Concept study for the Subsurface Sampling System for the Pasteur payload of the ExoMars mission

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INTRODUCTION

The ExoMars mission is the first Flagship mission of European Space Agency's Aurora program. The mission will include a Mars rover, which will carry a set of instruments in the rover's Pasteur payload. One of the instruments in the payload is a drill, which is supposed to retrieve samples from the Martian regolith.

In the last ASTRA conference, held in ESTEC in 2002, the author presented [1] some conclusions of the ESA-funded MRoSA2 project (a prototype of a Mars rover with a drilling and sampling system). After that, the team made some improvements to the rover, emphasizing to the drill system, to make it more functional in laboratory conditions. Later on, we built a test setup to the premises of the Helsinki University of Technology to find out the required drilling parameters in Martian-like regolith samples. These tests (the MIRANDA project, 2003) improved our knowledge on the required drilling power and some system requirements. The team also sketched some possible designs for the drill-bits to gather more information during the drilling process and from the borehole without retrieving the actual soil or core sample. After the MIRANDA tests, the author and the MIRANDA and MRoSA2 teams have revised the system parameters of the current drill system design to be consistent with the requirements of the ExoMars drill and possible other drillers in the upcoming Mars exploration projects, such as the Mars Sample Return mission.

These test results and improvements will be covered in this paper, as well as a concept of a drilling and sampling device which is capable to perform subsoil sampling in the limits of the technical requirements set to the Pasteur payload.

PLANETARY SAMPLING BY DRILLING

Since no robotic laboratory can fit all the same analysis equipment that can be used on Earth, a sample return mission would allow the best possible analysis for celestial samples. However, retrieving samples back to Earth poses several new challenges. Several methods have been proposed, and a few have been tried in past missions, and some are still under development. However, hitherto extraterrestrial samples have been retrieved only from the Moon (see Table 1), if one doesn't count solar wind samples taken by the Genesis spacecraft. The Moon has been sampled by the manned U.S. Apollo program and by the Russian's robotic Luna program.

Table 1: All-time sample-return missions.

Mission	Type	Sampling method	Sample mass	Mission timeline
Apollo 11-12,14-17	Manned	Hand, rake, drill etc.	Total ~380 kg	07/'69 - 12/'72
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Genesis	Halo orbit around Lagrange 1	Impact/sputtering plates	~0,4 mg	08/'01 - 09/'04
Stardust	Robotic, fly-by of comet Wild 2	Aerogel collector	~1 mg	02/'99 – 01/'06
Muses-C /Hayabusa	Robotic, fly-by of asteroid Itokawa	Bullet / dust gathering	~1 g	05/'03 – 06/'07

Getting the sample back from an asteroid, comet or a planet is challenging, but the effort of actually taking the sample has its own challenges too, especially regarding subsoil samples. Even if the sample has to be analyzed in-situ instead of returning it to Earth, an automated sample analysis laboratory can still be equipped with very capable instruments. The results are even better when the sample is pristine and represents natural local conditions. Since most surface samples have been exposed by environmental conditions (such as wind, Sun's UV radiation, cosmic rays etc. leading to weathering and oxidation), surface soil and rocks can gain only limited scientific information. In fact, possible organic signatures tend to be erased by these surface processes. Therefore a subsoil sample is favoured, especially if the samples could be taken from different layers of depth, from rocks and soil. This kind of sampling requires a drill system that can drill down into different materials and retrieve the rock core or soil sample back to the (robotic) analysis laboratory.

So far, a drill has been used in Russian Luna, US Apollo and in Russian Venera mission. There is also a drill system onboard the Philae lander in ongoing European Rosetta comet mission. The first drill that has operated in another celestial body than Earth was the Russian Luna 16 drill (1970). The drill was attached to robotic lander that returned its sample back to Earth. Following that, there were the Apollo 15-17 missions (1970-1972), where astronauts used hand drill (the Apollo Lunar Surface Drill, ALSD) to retrieve subsoil samples. In addition to lunar missions (three Luna landers and Apollo 15-17 missions), the Russian Venera 13-14 landers had a robotic driller too (1982). The trend, if the term may be used, is towards miniature drillers. Terrestrial drilling could relay on virtually limitless power, thrust and torque. Unfortunately this is not case with planetary exploration drilling. During the Apollo missions, the astronauts used the ALSD to retrieve core samples down to three meters depth. The drill wasn't very big, but the "mechanics module" for attaching and detaching the drill strings was the astronaut himself. The dexterity of astronaut in surprising situations is unbeatable, i.e. when the drill gets stuck. However, it is not feasible always to send astronauts instead of robots. The challenge is to get a robot to use a miniature drill in all possible drilling-related situations.

ESA has plans to launch the ExoMars mission in 2009. The mission will include a Mars orbiter and a landing craft, and the lander will deliver a robotic rover to Martian surface. The rover will include an automatic drill, which is capable to retrieve subsoil samples. The drill has to be quite small, and still it has to be able to drill down to 2 m and make multiple drilling and sampling operations. Compared to previously used drills in space missions, the challenge is great to make the drill both miniature in size and still versatile in operation. In addition, the drill must not consume too much power, and it must be mostly autonomous in operation (due to the long round-trip light time between Earth and Mars).

While there are several past, ongoing and planned drill-related projects, this paper concentrates on already-flown drills, the MRoSA2 drill and the ExoMars drill to compare the characteristics and performance and to sketch possible concept to fit into the ExoMars mission. As seen in Table 2, there have been four different drilling instruments in space, counting also the SD2 drill onboard the Philae lander of ESA's Rosetta mission. These four instruments are all different in operation, but some similarities can be seen. The ALSD is clearly the best in performance, but it cannot be counted because it doesn't include any autonomous functions, which are needed in robotic missions. The Venera drill was strongly made to Venusian environment (it relied on pressure difference in sample acquisition), so it cannot be used in similar manner for example in Mars or on the Moon. The comparison is then reasonable only between Luna and SD2 drills. Despite the fact that Luna drill concept is roughly 35 years old, the principle is good, and pretty much similar to SD2 drill. However, both these drills are more or less shallow-drilling devices, since they can penetrate only few tens of centimeters. The objective of future drills is to be able to drill down to more than one meter. The MRoSA2 concept is one possibility to achieve this.

Table 2: Comparison of past and ongoing missions' space drills [2-5].

Drill unit / mission	Mass kg	Electric power W	Dimensions mm	Maximum Drilling depth, mm
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Philae SD2 Drill	4,8 kg	1 W (stand-by), 4-12 W drilling	150 x 760	230 mm

THE MROSA2 PROJECTS

European Space Agency (ESA) initiated a GSTP activity “Micro Robots for Scientific Applications 2” (MRoSA2) in 1998 [6]. The project began in 1999 and came to a conclusion in November 2001, when the final presentation was held at the ESA ESTEC. The goal of the work was to develop a mobile drilling and sampling system composed of a rover, a drill, sample storage, and a docking and sample delivery port mounted on a lander module. The focus was on the drilling and sample handling; the rover was a functional mock-up and the lander module was a structural mock-up for mounting the docking and sample delivery port. Main work was done in concentrating to the Martian environment, although the concept is generic to any celestial body that is possible for landing and which offers adequate anchoring for drilling purposes. Later on, in the MRoSA2 Upgrade project, the system was improved. The goal of the ESA funded upgrade project (ESA Purchase Order project) was to upgrade the rover-drill-combination (see Fig. 1; the height of the rover is about 40 cm in the figure) from a single-function level to drilling and sampling readiness level in laboratory conditions.

The project team was mainly Finnish: Prime contractor was Space Systems Finland Ltd. (SSF), who was also responsible in the SW development and some systems and integration testing. The Helsinki University of Technology (HUT) was in charge of the rover and on-rover-electronics. A Russian company, The Rover Company Ltd (RCL), who built the rover chassis, assisted HUT in the rover development. The Technical Research Centre of Finland (VTT) / Automation department was in charge of the DSS development. The MRoSA2 Upgrade project was carried out by SSF (prime contractor), HUT Automation and RCL (as HUT’s sub-contractor).

The Drilling and Sampling Subsystem (DSS) is restricted in volume of 110x110x350 mm and in mass of 4.5 kg. In order to satisfy 2-meter penetration depth requirement the DSS features an extendable drill string. The string is assembled from up to 11 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 its 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. The MRoSA2 project is a key issue to this publication, since the drill module is one of the predecessors (in concept meaning) for the upcoming ESA’s ExoMars rover’s drill.

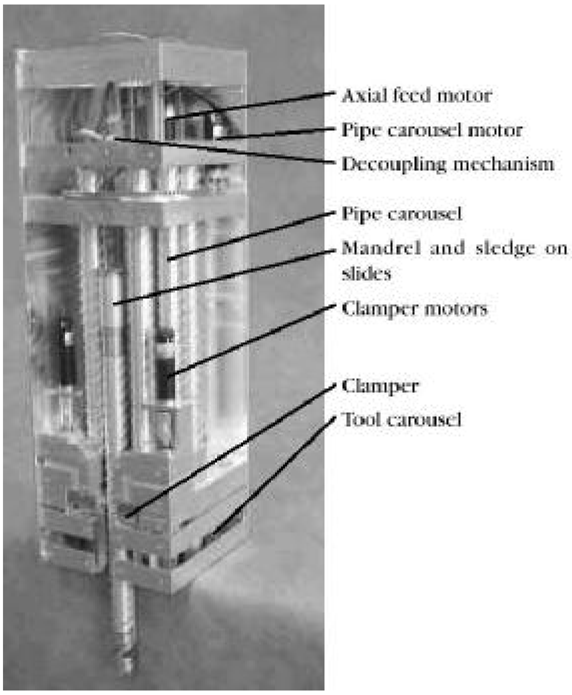


Fig. 1: The MRoSA2 rover in drilling position (Image: SSF). The DSS module is shown on the right (Image: VTT).

DRILLING TESTS

There have been four different test periods of drill hardware regarding the studies of the author, either the drill module (with and without the rover) or the drill pipes and drill tool only. These testing periods, including their themes, are:

- Tests conducted during the MRoSA2 project in 1999-2001:
  - VTT drilling tests.
  - Systems testing for the rover and drill module.
- Tests during the MRoSA2 Upgrade project in 2002-2003:
  - Systems testing.
  - Drill functionality testing.
- The MIRANDA project, 2003:
  - Soil drilling tests.
  - Rock drilling tests.
- The MIRANDA-2 tests, 2004:
  - Temperature tests during rock drilling.

The MRoSA2 and MRoSA2 Upgrade Tests

During the MRoSA2 project in 2001, the author conducted some reliability and drill-function tests. Before these functional tests, VTT Automation conducted several drilling performance tests. These tests were documented in [7]. Wider drill functional tests were conducted in 2002-2003 during the MRoSA2 Upgrade project.

The operational cycles of MRoSA2 DSS is explained in [8]. As detected in MRoSA2 tests [9], the reliability of each single operation (inside the DSS) is commonly more than 95%, in most cases close to 100%. However, when multiple operations are performed in a row, the total success rate decreases. These reliability tests were performed mainly with nothing to penetrate to, so the drill "drilled" into air, horizontally. The results of drilling ten-pipe length are shown in Table 3. Measured peak power during this test cycle was 5.0 W. It is notable that this does not include the power to drill into regolith, but only the electric power to manipulate the actuators inside the DSS. However, this power could easily be decreased to 3 W with some improvements of the drill string handling procedures [10].

It is notable that the total reliability is far too low to demonstrate adequate technology readiness level as flight model instrument. However, in this case the instrument is a prototype and the mechanical idea is clearly working, although the robustness must be greatly improved.

Table 3: Drilling down to two meters; power, time and reliability issues.

Depth cm	Total attachments + detachments	Cumulative time min	Cumulative energy Ws (J)	Cumulative theoretical reliability
20	2 (1) + 0 (3)	4	~400	80 %
40	4 (2) + 1 (4)	10	~1300	76 %
100	10 (2) + 4 (4)	28	~4100	65 %
200	20 (2) + 9 (4)	58	~8600	51 %

1= tool-to-pipe + pipe-to-gripper, 2 = as above + pipe-to-pipe + detached pipe head back to gripper, 3 = no detachments, 4 = detach the topmost pipe from the gripper.

The MIRANDA Tests

ESA announced the Aurora Student Competition in January 2003 for ESA member states' universities. The competition called for a team, which would then study and document its work aiming for future space technologies. HUT Automation Laboratory gathered a team, which was lead by the author of this publication. The team designed and built a drilling test bench in the 'MIRANDA' project. The scope of the work was to simulate deep drilling in Mars with existing MRoSA2 drill hardware and document the tested results. The project ended in July 2003. Later on, the author started another drill test project by using the existing MIRANDA hardware. This project, called the 'MIRANDA-2' (2004), aimed to analyze the temperature variations in the drill bit and in the drilled material during drilling and sampling. The existing drill test bench was modified to fit the new project's requirements to allow low-thrust drilling and temperature analysis.

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 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 feedback or data-transfer used solely for control purposes and having no scientific interest. Drilling is performed by using the ESA's MRoSA2 drill heads. As the drill sledge has mass of about 7 kg, a counterweight is being used to allow low-thrust drilling. The drill bit has temperature sensors (unlike the MRoSA2) to measure the sample temperature during drilling. The objective is to avoid increasing the temperature of the sample to melting point of water ice.

The sample to be drilled into is prepared inside a transparent vertical box two meters high (Fig. 2) [7]. For sample construction the best available knowledge of the Martian surface composition is used. For rock drilling, different rock types were used to measure the required drilling power and energy to extract core samples.

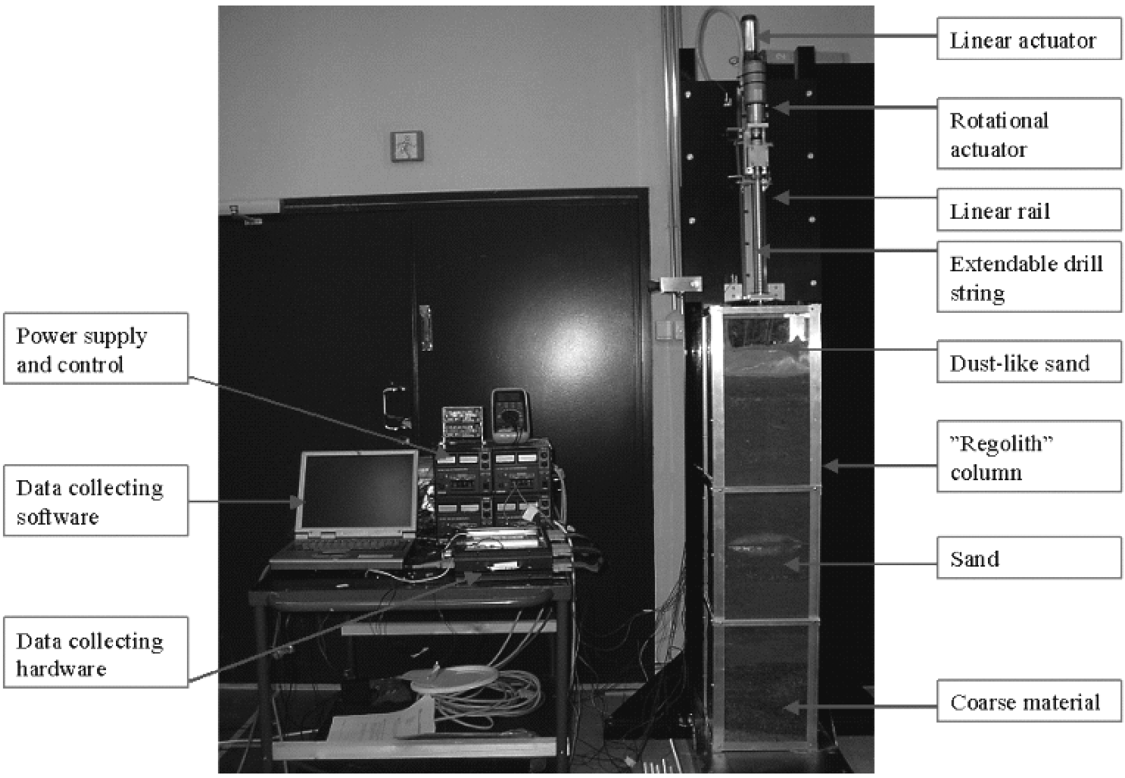
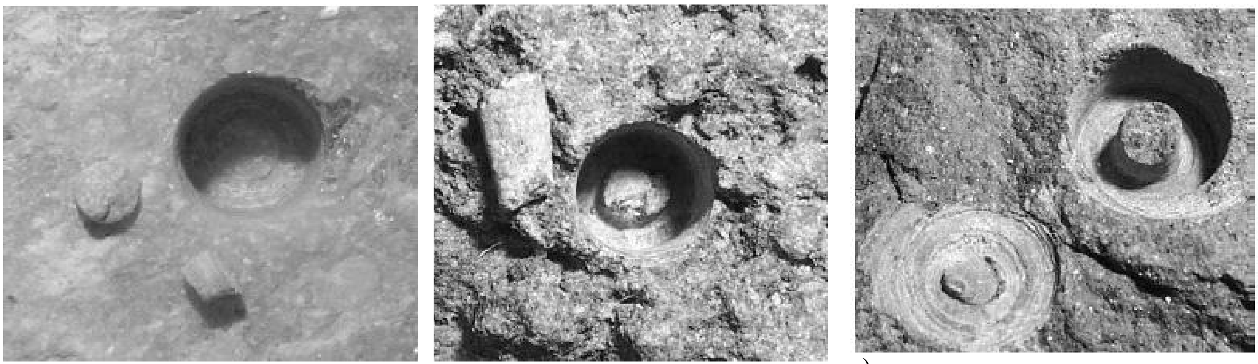


Fig. 2: The principle of the MIRANDA drilling test bench (Image: MA).

Table 4: Comparison of drilling results of different stones with a power of 10...20 W.

Rock type	Time min	Hole depth cm	Energy Wh	Energy Wh/cm	Speed of penetration cm/h
Carbonatite	16	2,1	3,8	1,8	8,1
Diabase	50	2,5	14,5	5,8	3,0
Mafurite	162	0,1	43,2	432	0.04



a) b) c)

Fig. 3: Carbonatite (a) and diabase (b) drilling holes and the corresponding retrieved core pieces. The borehole is 17 mm in diameter. Mafurite is shown in c) and the core sample has not yet been extracted (Images: MA).

The drilling power was set to 10-20 W in most of the tests to correspond typical planetary drill power budget, and drilling force was within 140-170 N. The results of these drilling sessions are summarized in Table 4. The time consumption of the drilling is first shown, along with the resulting hole depth on the stone. The third and fourth columns of Table 4 show the total energy in Wh dissipated during the drilling. This is integrated from the current and voltage data. These clearly highlight the softness of the carbonatite and the hardness of the mafurite.

The energy consumption per millimetre of the drilled rock, calculated from the values on the Table 4, was for carbonatite 0,58 Wh/mm, for diabase 0,40 Wh/mm, and for Mafurite 43 Wh/mm. Good core samples were achieved from both diabase and carbonatite. These accompanied by the holes produced on the stones (washed after drilling) are shown in Fig.3. These results are only part of the drilling results, and more drilling results are explained in [10].

EVALUATION OF REQUIREMENTS FOR FUTURE MISSIONS

The basic requirements for the drill operation are:

- Collect subsoil material from down to two-meter depth, and from the surface rocks.
- Preserve the physical and chemical properties of the sample.
- Deliver the sample to the Sample Preparation and Distribution Subsystem.
- Drill system's mass, size and power are limited.

These scientific and functional requirements lead to other requirements, which are mainly technical issues. As the ExoMars rover and the drill in the Pasteur payload are still in definition phase, some of the requirements will be revised. However, staying in the safe-side of these basic constraints will give a good approximate of a possible concept for the drill system.

Table 5: Comparison of past space drills, MRoSA2 drill and Pasteur drill parameters.

Drill unit	Mass	Electric power	Dimensions (WxLxH)	Maximum drilling depth
MRoSA2 (Upgraded)	4,5 kg (including drill pipes)	6 W rotary, 6 W linear feed (No percussion, no active drill tools. Drill control electronics not included).	110x110x350 mm w/o electronics	220 cm (11x20cm drill pipes)
Pasteur drill requirements	11 kg (with 2 DOF manipulator)	10 W average during drilling, peak limit 40 W.	160x160x500 mm	200 cm [11]

It is interesting to compare the technical requirements of the MRoSA2 drill unit and the requirements for the Pasteur drill. The Pasteur drill requirements are somewhat preliminary, but they indicate the range, which will be used in more accurate requirements in later phases of ExoMars pre-studies. Table 5 shows the technical parameters of MRoSA2 drill unit and the Pasteur drill's requirements.

Table 5 shows clearly that the MRoSA2 (Upgraded) drill concept would fit into Pasteur requirements. However, one must remember that the MRoSA2 drill unit is not a qualified flight model, but a prototype, which works in laboratory conditions with adequate reliability. MRoSA2 drill mass and size values don't include the electronics, or the manipulator, i.e. '*robot arm*'.

CONCEPT PROPOSAL

As told in previous chapters, the MRoSA2 DSS fits conceptually in the requirement frames of Pasteur drill for ExoMars mission. However, there are some fundamental changes that must be done:

- Drilling power must be increased to allow at least 10 W nominal power for drilling and 40 W peak power.
- The reliability of the DSS must be greatly improved by concentrating on the key issues of the mechanics.
- Drill tool should include temperature sensors and possibly some additional analysis instruments to allow in-situ (in borehole) analysis.
- Drill linear movement actuator (linear feed) should be equipped with spring-thrust device to allow smoother drilling and to avoid constant use of linear feed actuator.
- The drill must include 2-degree-of-freedom manipulator arm.

These add-ons and improvements should fit into the 11 kg mass budget of Pasteur drill unit. The increased power results in bigger DC motors and stiffer design. A spring-loaded linear feed will increase the size of the drill spindle, but the size will still be inside the 16 cm x 16 cm x 50 cm size budget. The concept is shown in greater details in [10].

CONCLUSION

The focus of these drill studies (MIRANDA 1 and 2) and tests during projects (MRoSA2 / Upgrade) has not been any specific mission, such as the ExoMars mission. However, the Pasteur drill (without the manipulator arm) resembles so closely the MRoSA2 drill that it poses excellent focus point to these kinds of studies. The main driver has been the clever mechanics inside the MRoSA2 drill and the challenge to study how to make it reliable and robust enough to possibly qualify as flight instrument in Martian conditions. The performed tests and studies have mainly been additional tests to the projects, and not all of them had been even required in the project plan. Mostly the tests have been performed in pure academic interest and in the frames of university educational projects.

The results presented here are mostly preliminary, and the concept proposal of Martial drill / sampler will be refined to more accurate level. The results, along with more in-depth analysis of past and current instruments and future requirements will be presented in a doctoral thesis [10] in 2005 by the author of this publication.

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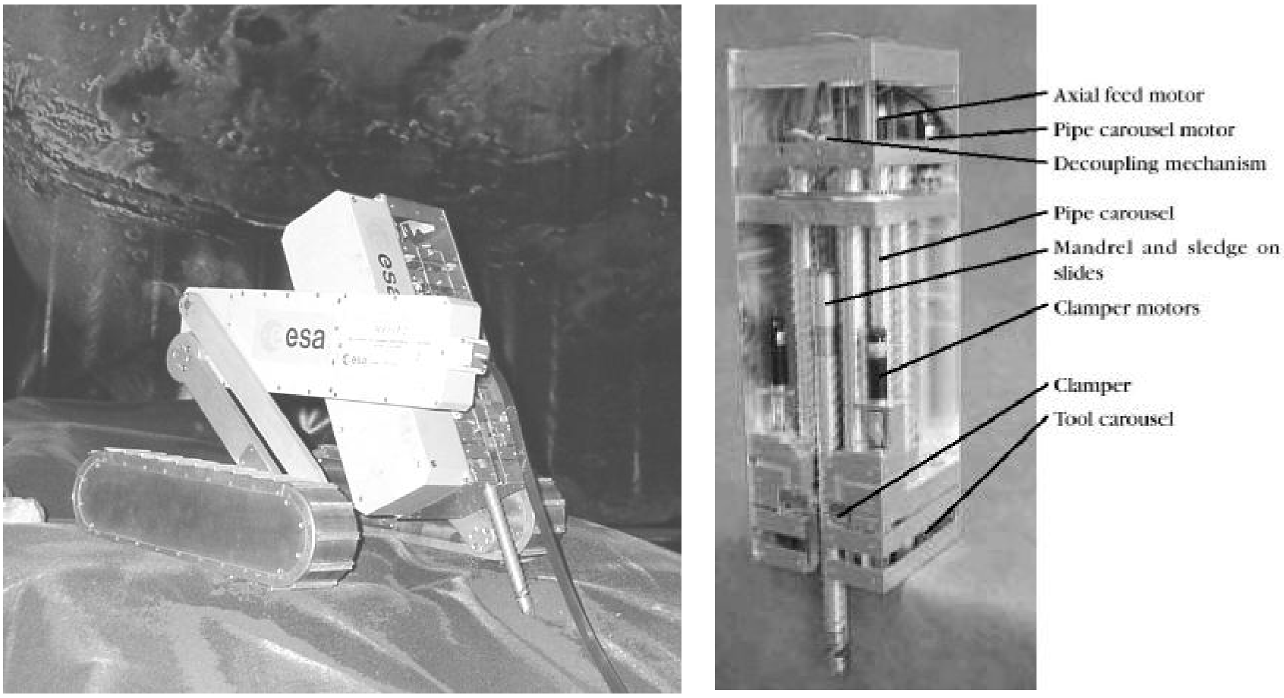

Fig. 1: The MRoSA2 rover in drilling position (Image: SSF). The DSS module is shown on the right (Image: VTT).

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The sample to be drilled into is prepared inside a transparent vertical box two meters high (Fig. 2) [7]. For sample construction the best available knowledge of the Martian surface composition is used. For rock drilling, different rock types were used to measure the required drilling power and energy to extract core samples.

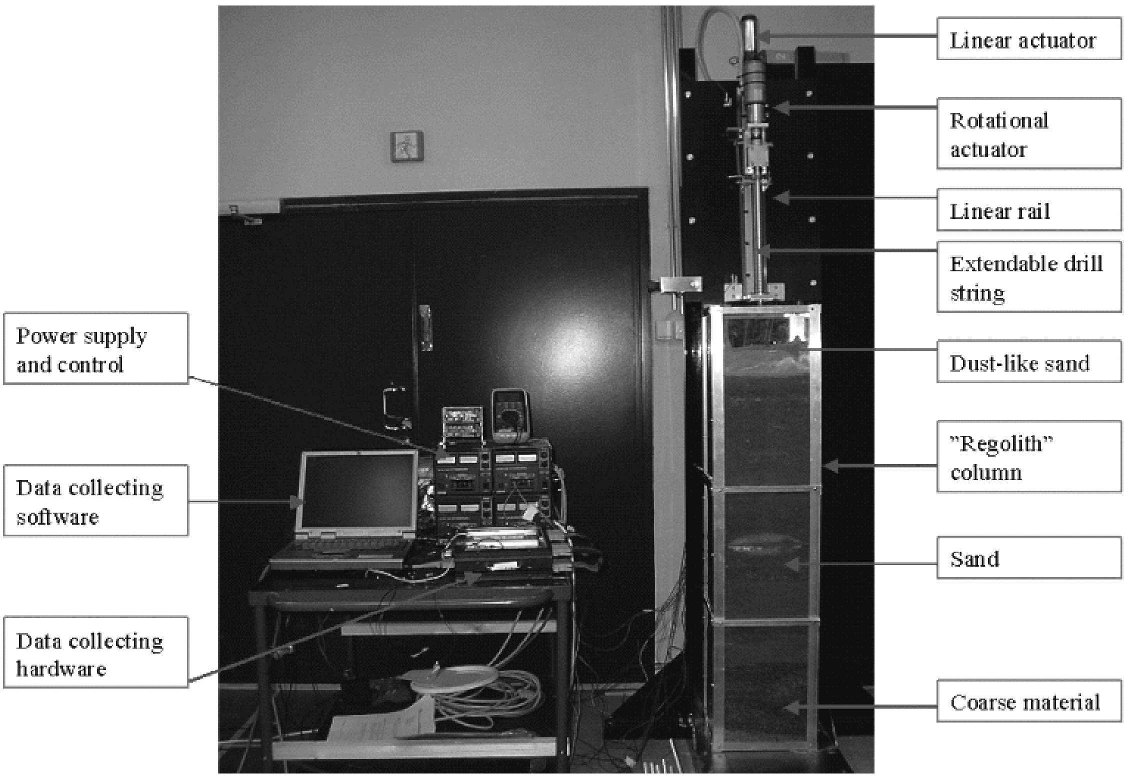
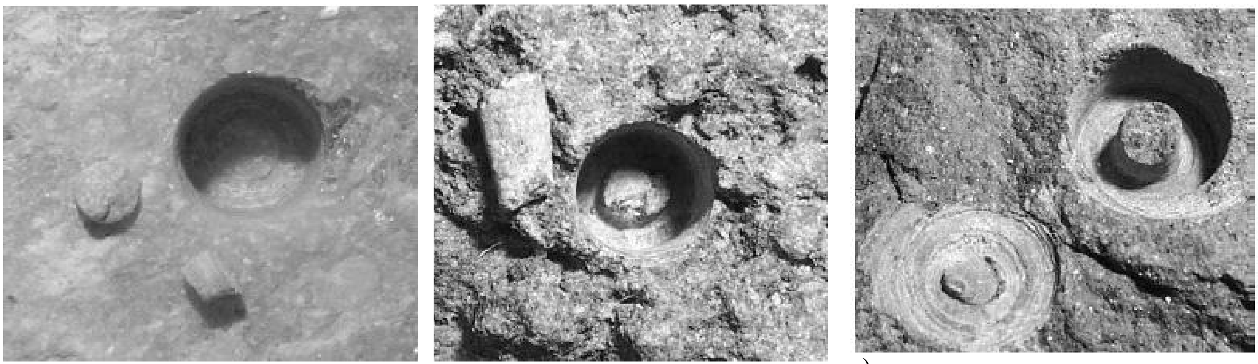


Fig. 2: The principle of the MIRANDA drilling test bench (Image: MA).

Table 4: Comparison of drilling results of different stones with a power of 10...20 W.

Rock type	Time min	Hole depth cm	Energy Wh	Energy Wh/cm	Speed of penetration cm/h
Carbonatite	16	2,1	3,8	1,8	8,1
Diabase	50	2,5	14,5	5,8	3,0
Mafurite	162	0,1	43,2	432	0,04



a) b) c)

Fig. 3: Carbonatite (a) and diabase (b) drilling holes and the corresponding retrieved core pieces. The borehole is 17 mm in diameter. Mafurite is shown in c) and the core sample has not yet been extracted (Images: MA).

The drilling power was set to 10-20 W in most of the tests to correspond typical planetary drill power budget, and drilling force was within 140-170 N. The results of these drilling sessions are summarized in Table 4. The time consumption of the drilling is first shown, along with the resulting hole depth on the stone. The third and fourth columns of Table 4 show the total energy in Wh dissipated during the drilling. This is integrated from the current and voltage data. These clearly highlight the softness of the carbonatite and the hardness of the mafurite.

The energy consumption per millimetre of the drilled rock, calculated from the values on the Table 4, was for carbonatite 0,58 Wh/mm, for diabase 0,40 Wh/mm, and for Mafurite 43 Wh/mm. Good core samples were achieved from both diabase and carbonatite. These accompanied by the holes produced on the stones (washed after drilling) are shown in Fig.3. These results are only part of the drilling results, and more drilling results are explained in [10].

EVALUATION OF REQUIREMENTS FOR FUTURE MISSIONS

The basic requirements for the drill operation are:

- Collect subsoil material from down to two-meter depth, and from the surface rocks.
- Preserve the physical and chemical properties of the sample.
- Deliver the sample to the Sample Preparation and Distribution Subsystem.
- Drill system's mass, size and power are limited.

These scientific and functional requirements lead to other requirements, which are mainly technical issues. As the ExoMars rover and the drill in the Pasteur payload are still in definition phase, some of the requirements will be revised. However, staying in the safe-side of these basic constraints will give a good approximate of a possible concept for the drill system.

Table 5: Comparison of past space drills, MRoSA2 drill and Pasteur drill parameters.

Drill unit	Mass	Electric power	Dimensions (WxLxH)	Maximum drilling depth
MRoSA2 (Upgraded)	4,5 kg (including drill pipes)	6 W rotary, 6 W linear feed (No percussion, no active drill tools. Drill control electronics not included).	110x110x350 mm w/o electronics	220 cm (11x20cm drill pipes)
Pasteur drill requirements	11 kg (with 2 DOF manipulator)	10 W average during drilling, peak limit 40 W.	160x160x500 mm	200 cm [11]

It is interesting to compare the technical requirements of the MRoSA2 drill unit and the requirements for the Pasteur drill. The Pasteur drill requirements are somewhat preliminary, but they indicate the range, which will be used in more accurate requirements in later phases of ExoMars pre-studies. Table 5 shows the technical parameters of MRoSA2 drill unit and the Pasteur drill's requirements.

Table 5 shows clearly that the MRoSA2 (Upgraded) drill concept would fit into Pasteur requirements. However, one must remember that the MRoSA2 drill unit is not a qualified flight model, but a prototype, which works in laboratory conditions with adequate reliability. MRoSA2 drill mass and size values don't include the electronics, or the manipulator, i.e. '*robot arm*'.

CONCEPT PROPOSAL

As told in previous chapters, the MRoSA2 DSS fits conceptually in the requirement frames of Pasteur drill for ExoMars mission. However, there are some fundamental changes that must be done:

- Drilling power must be increased to allow at least 10 W nominal power for drilling and 40 W peak power.
- The reliability of the DSS must be greatly improved by concentrating on the key issues of the mechanics.
- Drill tool should include temperature sensors and possibly some additional analysis instruments to allow in-situ (in borehole) analysis.
- Drill linear movement actuator (linear feed) should be equipped with spring-thrust device to allow smoother drilling and to avoid constant use of linear feed actuator.
- The drill must include 2-degree-of-freedom manipulator arm.

These add-ons and improvements should fit into the 11 kg mass budget of Pasteur drill unit. The increased power results in bigger DC motors and stiffer design. A spring-loaded linear feed will increase the size of the drill spindle, but the size will still be inside the 16 cm x 16 cm x 50 cm size budget. The concept is shown in greater details in [10].

CONCLUSION

The focus of these drill studies (MIRANDA 1 and 2) and tests during projects (MRoSA2 / Upgrade) has not been any specific mission, such as the ExoMars mission. However, the Pasteur drill (without the manipulator arm) resembles so closely the MRoSA2 drill that it poses excellent focus point to these kinds of studies. The main driver has been the clever mechanics inside the MRoSA2 drill and the challenge to study how to make it reliable and robust enough to possibly qualify as flight instrument in Martian conditions. The performed tests and studies have mainly been additional tests to the projects, and not all of them had been even required in the project plan. Mostly the tests have been performed in pure academic interest and in the frames of university educational projects.

The results presented here are mostly preliminary, and the concept proposal of Martial drill / sampler will be refined to more accurate level. The results, along with more in-depth analysis of past and current instruments and future requirements will be presented in a doctoral thesis [10] in 2005 by the author of this publication.

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Concept study for the Subsurface Sampling System for the Pasteur payload of the ExoMars mission

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INTRODUCTION

The ExoMars mission is the first Flagship mission of European Space Agency's Aurora program. The mission will include a Mars rover, which will carry a set of instruments in the rover's Pasteur payload. One of the instruments in the payload is a drill, which is supposed to retrieve samples from the Martian regolith.

In the last ASTRA conference, held in ESTEC in 2002, the author presented [1] some conclusions of the ESA-funded MRoSA2 project (a prototype of a Mars rover with a drilling and sampling system). After that, the team made some improvements to the rover, emphasizing to the drill system, to make it more functional in laboratory conditions. Later on, we built a test setup to the premises of the Helsinki University of Technology to find out the required drilling parameters in Martian-like regolith samples. These tests (the MIRANDA project, 2003) improved our knowledge on the required drilling power and some system requirements. The team also sketched some possible designs for the drill-bits to gather more information during the drilling process and from the borehole without retrieving the actual soil or core sample. After the MIRANDA tests, the author and the MIRANDA and MRoSA2 teams have revised the system parameters of the current drill system design to be consistent with the requirements of the ExoMars drill and possible other drillers in the upcoming Mars exploration projects, such as the Mars Sample Return mission.

These test results and improvements will be covered in this paper, as well as a concept of a drilling and sampling device which is capable to perform subsoil sampling in the limits of the technical requirements set to the Pasteur payload.

PLANETARY SAMPLING BY DRILLING

Since no robotic laboratory can fit all the same analysis equipment that can be used on Earth, a sample return mission would allow the best possible analysis for celestial samples. However, retrieving samples back to Earth poses several new challenges. Several methods have been proposed, and a few have been tried in past missions, and some are still under development. However, hitherto extraterrestrial samples have been retrieved only from the Moon (see Table 1), if one doesn't count solar wind samples taken by the Genesis spacecraft. The Moon has been sampled by the manned U.S. Apollo program and by the Russian's robotic Luna program.

Table 1: All-time sample-return missions.

Mission	Type	Sampling method	Sample mass	Mission timeline
Apollo 11-12,14-17	Manned	Hand, rake, drill etc.	Total ~380 kg	07/'69 - 12/'72
Luna 16, 20, 24	Robotic, Moon lander	Drill/corer	~101 g, 55 g, 170 g	09/'70, 02/'72, 08/'76
Genesis	Halo orbit around Lagrange 1	Impact/sputtering plates	~0,4 mg	08/'01 - 09/'04
Stardust	Robotic, fly-by of comet Wild 2	Aerogel collector	~1 mg	02/'99 – 01/'06
Muses-C /Hayabusa	Robotic, fly-by of asteroid Itokawa	Bullet / dust gathering	~1 g	05/'03 – 06/'07

Getting the sample back from an asteroid, comet or a planet is challenging, but the effort of actually taking the sample has its own challenges too, especially regarding subsoil samples. Even if the sample has to be analyzed in-situ instead of returning it to Earth, an automated sample analysis laboratory can still be equipped with very capable instruments. The results are even better when the sample is pristine and represents natural local conditions. Since most surface samples have been exposed by environmental conditions (such as wind, Sun's UV radiation, cosmic rays etc. leading to weathering and oxidation), surface soil and rocks can gain only limited scientific information. In fact, possible organic signatures tend to be erased by these surface processes. Therefore a subsoil sample is favoured, especially if the samples could be taken from different layers of depth, from rocks and soil. This kind of sampling requires a drill system that can drill down into different materials and retrieve the rock core or soil sample back to the (robotic) analysis laboratory.

So far, a drill has been used in Russian Luna, US Apollo and in Russian Venera mission. There is also a drill system onboard the Philae lander in ongoing European Rosetta comet mission. The first drill that has operated in another celestial body than Earth was the Russian Luna 16 drill (1970). The drill was attached to robotic lander that returned its sample back to Earth. Following that, there were the Apollo 15-17 missions (1970-1972), where astronauts used hand drill (the Apollo Lunar Surface Drill, ALSD) to retrieve subsoil samples. In addition to lunar missions (three Luna landers and Apollo 15-17 missions), the Russian Venera 13-14 landers had a robotic driller too (1982). The trend, if the term may be used, is towards miniature drillers. Terrestrial drilling could relay on virtually limitless power, thrust and torque. Unfortunately this is not case with planetary exploration drilling. During the Apollo missions, the astronauts used the ALSD to retrieve core samples down to three meters depth. The drill wasn't very big, but the "mechanics module" for attaching and detaching the drill strings was the astronaut himself. The dexterity of astronaut in surprising situations is unbeatable, i.e. when the drill gets stuck. However, it is not feasible always to send astronauts instead of robots. The challenge is to get a robot to use a miniature drill in all possible drilling-related situations.

ESA has plans to launch the ExoMars mission in 2009. The mission will include a Mars orbiter and a landing craft, and the lander will deliver a robotic rover to Martian surface. The rover will include an automatic drill, which is capable to retrieve subsoil samples. The drill has to be quite small, and still it has to be able to drill down to 2 m and make multiple drilling and sampling operations. Compared to previously used drills in space missions, the challenge is great to make the drill both miniature in size and still versatile in operation. In addition, the drill must not consume too much power, and it must be mostly autonomous in operation (due to the long round-trip light time between Earth and Mars).

While there are several past, ongoing and planned drill-related projects, this paper concentrates on already-flown drills, the MRoSA2 drill and the ExoMars drill to compare the characteristics and performance and to sketch possible concept to fit into the ExoMars mission. As seen in Table 2, there have been four different drilling instruments in space, counting also the SD2 drill onboard the Philae lander of ESA's Rosetta mission. These four instruments are all different in operation, but some similarities can be seen. The ALSD is clearly the best in performance, but it cannot be counted because it doesn't include any autonomous functions, which are needed in robotic missions. The Venera drill was strongly made to Venusian environment (it relied on pressure difference in sample acquisition), so it cannot be used in similar manner for example in Mars or on the Moon. The comparison is then reasonable only between Luna and SD2 drills. Despite the fact that Luna drill concept is roughly 35 years old, the principle is good, and pretty much similar to SD2 drill. However, both these drills are more or less shallow-drilling devices, since they can penetrate only few tens of centimeters. The objective of future drills is to be able to drill down to more than one meter. The MRoSA2 concept is one possibility to achieve this.

Table 2: Comparison of past and ongoing missions' space drills [2-5].

Drill unit / mission	**Mass kg**	**Electric power W**	**Dimensions mm**	**Maximum Drilling depth, mm**
Luna 16, 20 and 24	13,6 kg	140 W	690 x 290 (tube)	350 mm
Apollo (ALSD)	13,4 kg (without drill strings)	Unknown (several tens of watts)	577 x 244 x 178	3000 mm
Venera 13-14 Drill	26,2 kg	90 W (+ pyrotechnic pneumatic actuators and sample transfer)	~700 x ~200 (+ related pneumatics)	35 mm (working path 400 ± 10 mm)
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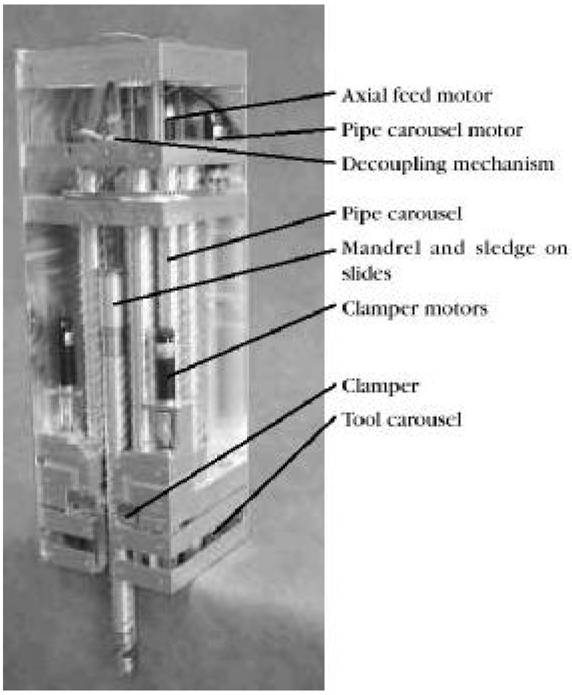

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ESA announced the Aurora Student Competition in January 2003 for ESA member states' universities. The competition called for a team, which would then study and document its work aiming for future space technologies. HUT Automation Laboratory gathered a team, which was lead by the author of this publication. The team designed and built a drilling test bench in the 'MIRANDA' project. The scope of the work was to simulate deep drilling in Mars with existing MRoSA2 drill hardware and document the tested results. The project ended in July 2003. Later on, the author started another drill test project by using the existing MIRANDA hardware. This project, called the 'MIRANDA-2' (2004), aimed to analyze the temperature variations in the drill bit and in the drilled material during drilling and sampling. The existing drill test bench was modified to fit the new project's requirements to allow low-thrust drilling and temperature analysis.

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 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 feedback or data-transfer used solely for control purposes and having no scientific interest. Drilling is performed by using the ESA's MRoSA2 drill heads. As the drill sledge has mass of about 7 kg, a counterweight is being used to allow low-thrust drilling. The drill bit has temperature sensors (unlike the MRoSA2) to measure the sample temperature during drilling. The objective is to avoid increasing the temperature of the sample to melting point of water ice.

The sample to be drilled into is prepared inside a transparent vertical box two meters high (Fig. 2) [7]. For sample construction the best available knowledge of the Martian surface composition is used. For rock drilling, different rock types were used to measure the required drilling power and energy to extract core samples.

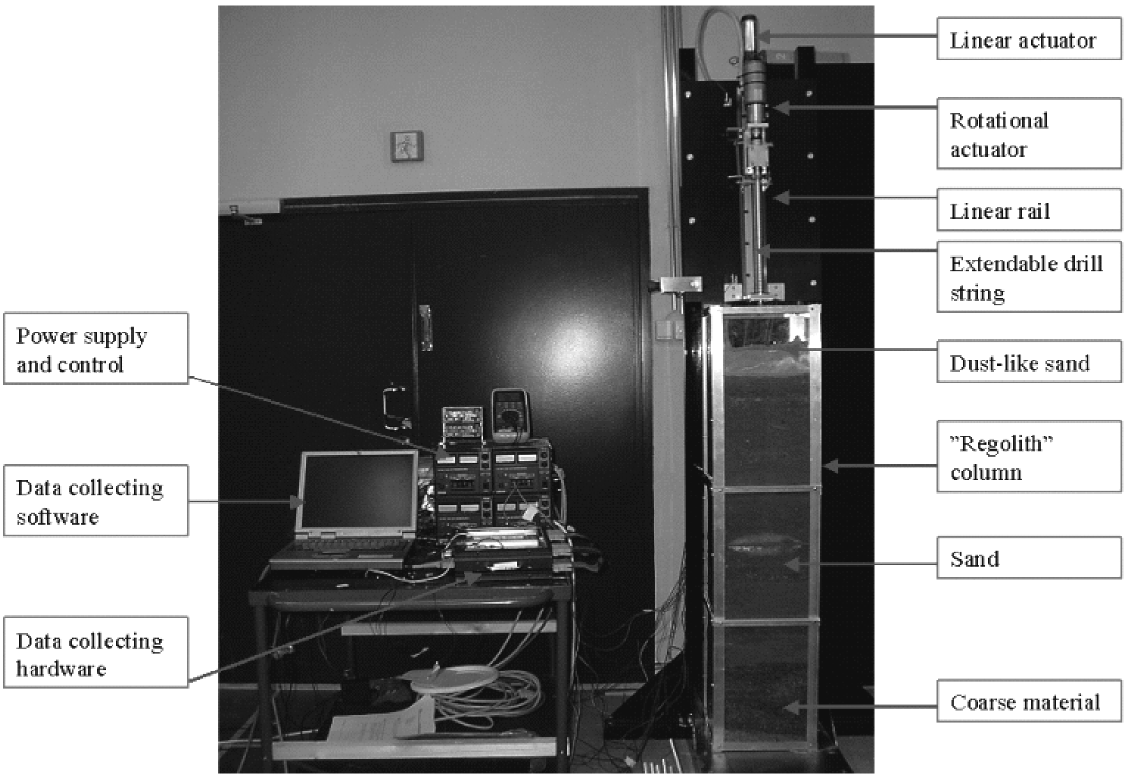
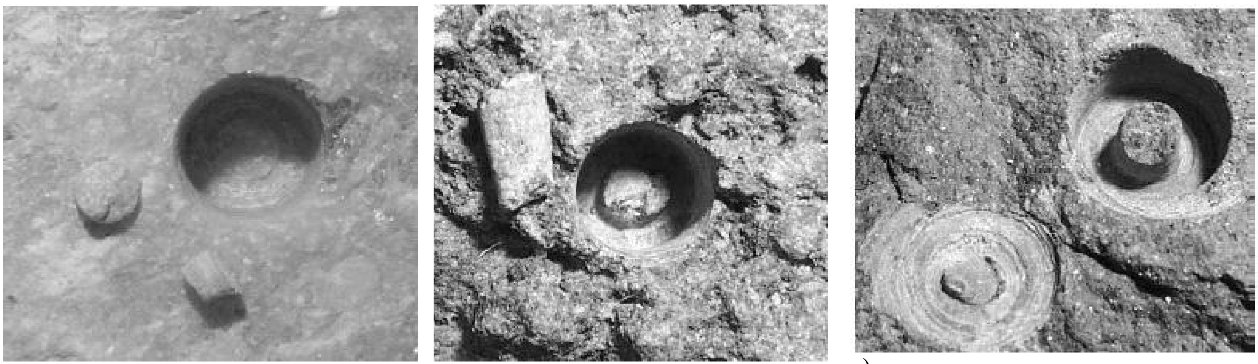


Fig. 2: The principle of the MIRANDA drilling test bench (Image: MA).

Table 4: Comparison of drilling results of different stones with a power of 10...20 W.

Rock type	Time min	Hole depth cm	Energy Wh	Energy Wh/cm	Speed of penetration cm/h
Carbonatite	16	2,1	3,8	1,8	8,1
Diabase	50	2,5	14,5	5,8	3,0
Mafurite	162	0,1	43,2	432	0,04



a) b) c)

Fig. 3: Carbonatite (a) and diabase (b) drilling holes and the corresponding retrieved core pieces. The borehole is 17 mm in diameter. Mafurite is shown in c) and the core sample has not yet been extracted (Images: MA).

The drilling power was set to 10-20 W in most of the tests to correspond typical planetary drill power budget, and drilling force was within 140-170 N. The results of these drilling sessions are summarized in Table 4. The time consumption of the drilling is first shown, along with the resulting hole depth on the stone. The third and fourth columns of Table 4 show the total energy in Wh dissipated during the drilling. This is integrated from the current and voltage data. These clearly highlight the softness of the carbonatite and the hardness of the mafurite.

The energy consumption per millimetre of the drilled rock, calculated from the values on the Table 4, was for carbonatite 0,58 Wh/mm, for diabase 0,40 Wh/mm, and for Mafurite 43 Wh/mm. Good core samples were achieved from both diabase and carbonatite. These accompanied by the holes produced on the stones (washed after drilling) are shown in Fig.3. These results are only part of the drilling results, and more drilling results are explained in [10].

EVALUATION OF REQUIREMENTS FOR FUTURE MISSIONS

The basic requirements for the drill operation are:

- Collect subsoil material from down to two-meter depth, and from the surface rocks.
- Preserve the physical and chemical properties of the sample.
- Deliver the sample to the Sample Preparation and Distribution Subsystem.
- Drill system's mass, size and power are limited.

These scientific and functional requirements lead to other requirements, which are mainly technical issues. As the ExoMars rover and the drill in the Pasteur payload are still in definition phase, some of the requirements will be revised. However, staying in the safe-side of these basic constraints will give a good approximate of a possible concept for the drill system.

Table 5: Comparison of past space drills, MRoSA2 drill and Pasteur drill parameters.

Drill unit	Mass	Electric power	Dimensions (WxLxH)	Maximum drilling depth
MRoSA2 (Upgraded)	4,5 kg (including drill pipes)	6 W rotary, 6 W linear feed (No percussion, no active drill tools. Drill control electronics not included).	110x110x350 mm w/o electronics	220 cm (11x20cm drill pipes)
Pasteur drill requirements	11 kg (with 2 DOF manipulator)	10 W average during drilling, peak limit 40 W.	160x160x500 mm	200 cm [11]

It is interesting to compare the technical requirements of the MRoSA2 drill unit and the requirements for the Pasteur drill. The Pasteur drill requirements are somewhat preliminary, but they indicate the range, which will be used in more accurate requirements in later phases of ExoMars pre-studies. Table 5 shows the technical parameters of MRoSA2 drill unit and the Pasteur drill's requirements.

Table 5 shows clearly that the MRoSA2 (Upgraded) drill concept would fit into Pasteur requirements. However, one must remember that the MRoSA2 drill unit is not a qualified flight model, but a prototype, which works in laboratory conditions with adequate reliability. MRoSA2 drill mass and size values don't include the electronics, or the manipulator, i.e. '*robot arm*'.

CONCEPT PROPOSAL

As told in previous chapters, the MRoSA2 DSS fits conceptually in the requirement frames of Pasteur drill for ExoMars mission. However, there are some fundamental changes that must be done:

- Drilling power must be increased to allow at least 10 W nominal power for drilling and 40 W peak power.
- The reliability of the DSS must be greatly improved by concentrating on the key issues of the mechanics.
- Drill tool should include temperature sensors and possibly some additional analysis instruments to allow in-situ (in borehole) analysis.
- Drill linear movement actuator (linear feed) should be equipped with spring-thrust device to allow smoother drilling and to avoid constant use of linear feed actuator.
- The drill must include 2-degree-of-freedom manipulator arm.

These add-ons and improvements should fit into the 11 kg mass budget of Pasteur drill unit. The increased power results in bigger DC motors and stiffer design. A spring-loaded linear feed will increase the size of the drill spindle, but the size will still be inside the 16 cm x 16 cm x 50 cm size budget. The concept is shown in greater details in [10].

CONCLUSION

The focus of these drill studies (MIRANDA 1 and 2) and tests during projects (MRoSA2 / Upgrade) has not been any specific mission, such as the ExoMars mission. However, the Pasteur drill (without the manipulator arm) resembles so closely the MRoSA2 drill that it poses excellent focus point to these kinds of studies. The main driver has been the clever mechanics inside the MRoSA2 drill and the challenge to study how to make it reliable and robust enough to possibly qualify as flight instrument in Martian conditions. The performed tests and studies have mainly been additional tests to the projects, and not all of them had been even required in the project plan. Mostly the tests have been performed in pure academic interest and in the frames of university educational projects.

The results presented here are mostly preliminary, and the concept proposal of Martial drill / sampler will be refined to more accurate level. The results, along with more in-depth analysis of past and current instruments and future requirements will be presented in a doctoral thesis [10] in 2005 by the author of this publication.

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