EXOMARS MULTI ROD DRILL DEVELOPMENT AND TESTING

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INTRODUCTION

One of the main goals of the ExoMars mission is the collection of subsurface samples down to a depth of 2 metres. Once collected the sample has to be distributed to a suite of scientific instruments for rover on board analysis.

The drill under development is a multi-rod system which allows the achievement of the desired drilling depth by summing up a string composed by one front end drill tool plus three extension rods.

In the frame of Phase B, a number of breadboards have been manufactured and extensively tested in order to support the verification of key requirements, including the capability to reach 2 meters depth. The breadboards developed are:

- Drill tool with sample collection capability,
- Extension rods (N°3 items manufactured),
- Complete Drill Box including basic drill functionalities like drill translation and rotation functions, and rod magazine with clamps for the verification of the ability to connect and disconnect the extension rods from the drill tool and the mandrel.
- Positioner rotation joint.

The paper presents the actual drill design and the main results achieved with breadboard development and testing.

DRILL CONFIGURATION

The drill makes use of four rods to obtain the full length drill string which allows to reach a penetration depth of 2 meters. The first rod is the real drill tool with sample collection capability; the other 3 rods are extension rods. The real drill tool is installed at the mandrel during launch, the other three rods are stored in a dedicated rod magazine together with a back up drill tool. All the rods are assembled together to collect a sample at 2 metres depth and then disassembled for recovery of the sample.

All the drill mechanisms and rods are contained in a light weight box (drill box) which is interfaced to the rover via a 2 degrees of freedom positioner (rotation plus translation joints). The positioner allows to remove the drill box from the horizontal stowage location and put it in vertical for drilling and then in a suitable inclined pose for discharging the collected sample into the sample container of the SPDS. Normally the sample container lies within the rover body and it is extracted from it just for the short time necessary to accept the sample from the drill tool.

The drill box overall mass is about 12 kg. Figs 1, 2 and 3 show the drill box in stowage, drilling and sample discharge position respectively.

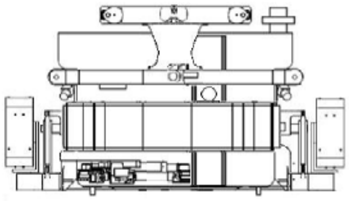


Fig. 1: Drill box in stowage position in the front of the rover

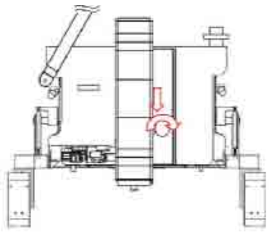


Fig. 2: Drill box in drilling position

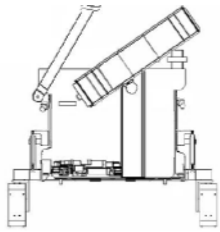


Fig. 3: Drill box in sample discharge position

The schematics of the drill and positioner architecture is shown in Fig. 4, listing all the degrees of freedom and an overview of the internal layout is shown in Fig. 5.

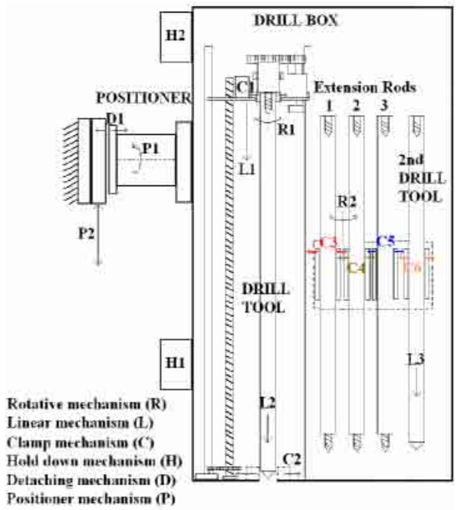


Fig. 4: Schematics of drill architecture

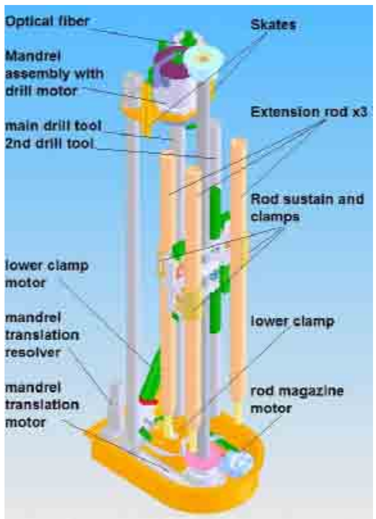


Fig. 5: Drill box internal layout

With reference to Fig. 4 and Fig. 5, the drill main parts are the following:

- *Drill sliding carriage*. It slides along two vertical guides (attached to the structural box) and is actuated by means of the translation group elements. The carriage supports the following main components:

  Rotating mandrel and relevant brushless motor-reducer for actuation

  Torque sensor

  Nut for sliding carriage translation and thrust sensor

  Sliding skates

  Mandrel clamp to allow transmission of the mandrel torque, in Counter Clock Wise direction, to the bottom of the extension rod when this has to be unscrewed from another rod or drill tool

  Electrical/mechanical/optical interface to the drill tool/extension rods

- *Drill translation group*. It has the purpose to move vertically the sliding carriage. Such vertical movement is guaranteed by two linear guides (made in invar) attached the drill box structure. The interface between the sliding carriage and the linear guides is obtained by means of two pads which provides compliance. The group is realised with a screw of 19 mm external diameter made of Aluminium, pitch of 2 mm. The brushless motor-gear is placed in horizontal position on the bottom cover of the drill box. The measurement of the sliding carriage position is obtained by a redundant resolver coupled with the translation screw by means of a gear-head

- *Rod magazine assembly*. It has the function to hold the three extension rods and the second drill tool. Four clamps are used to this purpose. The rod magazine can rotate to put in axis with the mandrel the extension rod which has to be assembled or disassembled from the drill string. To be able to efficiently latch the extension rods, the clamps are provided with a thread profile matching the auger of the rods. The clamp mechanism, actuated by a brushed motor, pre-loads a springs to assure the correct preload to the rod. End switches are used to verify both full open and full closed status.
- *Lower clamp*. This clamp is placed at the bottom of the drill box and is used to firmly hold the drill tool or an extension rod when the mandrel disconnect from it
- *Drill positioning device*. The drill unit is accommodated in stowage configuration in horizontal position transversal to the rover (Fig. 1). A positioner with two degrees of freedom is in charge of deployment to soil to start the drilling operations and orientation of the drill box for sample discharge into the SPDS. The positioner has a translation DOF (installed on the rover front panel) and a rotational DOF. Between the two DOFs there is placed the drill detachment (jettison) mechanism. The positioner overall mass is about 6 kg

Drill Tool

The drill tool is the key element to efficiently drill into the soil and to collect/discharge the sample; its schematics is shown in Fig. 6 (left). The drill tip is equipped with Polycrystalline Diamond Bits which gives the tool the ability to cut hard materials with low force impressed. The central piston can be uplifted inside the tool to allow the formation of a chamber to collect the sample (see Fig. 6, left). The piston is electrically actuated by a brushed motor-gear place in the upper part of the tool (actuation mechanism in Fig. 6, right). Once the sample is collected, discharge is made by pushing action of the piston itself. The external of the tool (which is made of Al, hard anodized) has a double auger to allow lifting of the chips generated during drilling.

Fig. 6: Drill tool schematics on the left and drill tool BB

The overall length of the tool is about 690 mm and its diameter is 25 mm, including the auger; mass is about 550 g. The dimensions of the sample core collected are 10 mm (diameter) x 25 mm length. The tool also incorporates optical parts (illuminator, optical head, optical fibre) of MA_MISS instrument.

Extension Rods

Three extension rods are necessary to allow the achievement of 2 meters penetration depth. Fig. 7 shows the breadboard of one extension rod.

Fig. 7: Picture of Extension Rod breadboard

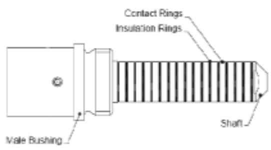


Fig. 8: Male end of the xtension rods

Each extension rod is mechanically, electrically and optically coupled to the adjoining elements (drill tool, extension rod, mandrel). Mechanical connection is via a conical thread; electrical connection is realised with a slip-ring type approach, that allows the coupling be performed in any angular position (see fig. 8). The different tracks are on separate layers, and do not get mixed if the mating parts are rotated relative to each other; only during mating, when the male and female parts are inserted axially, the contacts run through other lines too.

Optical Self Adjusting Connector

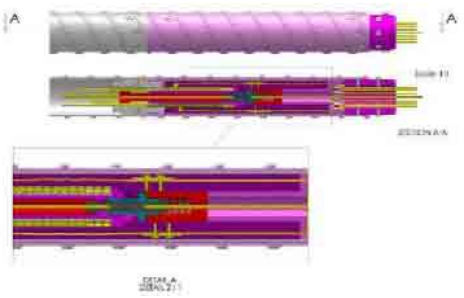


Fig. 9: Overall view of connector with a cylindrical interface (grey male I/F, pink female I/F)

The rod allows the accommodation of an optical fibre for MA_MISS instrument signal transmission along its tube and of two optical connectors in the male and female interfaces. The design of the optical connector for interfacing the rods/drill tool/mandrel male interface is shown in Fig. 9: a cylindrical I/F is used with a preloaded spring to align the optical fibre when the male I/F and female I/F are mated.

Drill Electronics

The drill electronics (which also manages all the SPDS functions) is composed by the Central Electronics -located inside the Rover Analytical Laboratory Drawer (ALD)- and by the Drill Box Electronics, located externally to the drill box. The two parts exchange information via a UART. All the motors drivers are in the Central Electronics while most circuitry devoted to sensor management is implemented in the drill box electronics. In this way the number of cables interconnecting the Central Electronics to the positioner and to the drill box is reduced with respect to a solution based on a single unit located inside the ALD. For what concerns redundancies, cold redundancy circuitry is implemented both in the Central Electronics and in the Drill Box electronics.

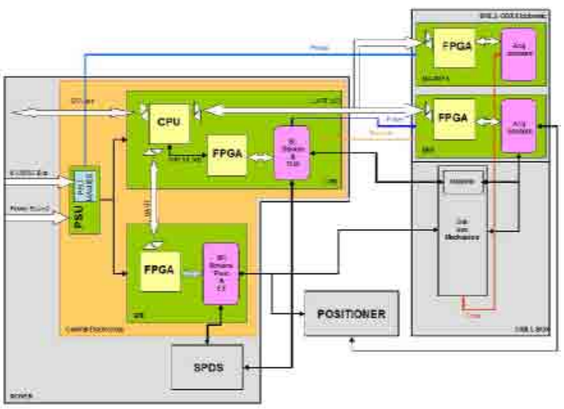


Fig. 10: Overall view of connector with a cylindrical interface (grey male I/F, pink female I/F)

STATUS OF BREADBOARDING ACTIVITIES

As mentioned in the introduction, a full drill box breadboard and the positioner rotation joint are available. These two have been integrated as shown in Fig.- 11 (drilling phase, left; actuation of the positioner rotation joint, right).

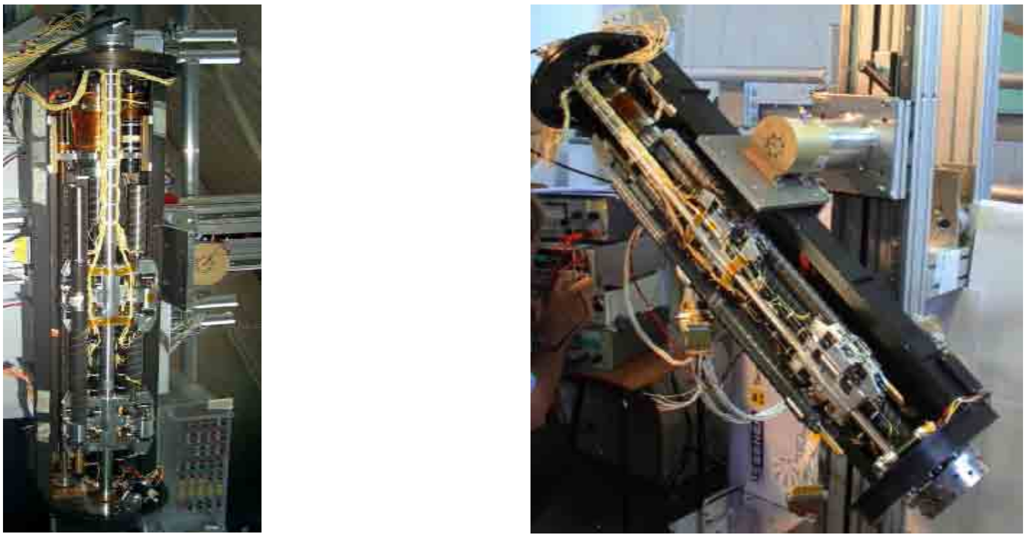


Fig. 11: BB Drill box\positioner assembly

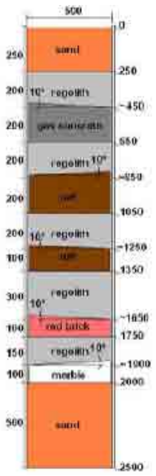
DRILL BOX BB TEST CAMPAIGN

In the following the main test campaigns performed with the breadboards are described.

Drill Box BB And 2m Depth Test Campaign

The breadboard of the drill box was designed and manufactured with the main aim to conduct test campaigns to demonstrate the ability of the system to drill and collect samples in depth, up to 2 m, and to drill into inclined surface material. The breadboard of the drill box was representative in terms of dimensions and design solutions envisaged for the flight model (e. g. type of motorisations and mechanisms for the drill translation and drill rotation functions). The main structure is in aluminium instead of the foreseen CF for the flight model. The breadboard incorporates also the drill thrust and torque sensors and the position sensors of both drill translation and drill rotation. Commercial drivers and a PC based MMI were used for the test campaign.

A dedicated set up was prepared to allow 2 m depth testing. This includes a sample container that that was filled with materials having different characteristics as shown in Fig. 12.



Material	*Density (g/cm^3)*	*Compressive strength*
Sand	1.41	
Regolith	1.37	
Gas concrete	0.46	1-2 MPA
Tuff	1.01	Soft matrix plus very hard inclusion
Red brick	1.80	20-30 MPA
Marble	2.75	100-110 MPA

Fig. 12: Set up for 2 m depth tests and stratigraphy of the soil specimen and the list of material used for 2 m depth tests

Tests At Nominal 2 Meters Depth

Two tests were conducted, each along one day, ending with the collection of a marble sample after drilling the layered soil specimen. Fig. 13 (relevant to the second test) shows the depth profile vs time.

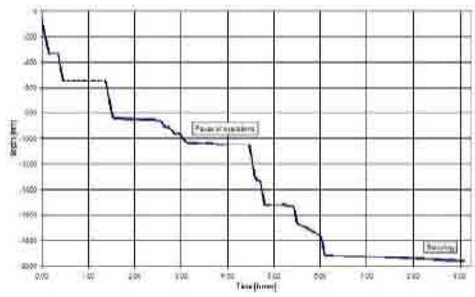


Fig. 13: Depth profile of the second test

Fig. 14: Drill box with drill tool and ext rods integrated for the 2 m depth test

Fig. 14 shows the drill box during the test at 2 m depth. The maximum depth of 2 meters was achieved by using the drill tool and the three extension rods connected together to form a long drill string. The connection between the drill tool and the extension rod was done by screwing (and un-screwing) the rods from the mandrel and to each other by using the mandrel motorisation itself and the thrust/torque sensors. Simple manual mechanisms, part of the drill box breadboard, allowed to put the rods to be installed in the right position below the mandrel and to hold them during operation as required by the procedure.

Fig. 15 shows the marble samples taken during the first and second test at 2 m depth.

	*First test* Sample mass: 5.2g Type of sample: solid core		*Second test* Sample mass: 6.3 g Type of sample: solid core

Fig. 15: Marble samples taken during the tests

During tests at 2 m depth power values from 7 W to 35 W were registered, depending on the type of material and also on the penetration depth for the same kind of material. For example drilling into regolith required just ~7 W for upper regolith (second layer of the soil specimen, from the top) to ~14 W for the regolith above the marble (second last layer of the soil specimen). This increment is due to the increased friction of the long drill string along the drilled hole. Also thrust and torque changes a lot, especially with type of material. Average torque values from tenths of Nm to 2 Nm were experienced, peak torque values are much higher and standard deviation from the average values are larger for the heterogeneous materials (e.g. tuff) and hard materials (marble). Average thrust ranges from a few N to 150 N, peak values can be as twice as the average values, especially for the heterogeneous and hard materials. Advancing speed were very changing depending on the type of material encountered, ranging from > 30 mm/minute in the weakest material, 3 mm/minute in medium rocks and 0.2-0.3 mm/minute in hard marble.

Inclined Material Tests

The tests on inclined material were conducted to investigate the behaviour of the drill bit while beginning a new hole when the surface to be assaulted is not perpendicular to the drill axis. Primarily the actual capability to begin a new hole had to be evaluated, but also a roughly estimation of the side reaction force on the drill bit has to be measured. The results were also intended to assess whether rigidizers and the drill box bottom were necessary or not.

Test were conducted in different materials (Gas concrete, tuff, red brick, travertine, marble) at different attack angles, from 10° to 30° in all of the materials. The results were successful and the rigidizer were judged not necessary. Axial forces from 50 N to 150 N were used and side forces from a few N to 70 N were measured. Some pictures taken during the tests are shown in Fig. 16.

Travertine 30° inclination *Marble 30° inclination*

Fig. 16: Some pictures of the tests with *inclined* materials

Drill Box BB T/V Test Campaign

The main objective of the test was to demonstrate the drilling and sample collection in Mars like conditions for what concerns temperature and pressure profiles.

The scope of the test included:

- the verification of the Drill Box (and Drill tool) to operate at low temperatures and at low pressure

- the verification of the effectiveness of the brush (located at the drill box bottom) to remove the deposited dust from the external of the drill tool at low temperature.

The test was conducted at the facility of CISAS-Padova.

For the test, the drill box was integrated on a supporting structure as shown in Fig. 17. The lower part of supporting structure hold the sample container for the soil specimen; this was prepared following the stratigraphy of Fig. 18. A soil specimen height of about 50 cm was available.

Fig. 17: Drill box integrated on the supporting structure before installation within the T/V chamber

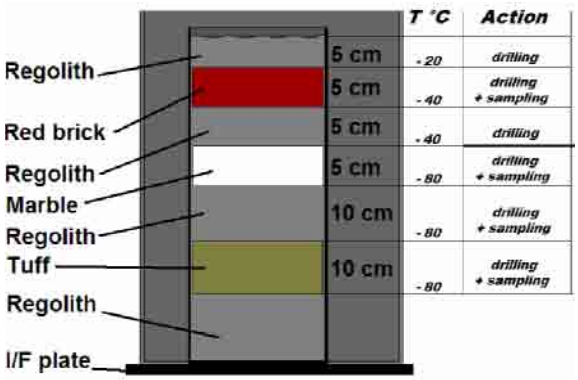


Fig. 18: Stratigraphy of the soil specimen for T/V tests

The sample temperature during drilling and sample collection/discharge was in the range of -80 °C +/-10 °C (or -40°C +/-10 °C depending on the test performed) with a pressure of about 10 mBar, -5/+10 mBar. Some components of the drill box and the drill tool were heated to be above -20°C (as requested by the data sheets of the commercial components utilized in the breadboard). During the test the successful collection of three samples was achieved:

- first sample taken into red brick (at -40°C), mass 3.8 g
- second sample taken into marble (at -80°C), mass 3.3 g
- third sample taken into regolith (at -80°C), mass 5 g

Such samples were discharge into individual sample containers, without opening the chamber between one sample collection and the subsequent. This was possible thanks to a special motorised device that was able to put an empty sample container below the drill tool for sample discharge. Sample discharge was monitored by a video camera installed within the T/V chamber. Fig. 19, taken after T/V chamber opening, shows the samples discharged into the containers.

Fig. 19: Samples discharged into the container (from right: red brick, marble, regolith)

Drill Box And Rod Magazine BBs Test For Drill String Automatic Assembly

One of the main challenging aspect of the multi rod drill system is the automatic connection and disconnection of the rods during drilling and sample recovery procedures.

To verify this aspect as soon as possible the drill box breadboard was upgraded during phase B1B by including all the mechanisms necessary for such a verification. These include:

- Rod magazine and clamps, all equipped with motorisation and sensors, for correct storage, positioning and holding of the three extension rods
- Lower clamp and upper (mandrel) clamp to allow automatic operation of rod engagement and disengagement.

The test conducted achieved full drill string length of 2 metres (drill tool plus three extension rods) in actual drilling condition along the material specimen.

All types of materials were perforated down to 2 meters utilising the realistic drilling conditions of torque and thrust in order to verify the effectiveness of the clamps and tightening of the various elements involved in the drilling process.

Specific issues properly verified included: holding of rods by magazine clamps, holding of drill tool and rods by lower clamp, holding of rods by upper clamp, correct positioning of magazine, engagement and disengagement of mandrel-drill tool-rods.

CONCLUSIONS

The drill system presented in this paper is the result of a thorough design and development activity supported by specific testing on very representative breadboards.

A positive confirmation on the feasibility of automatic drilling and sample collection down to 2 metres has been achieved by breadboarding.

The resources in terms of mass and power needed are in line with expectations as well as the characteristics of the collected samples.