DEFINING THE TECHNICAL REQUIREMENTS FOR SUBSURFACE MARS DRILLER. M. Anttila[1] and T. Ylikorpi[2], [1]Space Systems Finland Ltd., Kappelitie 6, FIN-02200 Espoo, Finland, matti.anttila@ssf.fi, [2]Helsinki University of Technology, Laboratory of Automation Technology, Konemiehentie 2, FIN-02015 TKK, tomi.ylikorpi@hut.fi

Introduction: The international plans for robotic Mars exploration are focusing on the subsurface sampling and sample analysing methods of Martian regolith. In the launch window of 2009, both ESA and NASA have preliminary plans to send a rover with deep-drilling capabilities.

International companies and organisations have designed prototypes and engineering test models for drilling purposes, such as the MRoSA2 driller (see Figure 1), Rosetta driller and several other planetary drilling applications. Authors of this publication have been personally involved in especially the ESA's MRoSA2 project [7]. The focus was to develop a prototype of miniaturized planetary driller, which could perform up to 2 meter deep drilling and sampling of Martian regolith.

Figure 1: MRoSA2 rover conducting a drilling task.

As the drillers are evolving and plans are for moving from prototypes to real space applications regarding the 2009 launch window, it is imperative to conduct wide testing for these drilling and sampling machines. With the knowledge and scientific results gained from the NASA's Pathfinder, Mars Global Surveyor and Odyssey missions we have developed a test bench to simulate Martian regolith from the surface down to two meters depth. All drilling parameters have been studied to define the best suitable drill performance that could fulfill the requirements for upcoming exploration missions.

Foundation of testing: The MRoSA2 drilling system constitutes of two subsystems: the roving platform (110x400x400 mm packed, 11kg) and the Drilling and Sampling Subsystem (DSS).

The roving vehicle, procured by Helsinki University of Technology; Automation Technology Laboratory, is a tracked tethered vehicle, serving as a platform for the DSS. It's function is to enable the DSS to sample at desired locations and to deliver these samples back to the lander. During the mission, the rover makes multiple trips between the lander and various sampling locations. The rover is commanded and supplied with power from the lander via a tether. The rotating axis of a payload cab holding the drilling device allows drilling and sampling at angles ranging from the vertical to the horizontal, allowing full 360° rotation.

The Drilling and Sampling Subsystem (DSS), designed and manufactured by VTT Automation, is restricted in very limited volume of 110x110x350 mm and in mass to 5 kg. In order to satisfy 2 meter penetration depth requirement the DSS features an extendable drill string. The string is assembled from up to ten separate pipes in a similar manner that is used on terrestrial automatic rock drilling machinery. Drilling is performed by two independent actuators, one for rotation (0-120 rpm, 0.3 Nm) and one for thrust (-100 to +400 N). The rotation actuator is mounted on a sledge moving in and out propelled by the thrust actuator and a ball-nut and -screw. Operation of the drill is similar to conventional automatic drilling machines. When drilling proceeds and the sledge reaches it's bottom limit, the pipe is detached from the spindle, the spindle is retracted to upper position and a new pipe can be attached from the pipe carousel to extend the string. The sequence of disassembly of a drill string during drill retraction is opposite to assembly sequence.

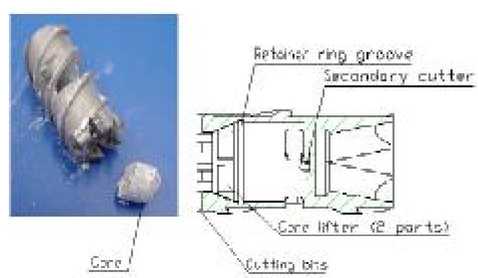

Figure 2: The MRoSA2 drill head and a rock sample [3].

The tool used for sampling duplicates as a drilling bit and a core drill. The tool is illustrated in Figure 2. During drilling a core develops inside the drill while the bit crown chips the material. Chips are conveyed to the surface by the external helical profile of the drill string. Once the coring section is full, the head cutter chips the core top. The effect is that the bit penetrates deeper into the material always holding a 20 mm height core sample presenting the current depth. When desired depth has been reached, the core is broken apart from base material with the aid of wedge-shaped core lifter by lifting and turning the drill. This action is similar to that used with conventional rock-core drills. For sampling of sand or other similar loose soil, specially designed flaps can be mounted next to the core lifter to hold sample inside the tool during lifting.

Preliminary tests with different types of cutting tools were carried out in early stage of the project. The tests show cutting power that would collect a limestone core 10 mm in diameter and 15 mm in height within few hours. Quick tests were carried also on very hard and abrasive Finnish granite and results indicate, that with given thrust and power it would be possible to collect similar rock core in a time frame of tens of hours, however, durability and selection of drill bit material will be a critical issue (see Table 1). The tools that were tested were as following:

- ∅6 and ∅16 mm impregnated diamond core drills for cutting of glass
- ∅16 conventional hard-alloy-tipped drill for hand-held hammering drills (Hilti)
- ∅16 mm hard-alloy tool for metal cutting (∅4 mm core)
- ∅16 mm custom made hard alloy core drill (Terätrio)
- a concept of two surgical knife blades rotating at ∅16 mm radius (~∅14 mm core)

Hole	Drill bit	Material	Speed RPM	Force N	Hole depth/mm	Speed mm/h	Duration h
1	diamond Ø16	Marble	30	24	8.8	0.3 .. 2.5	4
2	hard alloy	Marble	30	25	12.1	2.6	5
3	"Hilti"	Marble	30	25	17.6	1.9	14
4	diamond Ø16	Marble	30	24	16.6	1 .. 2.2	8
5	hard alloy	Marble	30	25	17.8	2.6	6.5
6	diamond Ø6	Marble	30	24	11.1	0.5 .. 2.1	6
7	diamond Ø6	Marble	60	24	13.2	0.7 .. 2.4	6
8	diamond Ø16	Marble	60	24	15.1	1 .. 2.2	8
9	diamond Ø6	Limestone	30	24	6.7	0.3 .. 3.9	4.5
10	diamond Ø16	Limestone	30	24	10.6	1.7 .. 3.4	5
11	knife blades	Limestone	30	25	3.4	6	0.5
12	sonic hard alloy	Limestone	30	12	4.3	1.5	Different sonic vibration
13	sonic hard alloy	Limestone	30	12	6.1	1.5	
14	sonic hard alloy	Limestone	30	12	2.3	1.5	
15	Terätrio	Limestone	30	27	9.8	18	0.5
16	Terätrio	Granite	50	high	0.9	3	10 minutes
17	Terätrio	Granite	120	high	6.2	36	10 minutes
18	Terätrio	Granite	120	27	2.3	2.2	1.3
19	sonic knife blades	Granite	30	12	1.5	0.2	2
20	knife blades	Granite	30, 120	12	1	0.2	3
21	Terätrio	Granite	120	45	3.1	2.0	1.5
22	Terätrio	Granite	120	45	12.9	0.2 .. 1.8	14

Table 1: Some preliminary MRoSA2 drilling test results [1]

Tecnospazio (TS, Italy) presents in ref. [2] drilling tests that were carried out during years 2001-2002. The TS drill tool had a completely different design and it drilled a hole 35 mm in diameter, and –upon command- acquired a core 14 mm in diameter. Drilling force, torque and power were, respectively, higher than those for the MRoSA2 drilling tests. The test equipment at Tecnospazio was a for-purpose developed drilling system that provides axial thrust and drill rotation. The drilling tests were carried into several materials: sand, gas concrete, tuff and travertine. Table 2 below presents the averaged test results and describes performance of this tool prototype.

Property	Sand	Gas concrete	Tuff	Travertine
Material density (g/cm^3)	1.43	0.46	1.01	2.44
Drill Thrust (kgf)	0.3	1.5	0.6	20.0
Drill Torque (Nm)	0.6	0.9	0.4	2.5
Drill RPM	22	130	150	70
Drill Feed Rate (mm/min)	10.0	4.0	1.4	1.3
Drill intake power (W)	**7.5**	**7.5**	**7.5**	**29.0**

Table 2: Tecnospazio 35-mm Drill tool performance in different materials [2]

After the tests in TS a new variable called 'Specific Drilling Power' (SDP) [W/(mm/min.)] was developed to determine cutting efficiency with respect to different drilling parameters. For scientists and mission planners time and energy needed for the sampling action is very important information. Time reserved for sampling action is away from any other scientific measurements and therefore speed of penetration is an important factor. Maximum power available may be limited due to limitations of solar cell area, RTG (radiothermal generator) output or tether cable capacity. Available energy may be limited due to time available for sampling or due to capacity of batteries or other temporary energy storage. SDP indicates directrly how much power [W] is needed to achieve a corresponding speed of penetration [mm/min.]. SDP depends on properties of test material, tool geometry, rotation speed, thrust, and drilling method (rotary, percussive or rotary-percussive). In these tests all other parameters were kept constant, but effect of drill rotation speed and feed rate was studied.

With a given drill rotation speed a higher thrust gives a higher efficiency, or a smaller SDP. Energy needed to make a hole depends on grain size developed. Energy used to separate a single grain is defined by material shear strength and the surface area that connects the grain to the base material. In rotary drilling the material is removed in the form of fine powder where size of grains is very small, and overall grain surface area is high. This leads into high energy consumption. With a higher thrust bigger cuttings are removed from the material which gives better energy efficiency. Increase in rotation speed tends to decrease the size of the cuttings (i.e. gives lower energy efficiency) unless thrust is increased accordingly.

SDP multiplied by the depth of hole [mm] gives the energy needed for the sample [W-min.] (1 W-min. is 60 J). The Table 3 below shows how SDP changes when feed rate is being increased. This gives a clear indication that for a higher efficiency also a higher power is needed [2].

Feed rate [mm/min.]	Specific Drilling Power [W/(mm/min.)]	Power input [W]
0.3	37	12
1.1	23	26

Table 3: TS 35-mm Drill tool performance in Travertine with different feed rates [2]

Test setup: For further testing a new test-setup was realized at the premises of Helsinki University of Technology. As for the moment shallow drilling tests has been carried out on stones of different hardness, or the tests have concentrated merely on sample acquisition, the new tests will emphasize on drilling in layered sand and in depth exceeding one meter.

The drilling system is constructed using vertical linear guide and a lead-screw as for the linear feed system, and a DC-motor as for the drill motor. The drill, however, will not be directly coupled to the lead screw, but the coupling will have a certain compliance. With this arrangement the linear feed can be driven step-by-step while between the steps the feed motor will be shut down. Continuous or closed-loop feed-control is not being used which is an attempt to save energy and provide a mechanically and electrically more simple system. Knowing the spring-ratio of the compliance the linear feed can be driven in a desired manner to maintain the thrust force at the desired level. At the extreme level this control loop can be realized completely mechanically which would minimize the need for any feed-back or data-transfer used solely for control purposes and having no scientific interest. Drilling is performed by using the ESA's MRoSA2 drill heads.

The sample to be drilled into is prepared inside a transparent vertical box two meters high (see Figure 3). For sample construction the best available knowledge of the Martian surface composition is used. Inside different layers of sedimentary materials also different types or rocks are inserted. Some of the tests are carried out in environmental chamber where temperature can be adjusted down to –20 centigrade. Then also some water can be mixed into test materials to demonstrate drilling into permafrost layer. Further a piping for liquid nitrogen can be placed inside the sample container to cool down the sample into even lower temperature to be adequate with Martian environment.

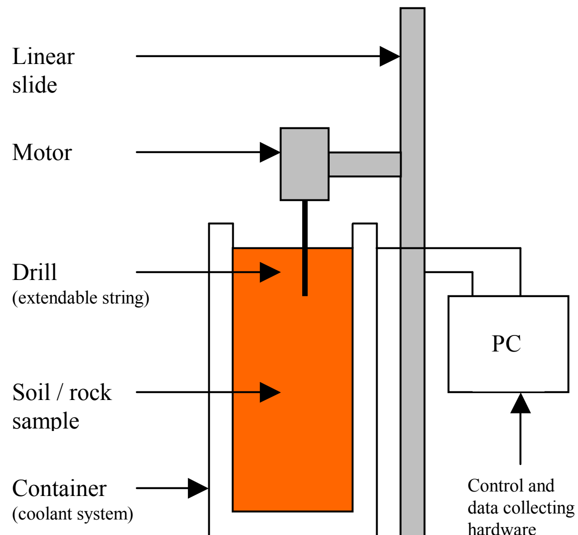

Figure 3 : Drilling test mechanical setup.

During drilling several variables are being monitored: drill motor power input, drill RPM, drill motor current (i.e. torque), feed compliance (i.e. thrust force) and speed of penetration. Further a temperature measuring device can be mounted inside the drill tool to monitor temperature of the sample during drilling process.

Imitating the Martian regolith: One of the remaining challenges, until we really drill through the Martian surface is, that there is no exact knowledge on what the drill will face. However, there are some commonly agreed speculations that what is the structure of the soil and rock layers near the surface. The Mars Odyssey orbiter has proved the possibility of water ice near the surface [8], which might lead to harder drilling. Even if there would be no rocks in the drilling spot, the soil might be tied tightly by ice.

For best guestimate of a typical Martian soil, various tests were conducted. These soil setups varied from loose soil to hard bedrock. A basic test setup consists of loose and fine sand, with grains on the order of a tens to few hundred microns to simulate Martian soil type and composition. For the deeper layers of the test setup, ranging from ~0,5m to 2 m, different rock layers were made. We used mafurite (Uganda, Kyambogo Crater) as an example of igneous stone, and carbonatite (from Finland, contains mainly calcite) as an example for easier rock drilling. Water ice was used to bind the loose soil, and to simulate actual hard, cold ice, which the drill would hopefully face.

Imitating the actual space drill: The preliminary MRoSA2 drilling tests were carried out with a system where the drill thrust was provided by a small mass added on top of the drill, and penetration speed was not controlled at all. The Tecnospazio drilling tests utilized a rigid drilling device that provided steady speed of penetration.

In MRoSA2 tests the test material and cutting efficiency of the tool define the speed of penetration. In absence of any control of axial feed the system rapidly started to oscillate up and down when the cutting tool followed the profile that generated at the bottom of the drill hole. The TS system, having a constant speed of feed, generated a varying amount of thrust that was depending on hardness of material and cutting efficiency of the tool.

The real planetary drill operating on the surface of Mars will have a weight higher than that used for MRoSA2 tests, but possibly less than maximum thrust utilized for TS tests. It is desired to maintaing drilling forces low enough to guarantee that the roving system will stand steady on the surface. In addition to weight consideration of the rover, also inertia, i.e. mass, has some importance. High inertia, that is mass, would allow short force or torque peaks to be generated, that would not yet be able to disturb balance of the system. For example, the ESA's ExoMars rover has planned mass of 220 kg [4] and NASA's MSL rover/platform more than 100 kg [5], possibly even 600 kg [6].

It is essential to define, what is the drilling thrust and torque to be, and what would be the rigidity of the drilling system. It is worthwhile also to consider if added inertia would be a good choice to simulate the inertia of the rover.

Also inertia of the drill rotating parts may have a positive effect on drilling performance. Drilling action itself is very noisy –especially in non-homogenous materials; average drilling torque is much less than peak torque. In order to overcome the torque peaks a mechanical inertia would set limits for needed motor peak power and current and would possibly prevent the tool from getting stuck in cavities or other non-homogenous features of rocks.

Conclusions and future work: The focus of this test setup is to define the minimum technical requirements for subsurface drilling of Martian regolith for future exploration missions. The drilling tests will continue on analysing different setups of rock layers, and combinations of sand and water. However, the testing team is also studying methods to perform the analysis in the downhole, instead of bringing all samples up. This in-situ analysis would lead to savings in time and energy in some cases. However, the data collected from the downhole is significantly less that can be acquired by a lander-based laboratory.

References: [1] Ylikorpi, T.; Visentin G.; Suomela J. A robotic rover-based deep driller for Mars exploration , Proceedings of the 35th Aerospace Mechanisms Symposium, Ames Research Center, 2001 (2001), 14 p. [2] Re, E.; Magnani, P.; Ylikorpi, T.; Cherubini, G.; Olivieri, A., 'DeeDri' Drill Tool Prototype and Drilling System Development for Mars Soil Sampling Applications, 7th ESA Workshop on Advanced Space Technologies for Robotics and Automation 'ASTRA 2002', 19-21 November 2002, ESTEC, Noordwijk, The Netherlands. [3] VTT, Final Presentation slides at ESA ESTEC, 2001. [4] ExoMars09, CDF Study Report: CDF-14(A), August 2002, ESA. [5] NASA Mars Exploration Program, Mars 2007 Smart Lander Mission, Science Definition Team Report, October 11, 2001, NASA. [6] Mars 2007 Smart Lander, Reference Science Scenario for SDT Report, 9/17/01, NASA. [7] The Micro RoSA2 Activity – Conclusion and Future Plans, Anttila, Matti; Suomela, Jussi; Saarinen, Jari. 7th ESA Workshop on Advanced Space Technologies for Robotics and Automation 'ASTRA 2002', ESTEC, The Netherlands. [8] Theory of Ground Ice on Mars and Implications to the Neutron Leakage Flux. M. T. Mellon, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, USA.

Acknowledgements: Many people and organisations contributed time, knowledge, skill, and support to this study, and we are pleased to acknowledge their contributions: ESTEC, HUT MIRANDA Team, Prof. M. Lehtinen, Finnish Museum of Natural History, Dr. J. Piironen, University of Helsinki.