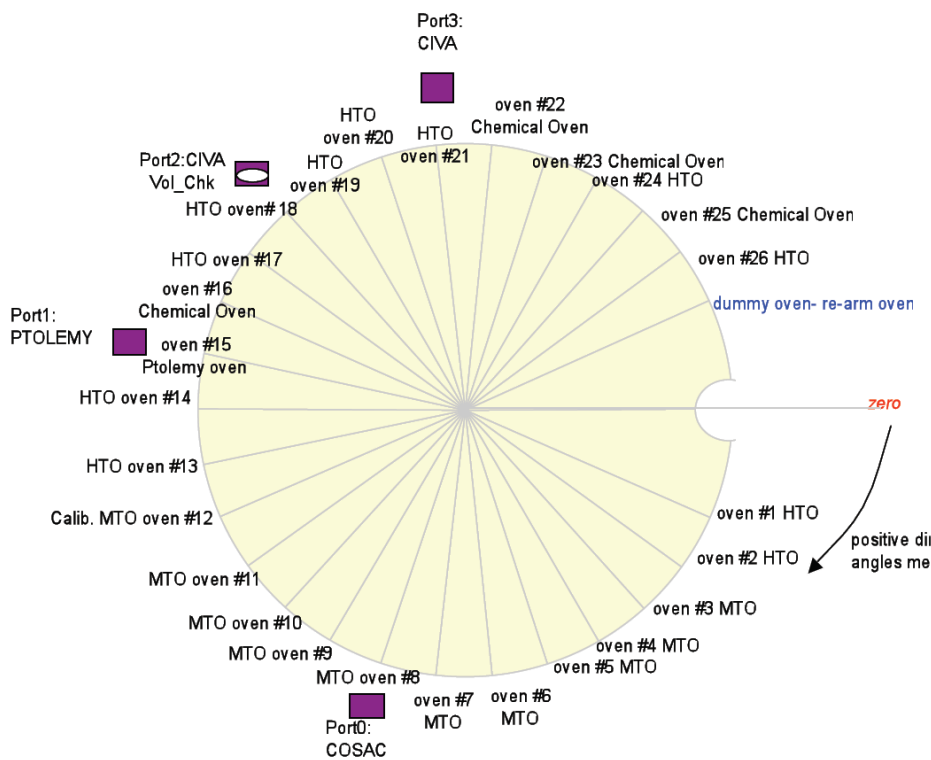
Figure 8 - Distribution of ovens and scientific ports around the carousel.

When a certain combination of oven and scientific port is selected from the window displayed in Figure 7, theangular position is automatically computed by the software using Table 6.

Oven	ÇIVA MV [arcmin]	ÇIVA MI [arcmin]	PTOLEMY [arcmin]	COSAC Main [arcmin]	COSAC Side [arcmin]	Volume Checker [arcmin]	Under drill [arcmin]
Number	[arcmin]	[arcmin]	[arcmin]	[arcmin]	[arcmin]	[arcmin]	[arcmin]
hole/drill	13680	15840	11520	6480	7200	13680	0
1	12240	14400	10080	5040	5760	12240	20160
2	11520	13680	9360	4320	5040	11520	19440
3	10800	12960	8640	3600	4320	10800	18720
...	...	...	...	...	...	...	...
24	17280	19440	15120	10080	10800	17280	3600
25	16560	18720	14400	9360	10080	16560	2880
26	15840	18000	13680	8640	9360	15840	2160
Dummy oven	15120	17280	12960	7920	8640	15120	1440

Table 6 - Carousel position conversion table.

Once the two angles have been determined, it is possible to compute the time required to complete the rotation using the following equation:
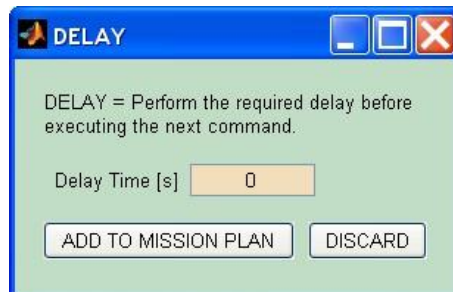
$$t = \frac{|a_{FINAL} - a_{INITIAL}|}{120 \; arcmin/s};$$

Where:

α_{FINAL} = final angular position taken from Table 6.

$\alpha_{INITIAL}$ = initial angular position taken from Table 6.

DELAY

When DELAY is activated, SD2 waits for a given time before executing the next command. The control window for DELAY is the following (see Figure 9):
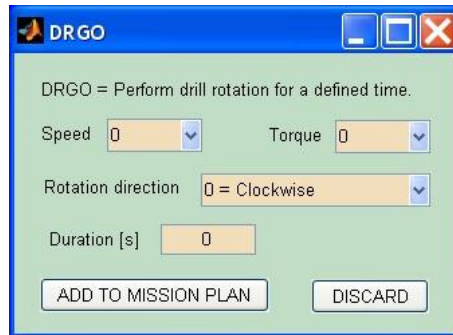

Figure 9 - DELAY control window.

DRGO

This command controls the rotation movement of the drill.There is a major difference between DRGO and all the other commands. In general, the CDMS sends each command only after the previous one is completed. An exception holds for DRGO: the CDMS immediately executes the command following DRGOeven if the drill rotation has not ended. So, if DRGOis followed by DELAY, the drill performs a pure rotation for a given time; alternatively, if the following command is DRTC, it performs a roto translation. The rotation can be stopped using the DRST command.

The control window for DRGO is reported in Figure 10.

Figure 10 - DRGO control window.

As it can be seen from Figure 10, the controls are very simple. The speed level can be set from 0 up to 31 while the torque level goes from 0 up to 7. For what concerns the duration, even if it hasn't been set any control system, it cannot exceed 18.2 hours (65520 s).

For the rotation of the drill, as well as for the translation movement, the power consumption related to the 28 V line is a function of the torque level. The values for torque level 4 and torque level 7 were available from experimental activity. Using these value it was possible to do a linear interpolation to extrapolate SD2 power consumption for each torquelevel, as illustrated in Figure 11.
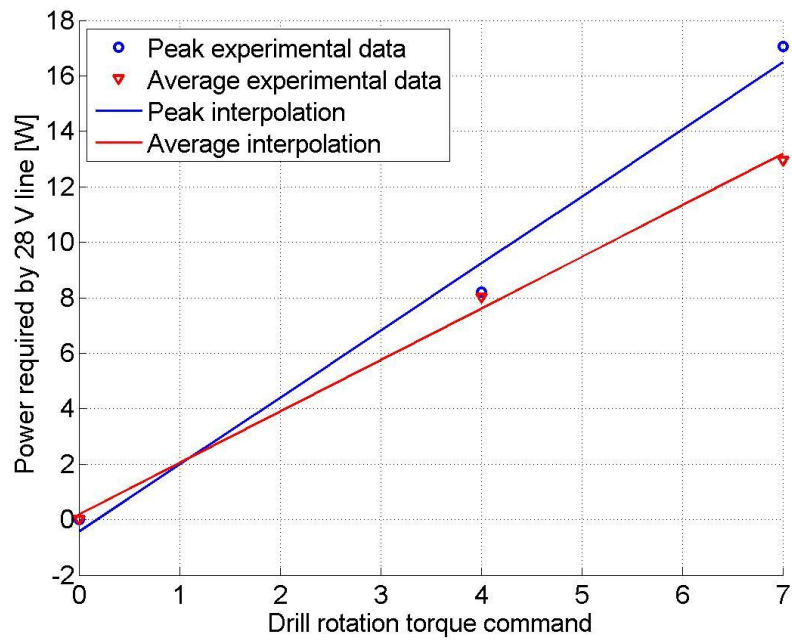
Figure 11 - Power vs.torque function for rotation command.

DRST

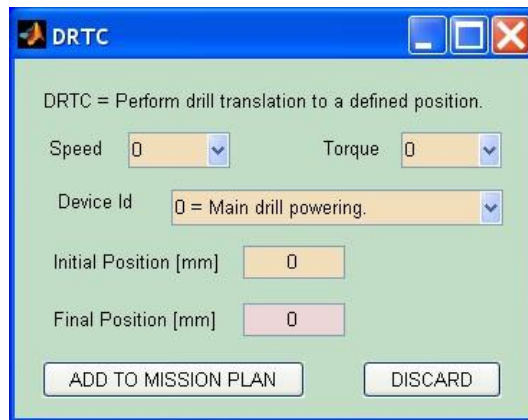This command stops the rotation movement of the drill. The control window is the following (see Figure 12).
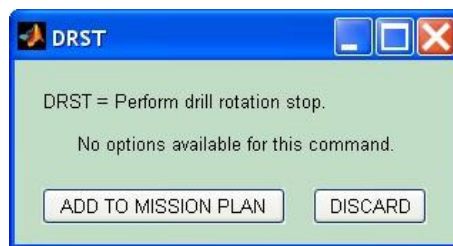

Figure 12 - DRST control window.

DRTC

This command controls the translation movement of the drill. Its control window is shown in Figure 13.

Figure 13 - DRTC control window.

Like the other commands, the translation speed is discretized into 32 finite values from 0 up to 31. In order to precisely compute the duration of this operation, a numerical function relating the speed level to the actual velocity has been found. This was done by using a linear interpolation of the experimental results. Since there were problems due to the high level of noise at low speed levels, two different equations were used: one for values up to 12 and a second one for values for values from 13 up to 31. The result is represented in Figure 14.
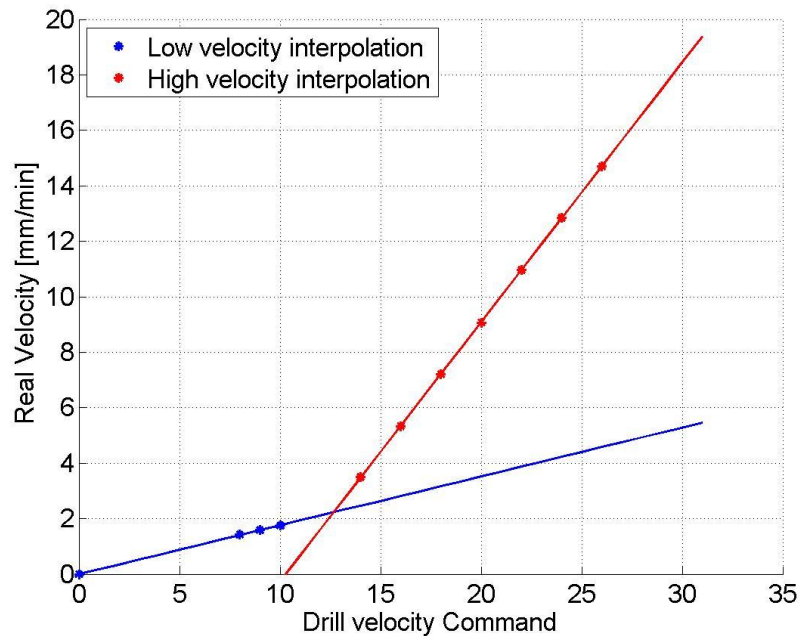
Figure 14 - Drill translation velocity interpolation.

For the actuation of this command, only the final position is required by SD2. The initial position must be selected to have the correct value of duration displayed on the Activity Planner table. Due to the physical limitations of SD2, the maximum value accepted is 625 mm.

A similar interpolation procedure was also followed to compute the power consumption of the 28 V line starting from the experimental results from the actual flight model of SD2. The resultsare reported in Figure 15.
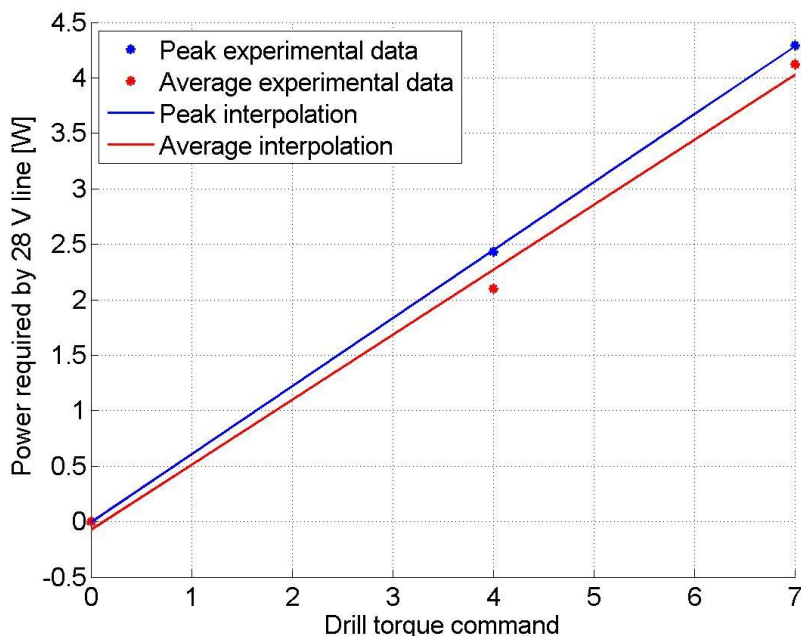

Figure 15 - Power to torque function for translation command.

EHEN
This command enables or disables the recovery procedures related to the currently detected error.
When selected, the control window is the following (see Figure 16).

Figure 16 - EHEN control window.

When the Drill translation check is enabled and an error is detected, SD2 switches from the main to the redundant winding and then, if it fails again, it turns on both the windings.

The other two options give the possibility to enable an abort procedure. In case of a Soft Emergency, SD2 turns off the motion drives with a steep ramp down motion, all the electronic interfaces and enters in DEAD mode. The hard recovery is very similar but it turns everything off without any transient.

LANDG

LANDG allows the loading of the data relevant to the landing gear: the range of the areas which are forbidden for the drilling activity and the index of the landing gear housekeepingdata containing its position.The control window for LANDG is reported in Figure 17.
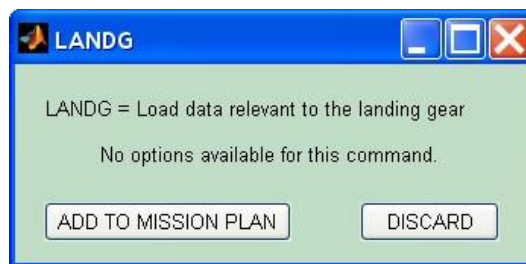
Figure 17 - LANDGcontrol window.

MHIT

This command can be used to either activate the dumping of the scientific data or to change the value of the acquisition frequency.The control window is the illustrated in Figure 18.
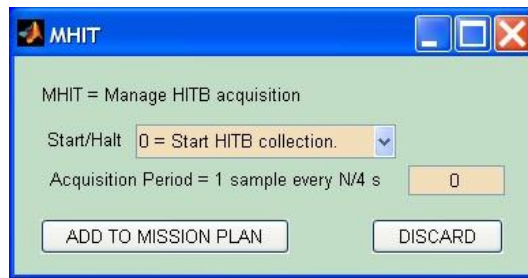
Figure 18 - MHIT control window.

In order to activate the dumping the scientific data, the Start/Halt value must be set to zero and, since the acquisition period will not be considered during the operation, it can be set to any value.

If this option has been chosen, the number of packets will be computed and displayed on the Activity Planner table. This value is computed taking into account the time required to complete all the operations between two scientific dumping commands without taking into account the duration of the download of the data (default value set equal to 130 s).

In particular the number of packets is equal to:

$$n_p = \frac{1}{4}\left(\frac{t}{T_A}\right);$$

Where t is the time required to complete the operations and T_A is the acquisition period.

This value can be manually set by selecting the second Start/Halt option available and typing the number in the box below. In particular, if the number is *N*, SD2 will take a sample every *N*/4 seconds. If the acquisition period is left untouched, the default value is 1 sample every 4 seconds, which corresponds to a value of N equal to 16.

Finally, it is important to point out that the acquisition frequency, will not automatically change to the default value after the scientific dumping but it must be manually set every time it is required.

ONOF

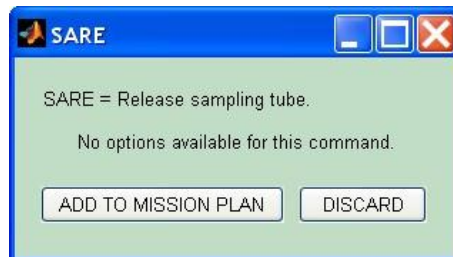This command switches on or off the actuation systems from SD2 electronic instrument board.

All the available options can be selected from the control window reported in Figure 19.
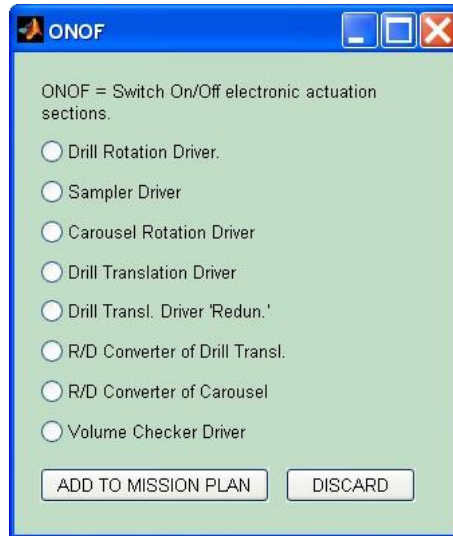
Figure19 - ONOF control window.

SARE

When SARE is activated, the sampling tube is released.

Figure20 - SARE control window.

Once the sampling tube has been released, there is no direct command to put it back into its initial position. In the test facility this can be done manually using a specially designed tool. Otherwise there is a specific sequence of operations which must be followed. This set of commands is contained into a specific

mission plan called "Drill Bit Rearming" which will be among the test examples in the following of this chapter.

STARTOP

STARTOP notifies that the following command is related to a complex operation, which can be either the motion of the drill or the movement of the carousel.The control window is reported in Figure 21.
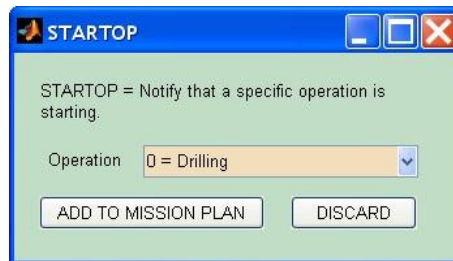
**Figure21 - STARTOP control window.**

STOPOP

This command notifies that a complex operation has been completed. If it follows either a drilling, sampling or a carousel rotation, the SD2 status is updated accordingly.These options can be selected from the control window illustrated in Figure 22.
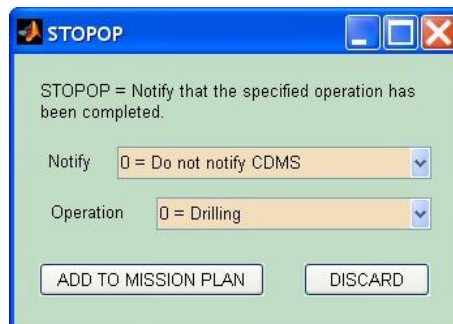
Figure22 - STOPOP control window.

2.4 Save a Mission Plan

Once a mission plan contains all the desired commands, it is possible to save it by clicking on the "Generate Mission Plan"button (see Figure 6),which activates the window reported in Figure 23.
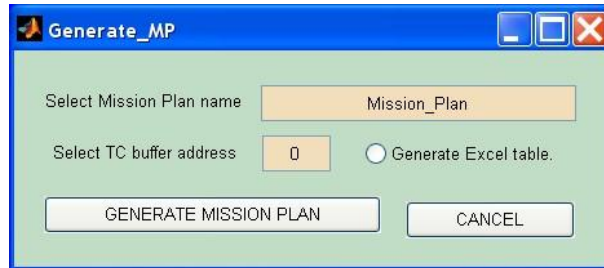

Figure 23 - Generate mission plan window.

From this windowthe user can select a name for the new mission plan and the location on the TC Buffer,between 0 and 512,where the first instruction must be saved.

When the "Generate mission plan" button is pressed, the program generates two text files: one containing all the instructions which can be directly converted into hexadecimal and sent to SD2 and one containing all the data from the Activity Planner table. These two files have similar names with the difference that the second one contains the word "Overall" in it.

Also, if required, it is possible to have a third file which is an Excel version of the Activity Planner table.As it was mentioned before, it is important to check the system settings to make sure that the format for numbers is set to the American one, which is the format used by Matlab.

2.5Create a Mission Program

From the initial window (see Figure 5), when the option "Create a Mission Program" is chosen, a new window is presented to the user. From here it is possible to recall previously saved mission plans to create a Mission Program.
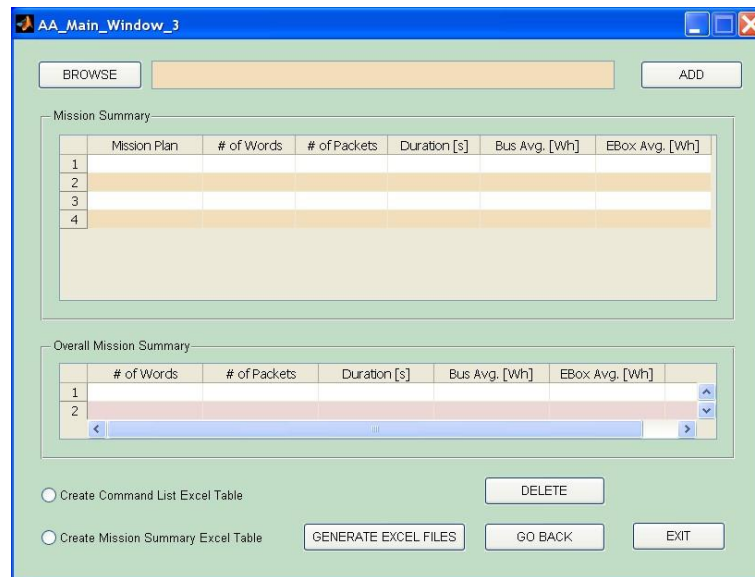
Figure 24 - Create a new mission program window.

In order to correctly operate the program, the user must select only the text files containing the operations for SD2. These files can be easily distinguished because they don't have the word "Overall" at the end. Once a mission plan is selected, its name is displayed above the first table to help the user to double check that he made the right selection. In case of a mistake, like during the creation of the mission plans, it is always possible to delete the last introduced line using the "Delete" button.

As it can be seen from Figure 24, this window also contains two tables. The first one is the Mission Summary and it is very similar to the Summary Table introduced in the previous chapter with the addition of a column containing the name of the mission plan. Also the second table, the Overall Mission Summary, has very similar features but it contains the sum of the values of each mission plan.

Unlike during the creation of a mission plan, in the end, no output file is automatically saved but it is up to the user to decide whether to keep the data storedor just discard them. In the first case, it is possible to select which Excel table will be generated.

The Command List Excel Table is a much bigger version of the Activity Planner introduced earlier and it includes, for each mission plan, all the commands and the specific time and energy consumptions. On the other hand, the Mission Summary Table, as its name suggests, is an Excel version of the Mission Summary. These files, if selected are automatically saved when the "Generate Excel Files" is pressed.

Again, to avoid wrong results displayed in the Excel file, it is important to check the system settings to make sure that the format for numbers is set to the American one, which is the format used by Matlab.

2.6 Practical example

Before entering in detail on how the Mission Plan Generator was used, it is important to introduce the concept of Elementary and Specific Mission Plans.
As it can be seen from the Table 7, sampling activitiesare made of a list of actions which can be aggregated according to their functions. These groups are called "Elementary Mission Plans".

Step	Action	Elementary Mission Plan
1	Carousel rotation to put the rearming oven under the drill.	Drill Bit Rearming
2	Translation of the drill to rearm the drill bit.	
3	Translation to return to the initial position.	
4	Carousel rotation to get back to the initial position.	
5	Roto-translation of the drill to the specific depth.	
6	Release of the sampling tube.	Sample Retrieval
7	Only rotation for a minute.	
8	Translation to get back to the initial position.	
9	Carousel rotation in order to put the desired oven underthe drill.	
10	Translation to discharge in to the oven.	Oven Feeding
11	Translation to get back to the 0 position.	
12	Carousel rotation to put the oven on the port of therequired instrument.	

Table 7 - List of operations for a sampling activity [7].

All the operations included into each Elementary Mission Plan are always the same and they do not depend on specific inputs.

On the other hand, from Table 7, it is possible to see that three operations are not included into any of the Elementary Mission Plans. The first one (Step 5) is a roto-translation to a given position while the other two (Step 9 and Step 12) are rotations of the carousel needed to place a certain oven in a given position. These three operations are very different from each other but they all have in common that they need very specific inputs to be executed. For this reason they are called "Specific Mission Plans" [7].

Now, in order to better understand how the Mission Plan Generator works, it is tested in the followings on a real scientific activity: the third sampling operation carried out during the FSS.The goal of this Mission Program is to retrieve a sample from a depth of 500 mm and to deliver it to three different scientific instruments [7]. Therefore it will contain all the following operations.

1. Rotation of the carousel to place the rearming oven under the drill;
2. Downward and upward translation of the drill to rearm the drill bit;
3. Rotation of the carousel to place the hole under the drill;
4. Downward roto translation to 500 mm;
5. Upward translation of 1 mm;
6. Release of the sampling tube;
7. Rotation of the drill for 1 minute;
8. Translation of the drill to the initial position;
9. Rotation of the carousel to place Oven 3 under ÇIVA MV for calibration;
10. Rotation of the carousel to place Oven 3 under the drill;
11. Downward and upward translation of the drill to place the sample in Oven 3;
12. Rotation of the carousel to place Oven 3 under ÇIVA MV;
13. Rotation of the carousel to place Oven 3 under ÇIVA MI;
14. Rotation of the carousel to place Oven 3 under COSAC MAIN;

Drill Bit Rearming

This Elementary Mission Plan contains the operations to rearm the Drill bit and to prepare SD2 for the sampling procedure. Since SD2 is now flying with the drill bit in the unarmed position, this will be the very first block of activities carried on by SD2 during the First Scientific Sequence. This procedure must also be repeated before starting any new drilling procedure.
The elementary block involves the following activities:

1. Rotation of the carousel to place the rearming oven under the drill.

	Activity	# of Packets	Duration [s]	28 V Peak [W]	28 V Avg [W]	+5 V
1	STARTOP	---------------------	1	0.200	0.200	1.080
2	MHIT	---------------------	1	0.200	0.200	1.080
3	CAPO	---------------------	12.0	4.690	4.580	1.130
4	CAPO	---------------------	1.0	4.690	4.580	1.130
5	ONOF	---------------------	1	0.200	0.200	1.080
6	DELAY	---------------------	1.0	0.200	0.200	1.110
7	ONOF	---------------------	1	0.200	0.200	1.080
8	MHIT	---------------------	1	0.200	0.200	1.080
9	MHIT	10	130	0.200	0.200	1.080
10	STOPOP	---------------------	1	0.200	0.200	1.080

Summary Table

|	# of Words	# of Packets	Duration [s]	BUS Avg. [Wh]	EBox Avg. [Wh]
1	25	10	150	0.051	0.225

Figure 25 - Drill Bit Rearming part 1.

In this mission plan (see Figure 24) as well as in all the mission plans where a carousel rotation is introduced, in order to have a higher level of precision, the command CAPO is repeated twice.

The command list is the following:

```
[MISSION PLAN]   0
STARTOP 2
MHIT 1 2
CAPO 9 7 1440 480
CAPO 9 7 1440 480
ONOF 0 1 1 0 0000
DELAY 4
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 2
```

2. Translation of the drill downward and upward
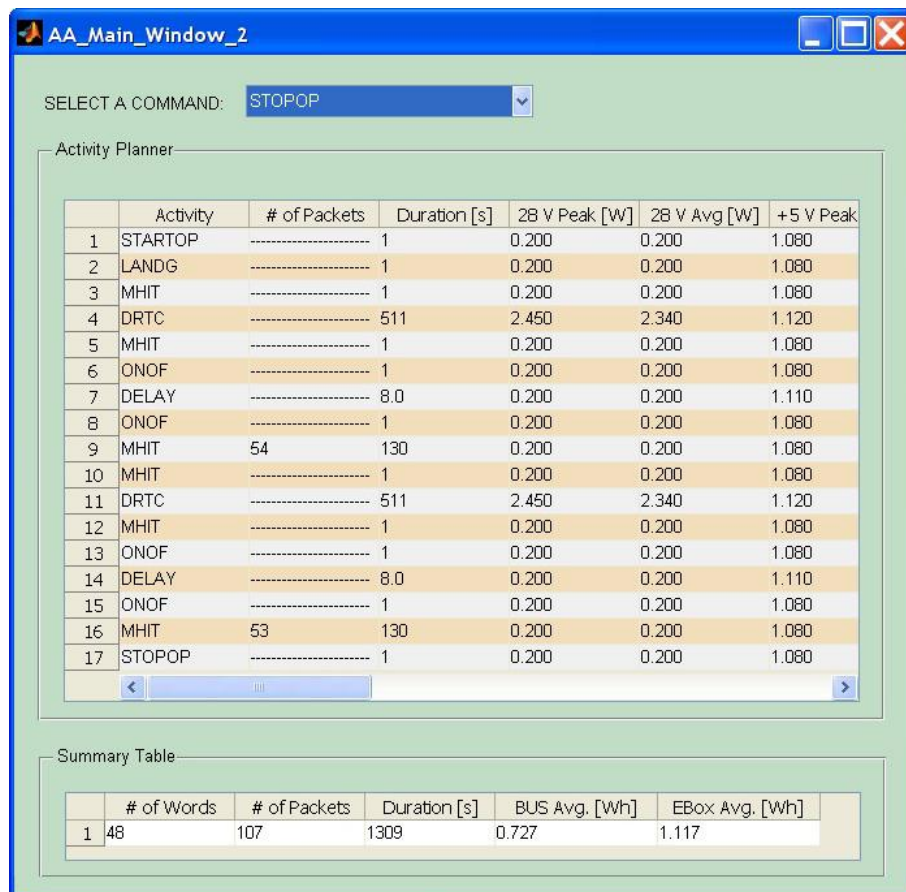
Figure26 - Drill Bit Rearming part 2.

The command list is the following.

```
[MISSION PLAN]    25
STARTOP 0
LANDG 0 101 105 301 400 2001 3000 20001 20100
MHIT 1 10
DRTC 10 4 0 1500
MHIT 1 16
ONOF 0 1 1 0 0000
DELAY 32
ONOF 0 0000000
MHIT 0 0
MHIT 1 10
DRTC 10 4 0 0
MHIT 1 16
ONOF 0 1 1 0 0000
DELAY 32
ONOF 0 0000000
MHIT 0 0
STOPOP 1 0
```

3. Rotation of the carousel to place the hole under the drill.
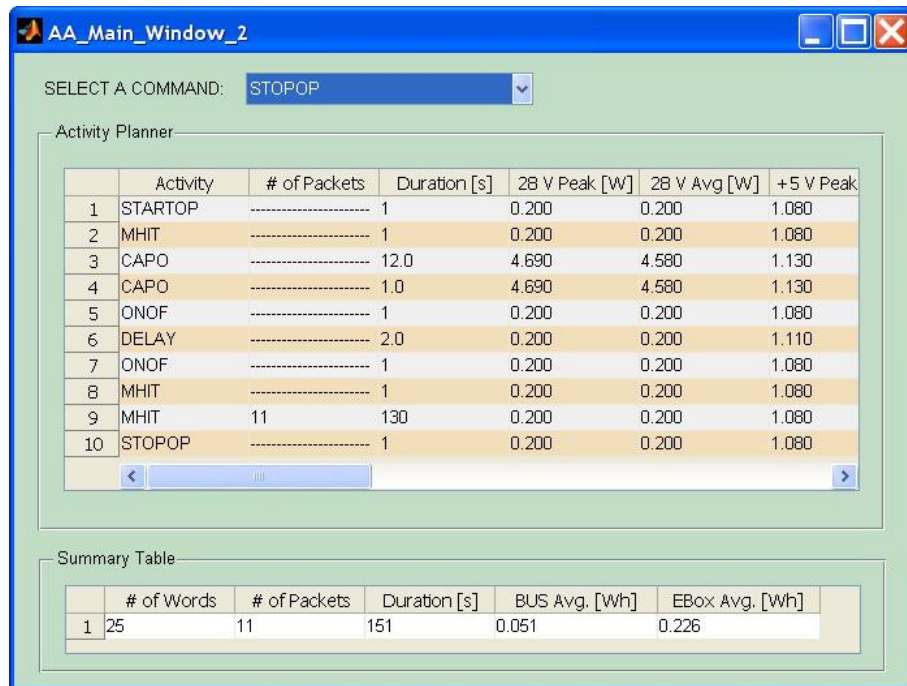
Figure 27 - Drill Bit Rearming part 3.

The command list is the following.

```
[MISSION PLAN]    74
STARTOP 2
MHIT 1 2
CAPO 9 7 0 480
CAPO 0 00 480
ONOF 0 1 1 0 0000
DELAY 8
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 2
```

Specific Mission Plan: Roto-Translation

The first part of this Specific Mission Plan contains all the operations to roto-translate the drill inside the comet for a depth of 500 mm.

Figure 28 - Specific Mission Plan: roto translation.

The command list is the following.

```
[MISSION PLAN]    100
STARTOP 0
LANDG 0 101 105 301 400 2001 3000 20001 20100
MHIT 1 72
DRGO 15 4 0 65520
DRTC 18 4 0 50000
DRST
MHIT 1 16
ONOF 0 1 1 0 0000
DELAY 32
ONOF 0 0000000
MHIT 0 0
STOPOP 0 0
STARTOP 1
MHIT 1 2
DRTC 18 4 0 49900
ONOF 0 1 1 0 0000
DELAY 4
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 1
```

Sample Retrieval

This Elementary Mission plan contains all the operations required to retrieve the comet sample after the drilling activity.
The elementary block involves the extraction of the sampling tube and the translation of the drill back to the home position.

	Activity	# of Packets	Duration [s]	28 V Peak [W]	28 V Avg [W]	+5 V Peak
1	STARTOP	----------------------	1	0.200	0.200	1.080
2	LANDG	----------------------	1	0.200	0.200	1.080
3	MHIT	----------------------	1	0.200	0.200	1.080
4	SARE	----------------------	1	0.200	0.200	1.080
5	DRGO	----------------------	1	0.200	0.200	1.080
6	DELAY	----------------------	66.0	9.229	7.602	1.060
7	MHIT	----------------------	1	0.200	0.200	1.080
8	DRTC	----------------------	2334	2.450	2.340	1.120
9	MHIT	----------------------	1	0.200	0.200	1.080
10	ONOF	----------------------	1	0.200	0.200	1.080
11	DELAY	----------------------	8.0	0.200	0.200	1.110
12	ONOF	----------------------	1	0.200	0.200	1.080
13	MHIT	48	130	0.200	0.200	1.080
14	STOPOP	----------------------	1	0.200	0.200	1.080

Summary Table

	# of Words	# of Packets	Duration [s]	BUS Avg. [Wh]	EBox Avg. [Wh]
1	42	48	2548	1.713	2.012

Figure 29 - Sample Retrieval.

The command list is the following.

```
[MISSION PLAN]    159
STARTOP 1
LANDG 0 101 105 301 400 2001 3000 20001 20100
MHIT 1 40
SARE
DRGO 15 4 0 60
DELAY 264
MHIT 1 54
DRTC 24 4 0 0
```

```
MHIT 1 16
ONOF 0 1 1 0 0000
DELAY 32
ONOF 0 0000000
MHIT 0 0
STOPOP 1 1
```

Specific Mission Plan: 1st carousel rotation activity

The second part of this Specific Mission Plan is divided into the following activities.

1. Rotation of the carousel to place Oven 3 under ÇIVA MV for calibration.
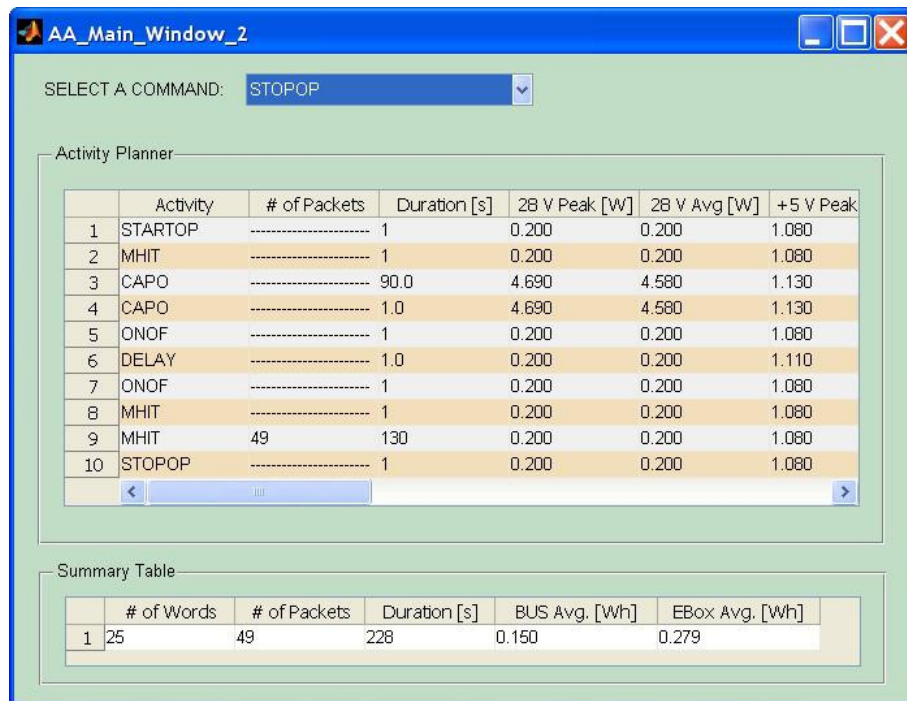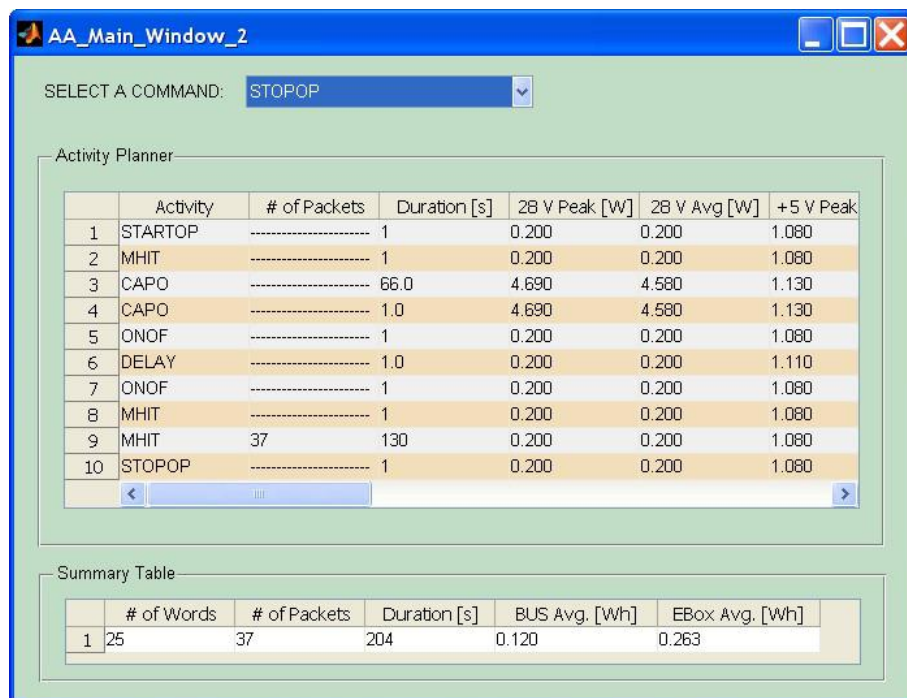

Figure 30 - Specific Mission Plan: 1st carousel rotation part 1.

The command list is the following.

```
[MISSION PLAN]    202
STARTOP 2
MHIT 1 2
CAPO 9 7 10800 480
CAPO 9 7 10800 480
ONOF 0 1 1 0 0000
DELAY 4
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 2
```

2. Rotation of the carousel to place Oven 3 under the drill.

Figure31 - Specific Mission Plan: 1st carousel rotation part 2.

The command list is the following.

```
[MISSION PLAN]    228
STARTOP 2
MHIT 1 2
CAPO 9 7 18720 480
CAPO 9 7 18720 480
ONOF 0 1 1 0 0000
DELAY 4
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 2
```

Oven Feeding

This Elementary Mission Plan is made of all the operations required to release a sample into an oven.
The elementary block involves the translation downward of the drill to place the sample inside the oven and the translation upward to return to the initial position.

Figure32 - Oven Feeding.

The command list is the following.

```
[MISSION PLAN]    254
STARTOP 0
LANDG 0 101 105 301 400 2001 3000 20001 20100
MHIT 1 7
DRTC 10 4 0 1000
MHIT 1 16
```

```
ONOF 0 1 1 0 0000
DELAY 32
ONOF 0 0000000
MHIT 0 0
MHIT 1 7
DRTC 10 4 0 0
MHIT 1 16
ONOF 0 1 1 0 0000
DELAY 32
ONOF 0 0000000
MHIT 0 0
STOPOP 1 0
```

Specific Mission Plan: 2nd carousel rotation activity

The third part of this Specific Mission Plan is divided into the following activities.

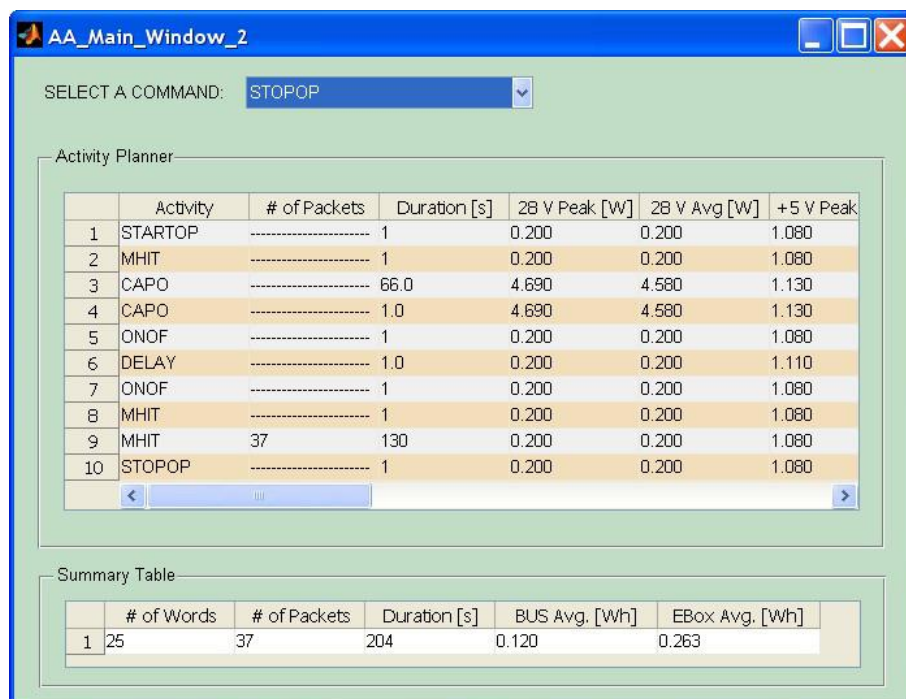1. Rotation of the carousel to place Oven 3 under ÇIVA MV.

Figure 33 - Specific Mission Plan: 2nd carousel rotation part 1.

The command list is the following.

```
[MISSION PLAN]    303
STARTOP 2
MHIT 1 2
CAPO 9 7 10800 480
CAPO 9 7 10800 480
ONOF 0 1 1 0 0000
DELAY 4
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 2
```

2. Rotation of the carousel to place Oven 3 under ÇIVA MI.

Figure 34 - Specific Mission Plan: 2nd carousel rotation part 2.

The command list is the following.

```
[MISSION PLAN]    329
STARTOP 2
MHIT 1 2
CAPO 9 7 12960 480
CAPO 9 7 12960 480
ONOF 0 1 1 0 0000
DELAY 4
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 2
```

3. Rotation of the carousel to place Oven 3 under COSAC Main.
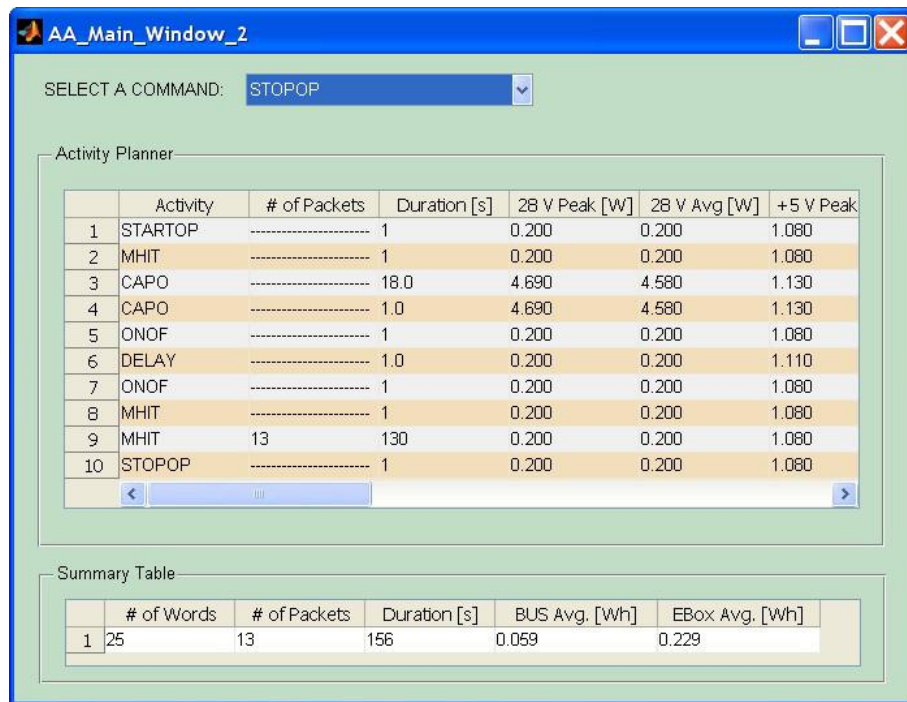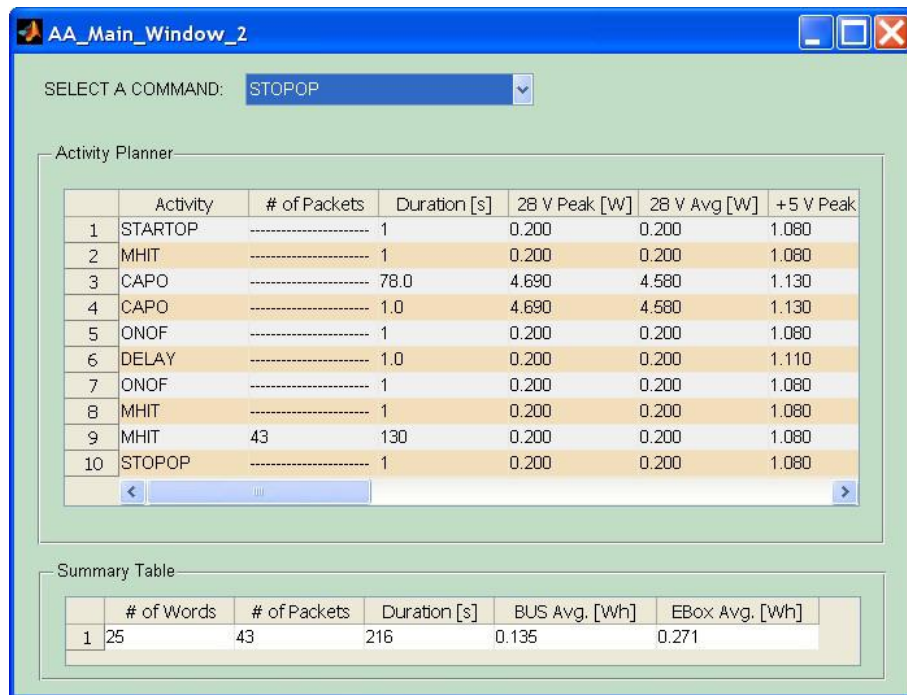

Figure 35 - Specific Mission Plan: 2nd carousel rotation part 3.

The command list is the following.

```
[MISSION PLAN]    355
STARTOP 2
MHIT 1 2
CAPO 9 7 3600 480
CAPO 9 7 3600 480
ONOF 0 1 1 0 0000
DELAY 4
ONOF 0 0000000
MHIT 1 16
MHIT 0 0
STOPOP 1 2
```

Once all the mission plans have been created it is possible to use the second option of the Mission Plan Generator to create the Mission Program.
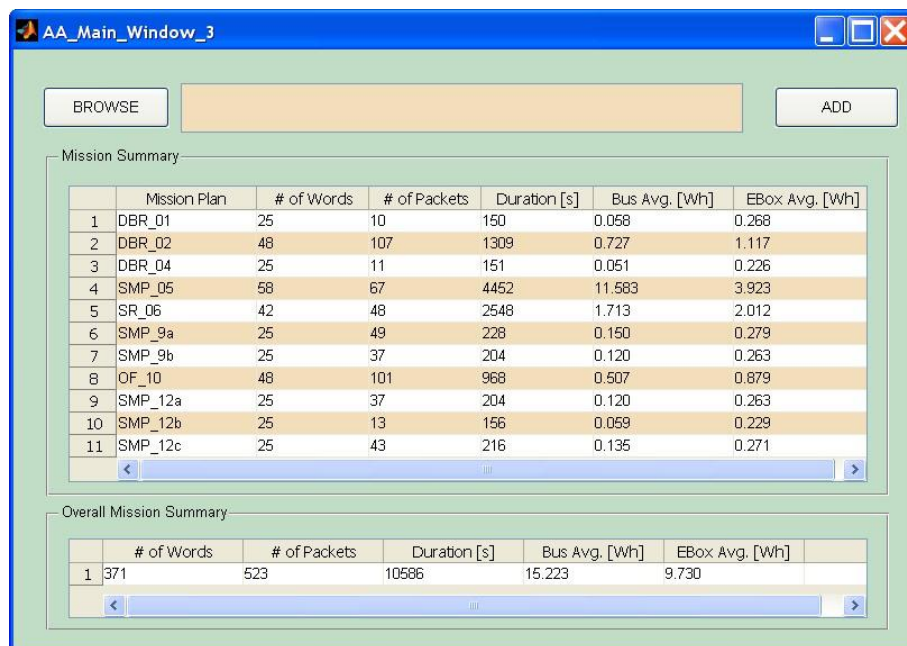
Figure 36 - Mission program for sampling at 500 mm.

From Figure 36 it is possible to see that the most critical mission plan for both the duration and the power consumption is the Specific Mission Plan which contains the roto-translation movement (SMP_05) followed by the Sample Retrieval (SR_06).

In order to demonstrate the versatility of the Mission Plan Generator and to present a possible solution to reduce the amount of energy required to complete this activity, it was decided to make a modification to SMP_05. In particular, the roto-translation from 0 to 500 mm was substituted with two activities: a pure translation from 0 to 380 mm and a roto translation to reach 500 mm. The value 380 mm is the theoretical distance between SD2 and the cometary soil if considered as a flat surface. This value will be evaluated and updated on site.

The new Mission Program for the sampling activity at 500 mm is represented in Figure 37.

Figure 37 - New Mission Program for sampling at 500 mm.

From a comparison between the two Overall Mission Summary tables represented in Figure 36 and Figure 37 it is possible to make the following conclusions:

1. Since the new mission plan contains one more command, the overall number of words has slightly increased from 371 to 375.
2. The duration of the activity did not change because the speed level of the translation was not modified.
3. Since the number of words produced depends only on the duration of the activities and on the acquisition period (see Chapter 2), this value did not change as well.
4. The overall energy consumption decreased from 24.95 Wh to 17.95 Wh, which means a reduction of 28%.

Chapter 3

Scientific use of SD2

Recent studies and experimental activities have proven that there is a relation between the drill behavior during the perforation activities and the mechanical characteristics of the soil. This discovery introduced the possibility to use SD2 not only as a tool to deliver samples to ÇIVA, PTOLEMY, and COSAC but to use it as a scientific instrument itself. For this reason, a precise correlation between SD2 telemetry and the soil characteristic must be identified.

Constraints

- The available telemetry is limited to:
  - (i)   the position of SD2 drill bit (SD2-DB) during the perforation;
  - (ii)   flag for drill failure (the drill gets stuck);
  - (iii) SD2 power consumption.
- Drill rotation and translation are produced by stepper motors: the variation of power consumption cannot be used as an indicator of a variation of the soil characteristics. In fact, a stepper motor works with a fixed current value for each imposed speed value.
- The available energy for the Long Term Science is very limited, thus the number of perforations needs to be minimized.

One of the early ideas for the experimental activity was to develop a database of working zones. Therefore for each combination of translation and rotation speed and torque levels a test had to be made to see if SD2 was able to complete the drilling activity or not. From the constraints above, it is clear that, due to the large number of perforations required, a new experimental strategy had to be developed.

This new concept, which is presented in the following of this chapter, is to use SD2 as a quasi-static penetrator to estimate the resistance of the soil to drill penetration. Therefore, the drill is used to perform only translations to a given depth at increasing values of torque level. The cometary soil penetration

resistance can be then estimated by finding the minimum value of torque levelfor which the translation succeeds.

The advantages of the proposed strategy with respect to the working zone approach are the following:

- As the drill rotation is not used, power and energy consumptions are reduced;
- In the worst case the number of drill movements is limited to 7 (all the possible torque levels), with a further reducing of energy consumption;
- There is no need to rotate the lander as drill movements arealways performed in the same hole and always at the same depth;
- The strategy is independent from drill translation velocity; thus, energy consumption can be reduced by selecting a high value of speed level;
- There is a direct relation between the strategy output and the soil mechanical properties.

On the other hand, this strategy shares the same risk of the working zone approach which is the possibility that, when the translation activity fails, a large force (hundreds of Newton) is transferred back to the lander which could be lifted.

All the laboratory tests carried out to implement this proposed strategy are summarized in the following sections.

3.1 Relation between force and torque

The goal of this first set of tests was to improve the previous experimental results which related the actual force measured by the sensors to the torque levels assigned to the drill at a given speed value.
To do so, the drill was set to translate at constant speed level 20 (0.15 mm/s) towards an iron plate at increasing values of torque. The choice of iron as a test material was made to be sure that the drill got stuck as soon as it hits the surface.
The final set up for these tests can be seen in Figure 38. After the contact,when the force value was stabilized, the data were recorded.

Figure 38 - Iron plate experimental set up.

Due to the high level of force produced with the torque level set to 4 (see Table 7), it was decided to do only one test at this value. The rest of the results, from torque level 5 to 7 were extrapolated from the previous results. Also, to improve the results, the current data were merged with the ones from previous experimental activities.

The results are gathered in the Table 8:

Torque	1st test	2nd test	3rd test	Older tests				Average
1	47.1 N	46.8 N	47.7 N	45 N	47 N	46 N	46 N	46.5 N
2	69.5 N	68.6 N	66.7 N	74 N	74 N	68 N	71.5 N	70.3 N
3	108.7 N	103.5 N	108.4 N	92 N	98 N	99 N	97 N	103.9 N
4	138.6 N						122.5 N	130.6 N

Table 8 - Relation between force and torque at speed level 20.

These data were then processed with Matlab to obtain a linear approximation which best fitted the experimental results. The following function was also used to extrapolate the values of force for torque levels above 4.

$$F = a * T + b = (a \pm 3 * \sigma_a) * T + (b \pm 3 * \sigma_b)$$

Where:
a = 26.27;
b = 20.69 N;
T = torque level;
σ_a = 1.02;
σ_b = 2.00;

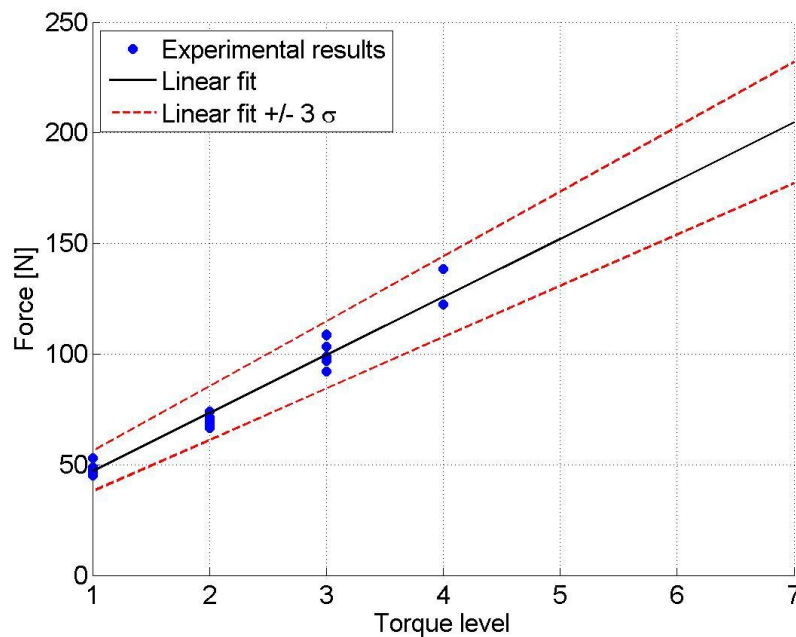The experimental data as well as the linear interpolation were plotted into the graph visible in Figure 39:

Figure 39 - Relation between force and torque at speed level 20.

3.2 Sample materials used in the experimental activity

In order to resemble what is generally believed to be the cometary crust and to achieve good results, the material must be homogeneous, with low density, high porosity, soft enough to be penetrated using low levels of torque and it must not have an elastic behavior. Not many materials match all these characteristics but a good trade off was found using samples made of a glass foam material produced by a Swiss factory called Foamglas. This material, which has many applications in civil engineering as a thermal insulation, has an enclosed cells structure and it is made entirely of recycled glass. The other materials used in the manufacturing process are: feldspars, iron oxide, manganese oxide, carbon black, sulfates of sodium and sodium nitrate [13].

Foamglas produces four types of materials which, according to the data sheets, have the following density and compressive strength.

Material name:	Density [kg/m2]	Compressive strength [MPa]
F+W	100	≥ 0.4
T4+	115	≥ 0.6
S3	130	≥ 0.9
F	165	≥ 1.6

Table 9 - Glass foam materials properties [13].

3.3 Characterization of compressive behavior of sample materials

To better characterize the Foamglas materials and to study the behavior of SD2 drill bit when penetrating these specimens, laboratory tests were performed using the material-testing machine MTS Mini Bionix II.

This machine, shown in Figure 42, is made of a flat fixed surface on the bottom where the sample is placed and a moving hydraulic wedge holding the testing tool on top of it. Since all the tests were made in compression, nothing has been used to hold the sample on the testing plate.

This testing activity was divided in two parts using two different tools.

Experiments using a copy of SD2 drill bit

The first tool used in the experimental activity was an exact copy of SD2 dill bit provided by SelexEs.

Figure 40 - Spare drill bit used for the experiments.

In order to securely clamp the drill bit to the machine, a specific holding device was produced. This tool, after the initial piece required to be connected to the machine, is made of a steel hollow cylinder with an inner diameter equal to the one of the drill bit (12 mm). Any possible movement during the tests was blocked by adding two screws at different positions.
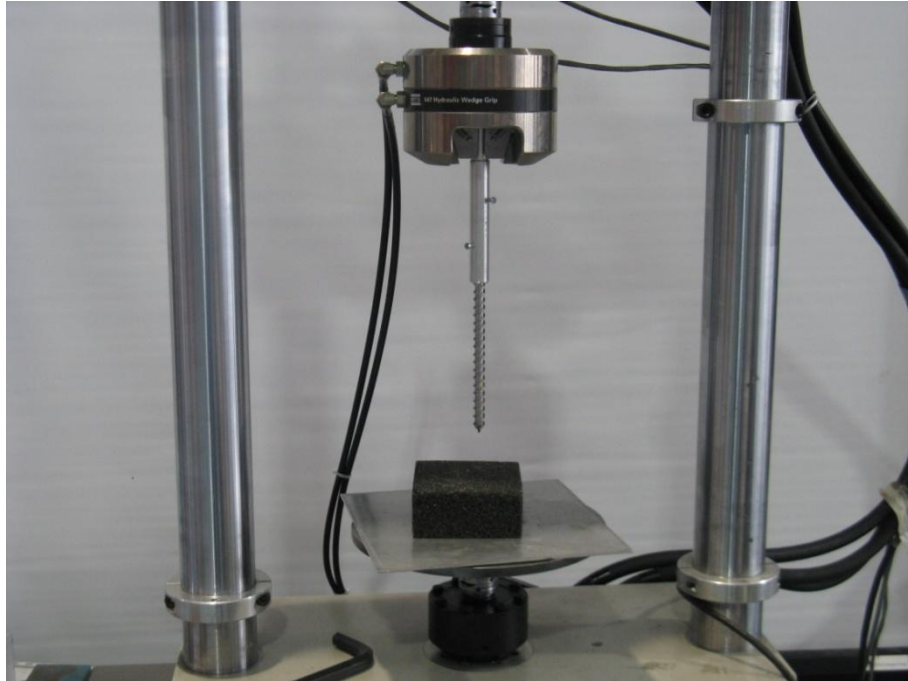
The result can be seen in Figure 41.

Figure 41 - Holding device for the experiment with the spare drill bit.

The final setup for the experiments was the following:

Figure 42 - Set up of the machine.

Using this set up, the machine was programmed to move the drill bit inside the material at a constant speed of 0.15 mm/s which represents SD2 translation speed level 20for a depth of 30 mm recording the values of force produced. This test was done once for each material and then repeated a few times for the two softest ones.

The average results for each sample are plotted in Figure 43 - Figure 46, where polynomial fits of the data are reported too. It's important to point out that the fluctuations of forces are due to the crushing of material's cell walls produced by the tool's advancement.
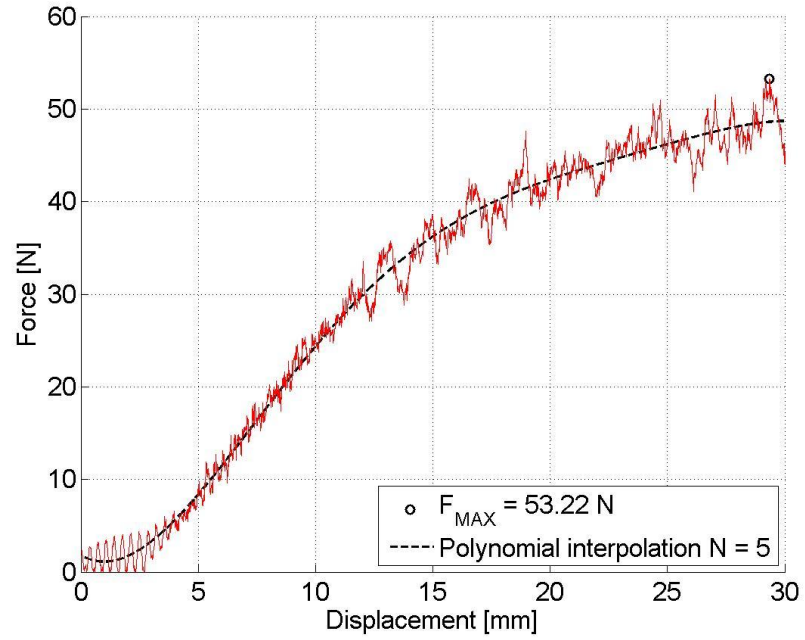
Figure 43 – Average penetration test result for W+F material using the spare drill bit.
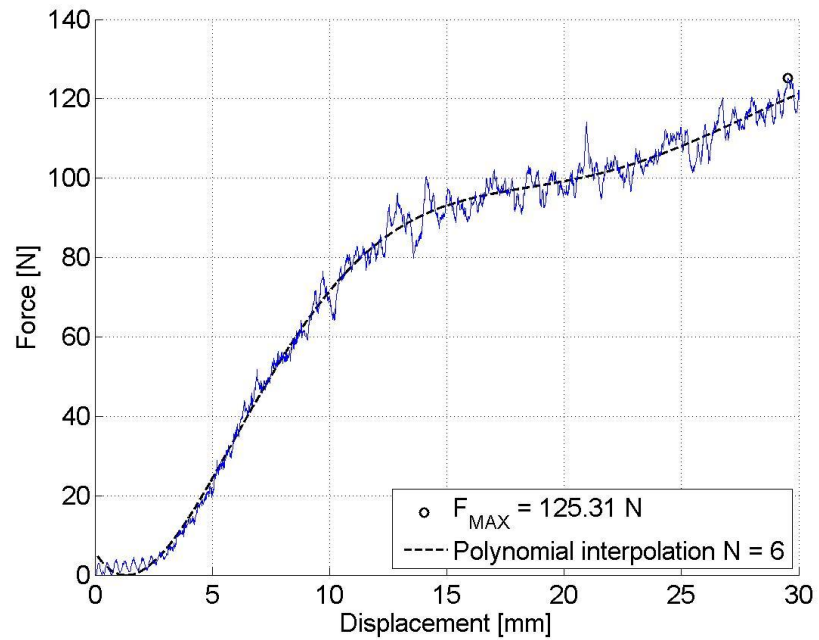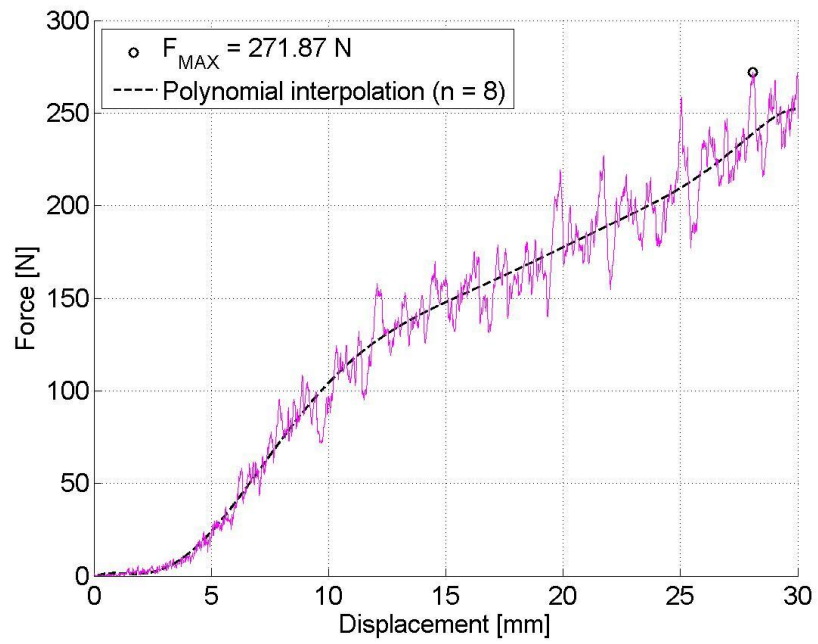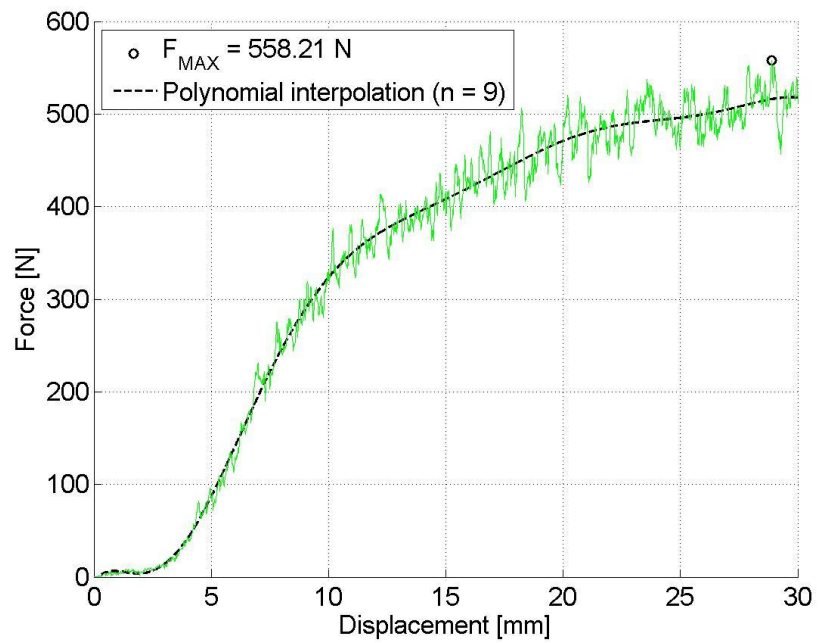

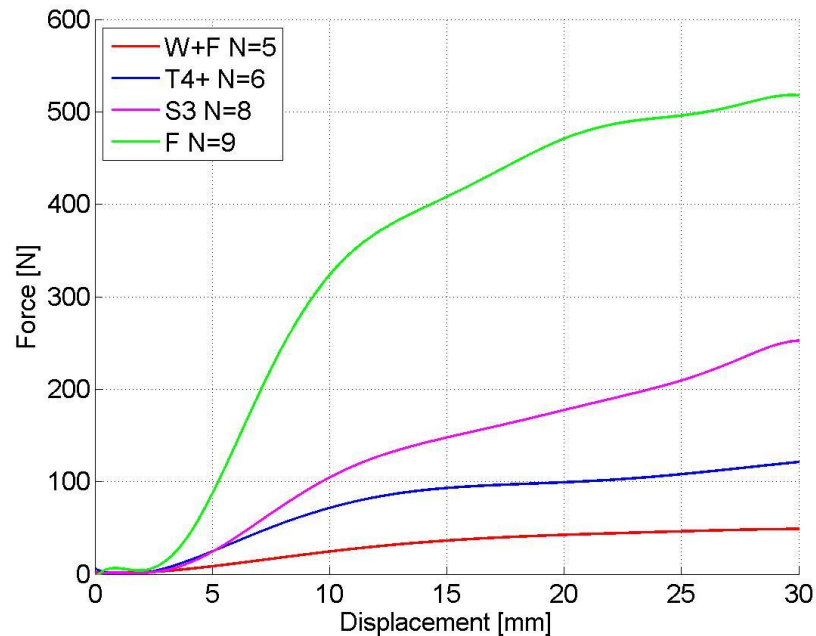**Figure 44 – Average penetration test result for T4+ material using the spare drill bit.**

Figure 45 - Penetration test result for S3 material using the spare drill bit.

Figure 46 - Penetration test result for F material using the spare drill bit.

An overall view of the polynomial fits for each material can be seen in Figure 47.

Figure 47 - Drill bit penetration tests: interpolated results for different glass foam materials.

## Experiments using a specially designed penetration testing tool

The second tool used in this experimental activity was specially designed and manufactured for these tests. As shown in Figure 44 it has a flat 1 mm thick round base with a diameter equal to the maximum one of SD2 (12 mm) to simulate the largest contact surface between the drill and the material. The second part, with a diameter of 10 mm was made this way to avoid contact with the material during the translation, therefore the force, after the initial transient, should remain constant during the whole operation.

Finally, there is a second part with a diameter of 12 mm because it was planned to use the same holding device used for the copy of drill bit but, in the end, the tool was made to fit directly on the machine.

Figure 48 - Alternative tool used for the tests.

The final setup of the experiment was very similar to the one using the copy of SD2 drill bit and it can be seen in the following image.
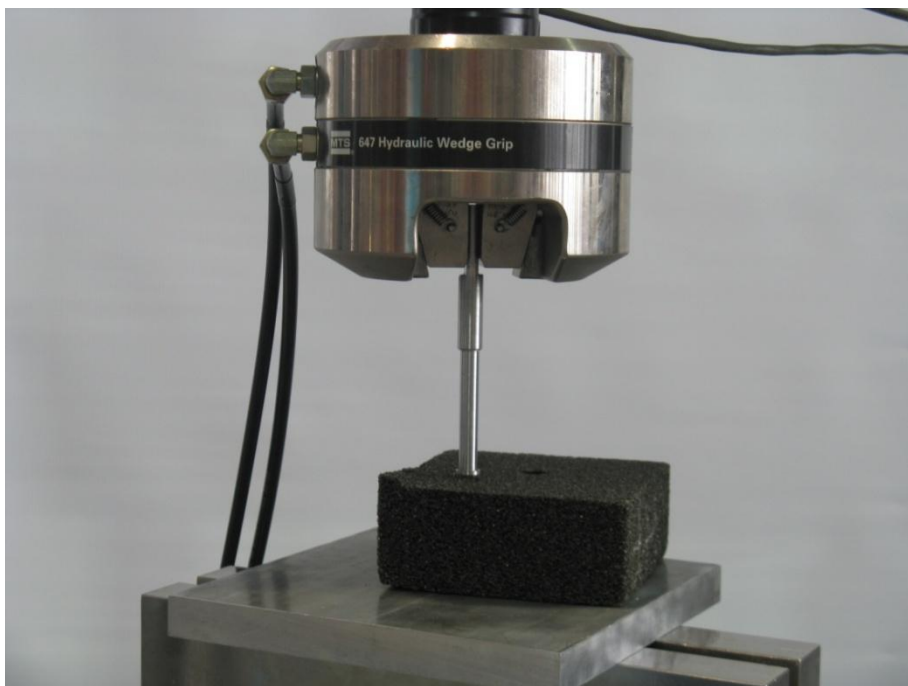
Figure 49 - Set up of the machine with the alternative tool.

The diagrams displayed in Figure 50 - Figure 53 are a comparison between the data from the experiments made with the copy of the drill bit and the ones made with the penetration testing tool. The polynomial fits of the data are reported too. It's important to point out that the large fluctuations of forces are due to the crushing of material's cell walls produced by the tool's advancement.
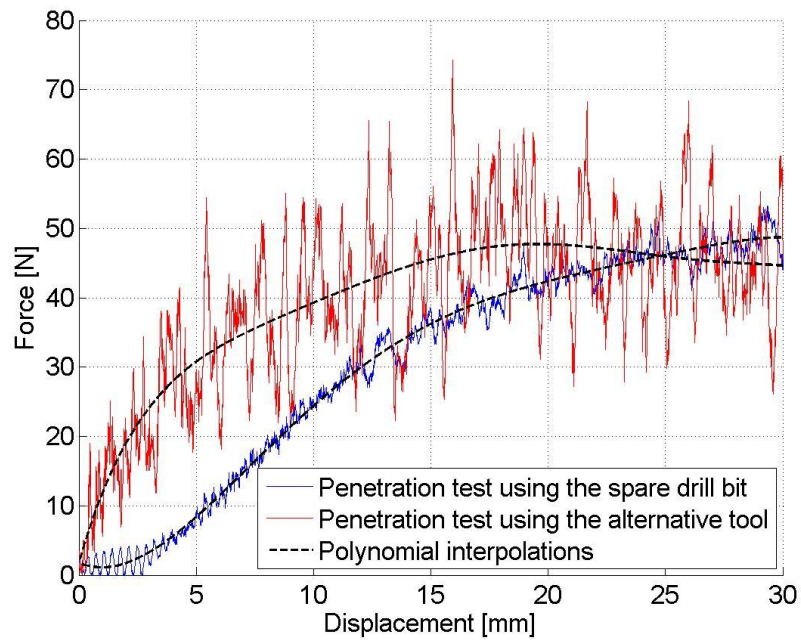
Figure 50 - Comparison of test results for W+F material.
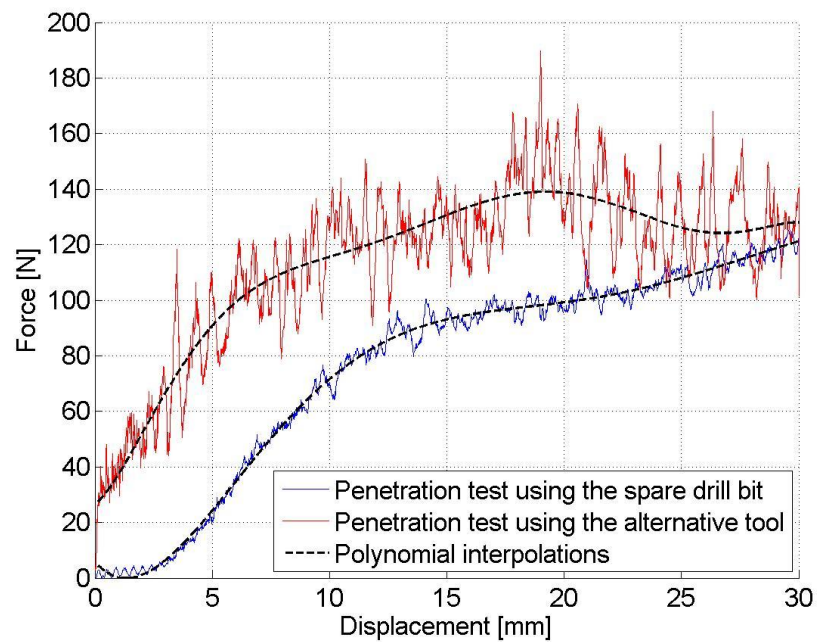
Figure 51 - Comparison of test results for T4+ material.
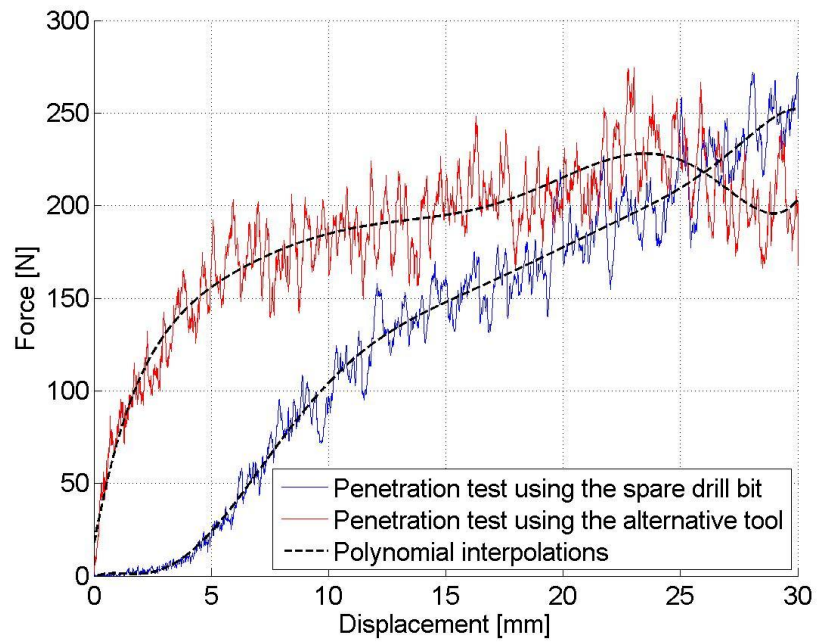
Figure 52 - Comparison of test results for S3 material.
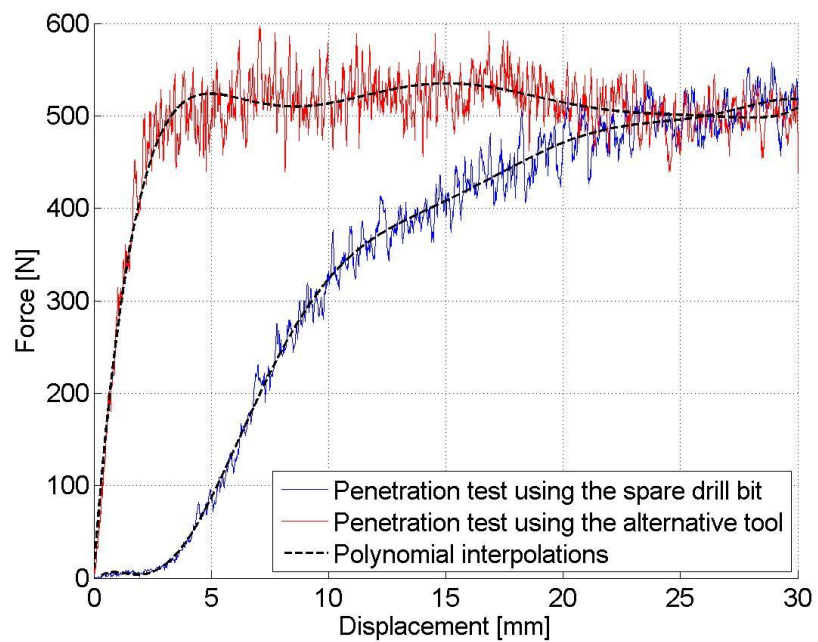
Figure 53 - Comparison of test results for F material.

From the above figures it is possible to point out that theincreasing force profile obtained with the copy of SD2 drill bit is mainly due to the increase of the penetration area with the depth.

On the other hand, the profile obtained with the penetration testing tool shows the typical behavior of cellular materials displayed in Figure 50 [12].

Figure 54 - σ-ε curve for a cellular material [10].

In the first part it is possible to observe a linear elastic deformation which goes on until the maximum compressive stress is reached. During this phase, the cells are bent under the applied load without being damaged [12].

Figure 55 - Representation of the cell's walls' bending [12].

The second part, which is almost constant, is due to the braking of the cells composing the structure of the foam material. In this phase there is equilibrium between the collapsing cells and the densification of the material [12].
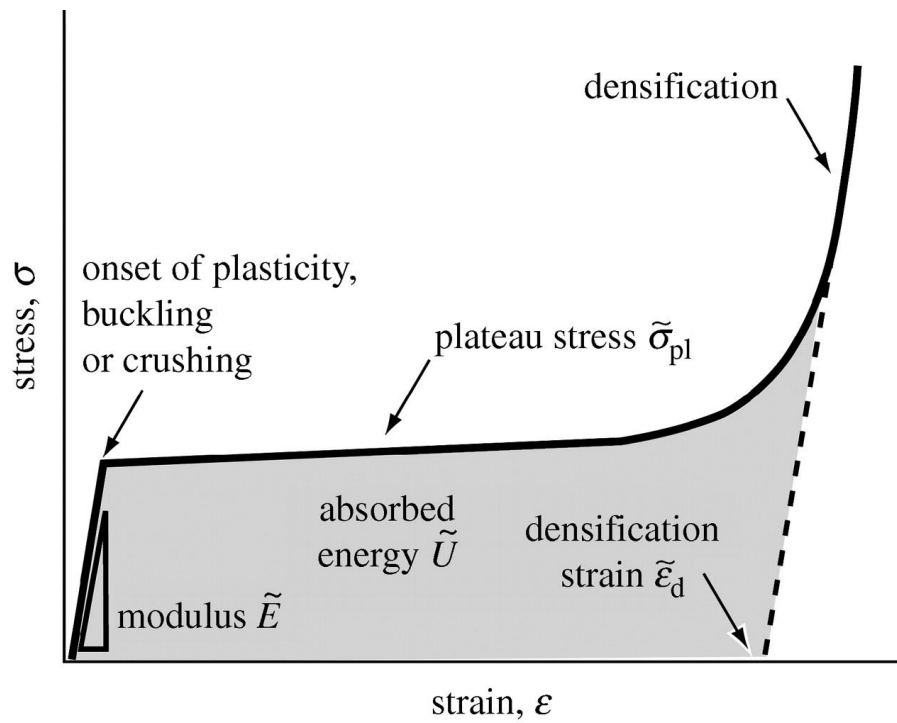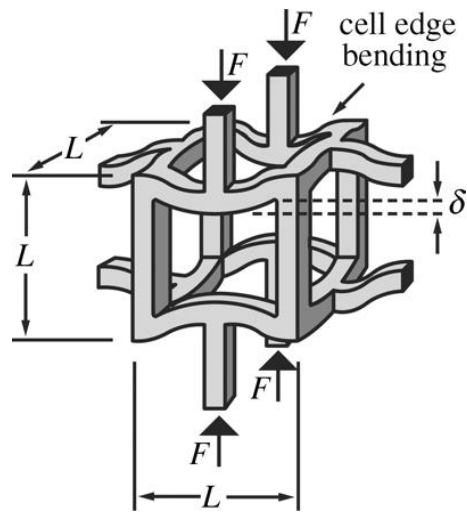
Finally, when the load starts again to increase, the breakdown of the cells reaches its maximum and the stress increases due to the densification of the material's structure. In particular, what happens inside the material is that the opposite walls of each cell are in contact producing a high value of friction with the remaining dust. At this point the cellular structure is not recognizable anymore.

Computation of the drill theoretical diameter

From the tests performed with the specially designed testing tool, it was possible to estimate the average penetration resistance of the Foamglas materials. This result was computed by dividing the mean value of force computed from a depth of 15 mm by the maximum area of the tool (113.1 mm^2).

The results are reported in Table 10.

Material	Average force [N]	Average penetration resistance [MPa]
F+W	50.43	0.4459
T4+	130.49	1.1538
S3	216.92	1.9180
F	506.93	4.4822

Table 10 - Foamglas material average measured penetration resistance.

Once the average penetration resistance was computed for each material, it was possible to estimate the equivalent penetration diameter of SD2 drill bit as a function of the penetration depth.

In particular, the following expression was used:

$$d = \sqrt{\frac{4F}{\pi P}};$$

Where:

F = result of the test carried on using the drill bit;

P = average penetration resistance computed using the results obtained from the experiments with the penetration testing tool from a depth of 15 mm and the maximum diameter of the drill bit (12 mm). See Table 10.

The results found for the different glass foam materials can be seen in the Figure 56.
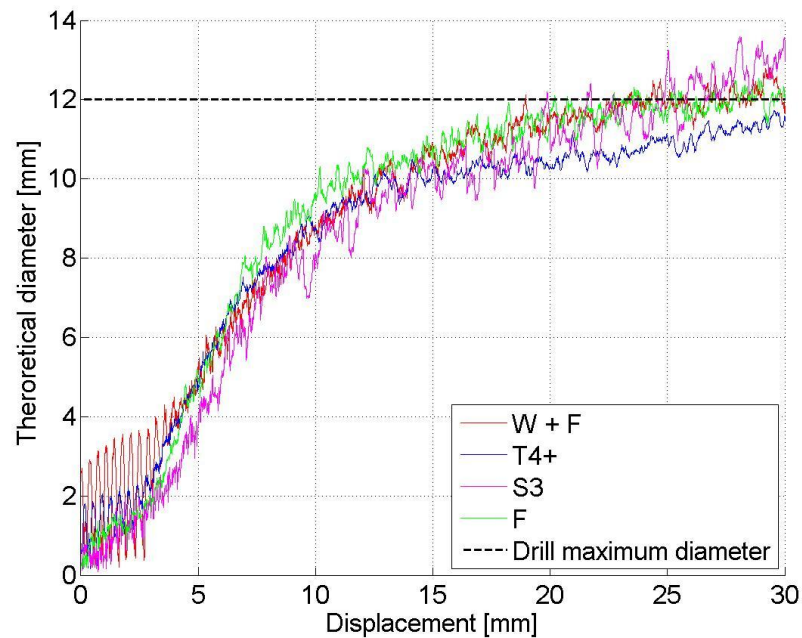
Figure 56 - Bit theoretical diameter as a function of the displacement.

To have a better understanding of the behavior of each diagram, it was decided to apply a polynomial interpolation which is plotted as a function of the displacement in Figure 53.
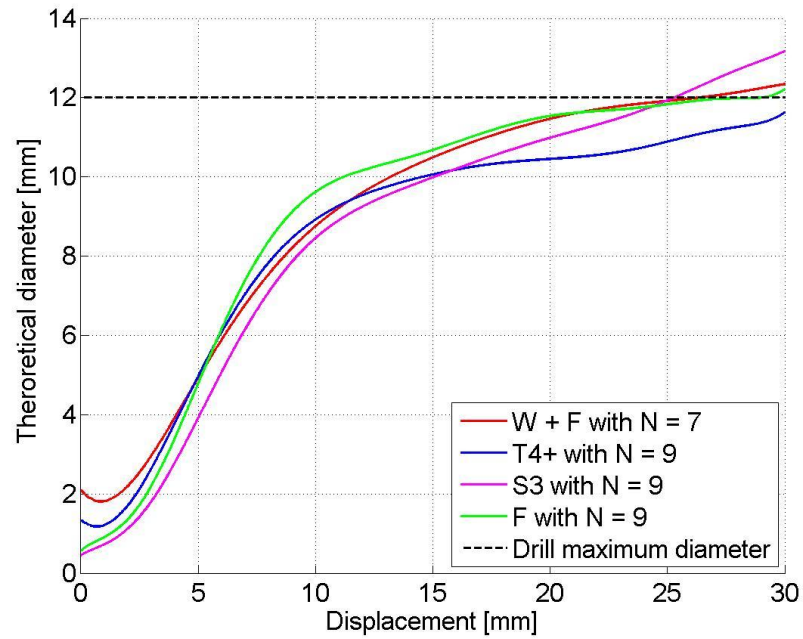
Figure 57 - Polynomial interpolations of the bit theoretical as a function of the displacement.

With the above results, it was possible to compute the average diameter which is also plotted as a function of the diameter in the Figure 58.
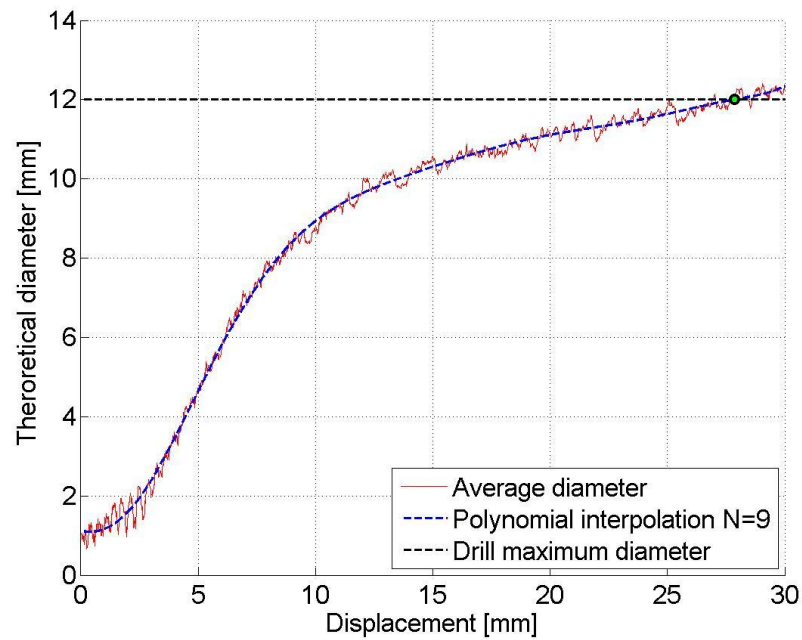
Figure 58 - Bit average theoretical diameter as a function of the displacement.

The green mark displayed on the previous figure represents the point where the polynomial interpolation of the average theoretical diameter reaches the value of 12 mm which is the maximum diameter of SD2. This happens at a depth of 28 mm.

This value was substituted into the polynomial interpolations of the curves obtained earlier (see Figure 55) computing the theoretical diameter of the drill bit for each material. With the diameter it was also possible to compute the theoretical area.

These results are displayed in Table 10.

Material	Theoretical diameter [mm]	Theoretical area [mm^2]
W+F	12.12	115.39
T4+	11.25	99.35
S3	12.66	125.89
F	11.98	112.71

Table 11 - Drill theoretical diameter and area at x = 28 mm

Relation between pressure and torque level

At this point, with the average drill area and its standard deviation, it was possible to take the force to torque level relation obtained at 3.1 and translate it to a pressure to torque level relation.

The average pressure was computed as:

$$P(T) = \frac{F(T)}{A_m} = \frac{a*T+b}{A_m};$$

Where:
F(T) = force to torque interpolating equation introduced in 3.1.
a = 26.27 N;
b = 20.69 N;
T = torque level;
A_m = maximum area of the drill bit = 113.1 mm^2.

The pressure's standard deviation was computed as:

$$\sigma_P^2(T) = \begin{bmatrix} \dfrac{dP}{da} & \dfrac{dP}{db} & \dfrac{dP}{dA_m} \end{bmatrix} \begin{bmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_A \end{bmatrix} \begin{bmatrix} dP/da \\ dP/db \\ dP/dA_m \end{bmatrix};$$

Where:
σ_A = 10.92;
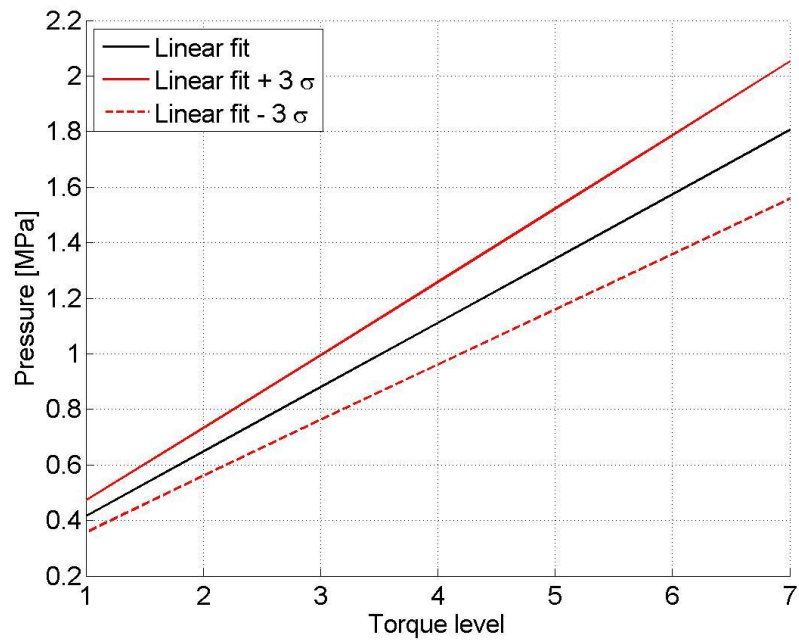$$\frac{dP}{da} = \frac{T}{A_m};$$
$$\frac{dP}{db} = \frac{1}{A_m};$$
$$\frac{dP}{dA} = -\frac{a*T+b}{A_m^2};$$

The pressure standard deviation as a function of the torque level is plotted in Figure 59.
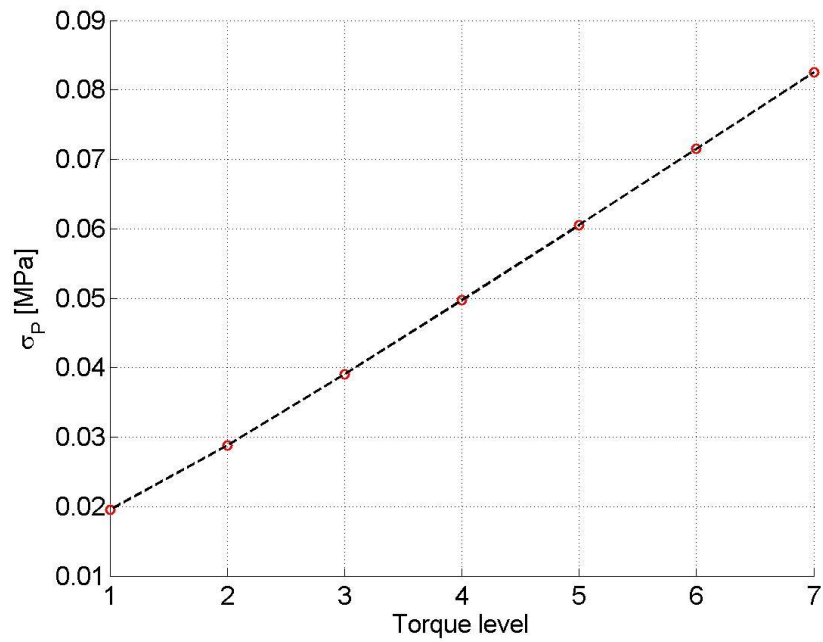
Figure 59 - Pressure standard deviation as a function of the torque level.

These results give the plot visible in Figure 60:

Figure 60 - Pressure to torque level plot including linear regression.

Finally, to complete the plot, the maximum penetration resistances for the W+F and T4+ materials were added. It's important to point out that, since these are the maximum values, they are higher than those computed in 3.3 (see Table 10).
The given plot is represented in Figure 61.
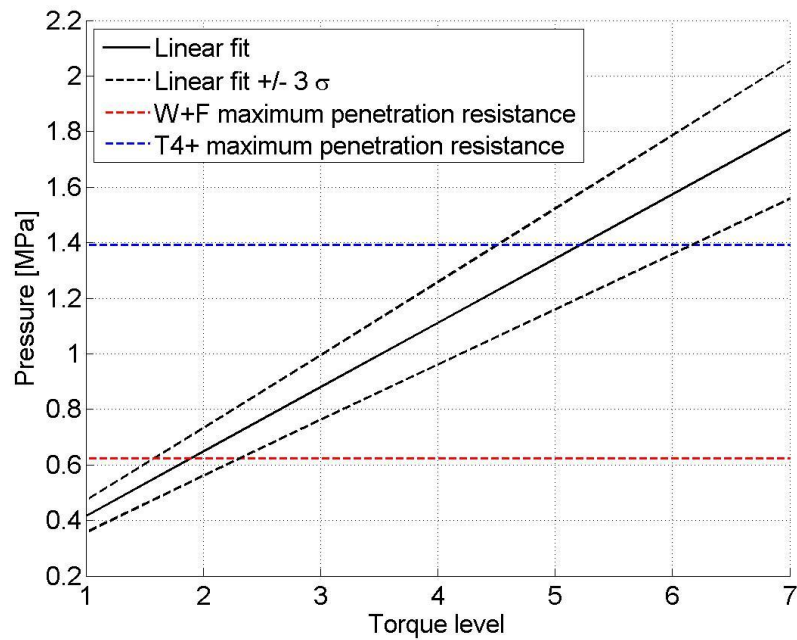
Figure 61 - Pressure to torque level plot including material compressive strength.

This final plot (see Fig. 61) can be read in the following way: for an applied torque level it is possible to estimate the range of pressure produced when the final depth is reached. Since the equivalent diameter increases as SD2 goes deeper into the material, the pressure applied by the drill bit during the beginning of its activity is higher than the values plotted in the figure. This means that, if the drill, at a given value of torque level, is able to reach the final depth into the cometary soil, then it can be assumed that the maximum penetration resistance for the soil is below the lower bound of the applied pressure.

From Figure 61 it is also possible to make the following prediction: to obtain a successful penetration, a torque level equal to 3 is necessary for the W+F material while T4+ requires a value of 7. In fact, for these values of torque, the lower bound of the pressure applied by the drill is higher than the maximum resistance pressure of the sample material.

Experiments using SD2

This last conclusion was validated by performing SD2 pure translation tests on Foamglass specimens in the facility described in Chapter 2.

For each type of glass foam, the drill was set to translate into it for a depth of 30 mm at speed level 20 (0.15 mm/s) and with a given torque level. Since SD2 automatically turns itself off when the target position is reached, it was easy to see whether the operation was successful or not. Also, when this was not clear from a visual analysis, it was possible to understand if the drill was still moving or not from the different sounds of the stepper motors and from the force level measured by the sensors. Finally, the last check was to download the telemetry to compare the last available position with the one imposed at the beginning.
In case the drilling operation could not be completed at the current torque level, the drill was manually turned off, then it was translated back to the starting position, the sample was replaced with a new one and the whole process was repeated with the next higher value of torque.

The results of this experiment were gathered in the Table 12:

	W+F	**T4+**
Torque 2	28.92 mm	
Torque 3	30.0 mm	
Torque 4	30.0 mm	28.53 mm
Torque 5	30.0 mm	28.90 mm
Torque 6	30.0 mm	30.0 mm
Torque 7	30.0 mm	30.0 mm

Table 12 – Experimental results using SD2.

These test results confirm what was expected from Figure 61 even if, in some cases SD2 was able to penetrate in the T4+ material at torque level equal to 6. This can be explained by the small difference between the lower bound of the applied pressure at this value of torque and the maximum penetration resistance of T4+.
Furthermore, with translation only, SD2 was not able to penetrate the Foamglas S3 and F sample materials. Also this result was expected due to the high value of penetration resistance of these specimens.

3.4 SD2 scientific strategy

Based on the analyses illustrated in the former sections, the proposed strategy for the scientific use of SD2 during the Long Term Science phase can be summarized as:

1. Command a drill translation at speed level 20 (0.15 mm/s) to penetrate in the cometary soil to a depth of 28 mm;
2. Set the torque level to 1 and then increase it progressively until the final depth is reached;
3. Estimate the maximum soil penetration resistance through Table 13.

Torque level	Estimated maximum penetration resistance [MPa]
1	<0.36
2	[0.36, 0.56]
3	[0.56, 0.76]
4	[0.76, 0.96]
5	[0.96, 1.16]
6	[1.16, 1.36]
7	[1.36, 1.56]
None	>1.56

Table 13 - Estimated maximum penetration resistance.

This strategy can be translated into mission plans using the previously described Mission Plan Generator (see Chapter 2). Since it requires a drilling activity for each torque level from 1 to 7, a specific mission plan must be created for each one of them.

For their creation it was assumed that the drill bit was in the armed configuration and initially in contact with the cometary soil. If the terrain is considered as a flat surface, this mean an initial position of 380 mm, which will be updated from the measurements obtained on site.

As an example, Figure 62 represents the mission plan required for the drilling activity at torque level 1.
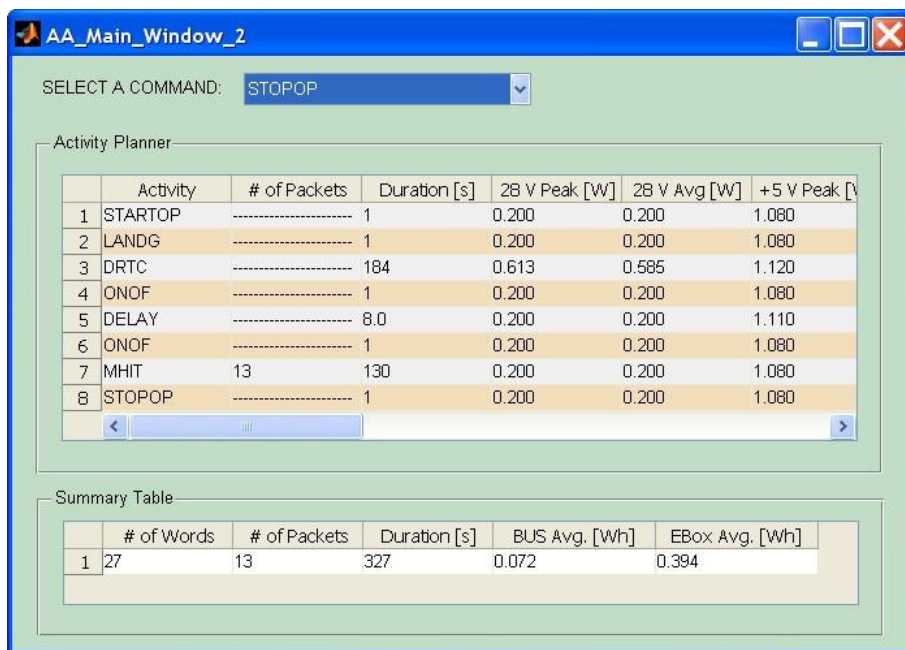
Figure 62 - Mission Plan for Long Term Science activity at torque level 1.

The command list for this mission plan is the following:

```
[MISSION PLAN]    0
STARTOP 0
LANDG 0 101 105 301 400 2001 3000 20001 20100
DRTC 20 1 0 40782
ONOF 0 1 1 0 0000
DELAY 32
ONOF 0 0000000
MHIT 0 0
STOPOP 1 0
```

Figure 62 shows that this kind of activity, if a successful translation is considered, requires approximately 5 minutes and the power consumption is lower than 1 Wh.

If the torque level is increased to 7, the resulting Summary Table is the following.

Figure 63 - Summary Table for drilling activity at torque level 7.

This confirms that the energy required to test the cometary soil is very low even in the worst-case scenario, which would be to try every torque level.

Conclusions and future developments

The main goals pursued in this work were:

- The creation of a Mission Plan Generator software.
- The creation of a new strategy to use SD2 as a scientific tool during the Long Term Science phase.

Both the goals were successfully reached.

The Mission Plan Generator was successfully created using the Guide tool provided in Matlab. Thanks to a very simple and clear graphic it is very easy to use and it does not require any background knowledge on either the Rosetta Mission or the SD2 subsystem to be operated. Furthermore, it was successfully tested on one of the drilling activities planned for the First Scientific Sequence giving accurate results for both the duration of the activity and the energy consumption. This proved that the Mission Plan Generator software is a very helpful tool to quickly produce the mission plans required to operate SD2.

On the other hand, there are still a few details which can be improved to increase its versatility.

1. Add more commands to the command list;
2. Add the possibility to enter a command in a specific location in the mission plan;
3. Add the possibility to delete a selected command;
4. Add the possibility to load a previously created mission plan;
5. Add the possibility to load a previously created mission program;

In the second part of this work, a new strategy for the scientific use of SD2 during the Long Term Science phase was presented. The idea behind it is to use the SD2 as a quasi-static penetrator.

In order to prove its feasibility, a series of test was carried on using a set of Foamglas materials to simulate the actual cometary terrain. These tests have shown that, with a limited amount of drill translations (maximum 7), it is

possible to estimate the penetration resistance of the cometary soil within 8 ranges.

This new solution, if compared with the old working zone approach, highly reduces the number of drilling activities required and, therefore, the overall power consumption. Also, the provided results are more accurate and give a better correlation with the mechanical properties of the soil.

On the other hand the knowledge about the actual property of the terrain on the comet is very limited. Therefore, since the results provided are accurate only within a 0.36 MPa - 1.56 MPa range it is possible that, as it is, this strategy may not guarantee a successful analysis of the cometary soil. Also, with the current strategy, in order to obtain accurate results, the soil must present certain mechanical characteristics like being compact and not presenting an elastic behavior.

Another strong assumption that was made during these experiments was that the cometary terrain does not present any kind of stratification. If this happens, the results may not contain information about all the different layers encountered. In order to check if this is the case for the cometary soil, a solution could be, once the torque level has been found, to increase the depth to check if the mechanical properties remain constant.

Finally, due to the unknown structure and conformation of the terrain on the comet, the exact distance between Philae and the cometary surface is unknown. This information is very important to set the correct parameters to control SD2 and to obtain useful results. Therefore, all the parameters required to set this strategy must be updated once the precise distance will be available.

For these reasons it is important to continue the experimental activity introducing, if possible, new materials to better simulate the actual scenario SD2 will encounter.

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