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CONCEPT EVALUATION OF MARS DRILLING AND SAMPLING INSTRUMENT

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On the surface of Mars, the Sun is about half the size as seen from Earth.
The nights are colder than Antarctica has ever been, and even summer days are freezing.
The atmosphere is so thin, that it would boil our blood from the smallest wound, and the air consists of deadly amounts of carbon dioxide.
There is no life, there is no running water and there is no shelter to escape the Sun's ultra-violet radiation that sterilizes everything left to the Red Planet's surface. The whole planet is a large, dead desert.

And yet, after Earth, it is the most hospitable place for humans in the Solar System!

Mars, meaning the God of War, has two tiny moons, Phobos and Deimos. The Greek names mean fear and terror. This illustrates the planet well as a place for humans to go. And still we will go. Eventually, we will step our feet to the Red Planet. Because we must.

But first come the robots!

- The Author

Image on the cover sheet: Bonneville crater, Gusev crater region, Mars. Image taken on 13th March 2004 by NASA's Mars Exploration Rover 'Spirit'. Image credit: NASA/JPL/Cornell.

Abstract

The search for possible extinct or existing life is the goal of the exobiology investigations to be undertaken during future Mars missions. As it has been learnt from the NASA Viking, Pathfinder and Mars Exploration Rover mission, sampling of surface soil and rocks can gain only limited scientific information. In fact, possible organic signatures tend to be erased by surface processes (weathering, oxidation and exposure to UV radiation from the Sun).

The challenge of the missions have mostly been getting there; only roughly one third of all Mars missions have reached their goal, either an orbit around the planet, or landing to the surface. The two Viking landers in the 1970's were the first to touch down the soil of Mars in working order and performing scientific studies there. After that there was a long gap, until 1997 the Pathfinder landed safely on the surface and released a little rover, the Sojourner. In 2004 other rovers came: the Mars Exploration Rover Spirit and a while after that, the sister rover Opportunity. These five successful landings are less than half of all attempts to land on Mars. Russia, Europe and the United States have all had their landers, but Mars is challenging. Even Mars orbit has been tough to reach by many nations' orbiters. It is then understandable that of these five successful landings, performed by National Aeronautics and Space Administration (NASA), there have not yet been very complicated mechanical deep-drilling instruments onboard. The risks to get there are great, and the risk of malfunctioning of a complicated instrument there is also high. Another reason to avoid a deep-driller from the lander payload is simply the mass constrains. A drill is a heavy piece of payload, and the mass allocations for scientific instruments are small.

In the launch window of 2009, both European Space Agency (ESA) and NASA have their plans to send a rover to Mars. Both of them will include some means to analyse the subsurface material. ESA's rover, called the ExoMars rover, will carry a deep-driller onboard in its Pasteur payload. At the time of writing this thesis, an exact definition of the Pasteur drill has not yet been defined.

The author of this thesis has studied the driller instruments in his past work projects and in his doctoral studies. The main focus of this thesis is to analyse the feasibility of different drill configurations to fit to the requirements of the ExoMars' Pasteur payload drill by using the information gathered from the past projects. In this thesis, the author introduces a new concept of a robotic driller, called the MASA drill. The MASA drill fulfils the needs for the drill instrument onboard the Pasteur payload. The main study in this thesis concentrates on design work of the MASA drill, as well as analysis of its operation and performance capabilities in the difficult task of drilling and sampling.

Foreword

I had the pleasure of joining the ESA-funded MRoSA2 "Mars rover" project in the beginning of 2001 as a systems engineer in my work place, Space Systems Finland Ltd. The work with the prototype Mars rover was much harder than I first thought: a real hands-on experience with mechanics, electronics and software. But it was fun! It was what I wanted to do, to put my hands inside the machine and try to make it work. Although I have been a real space-enthusiastic for whole my life, this was the point when I began thinking about Mars in-situ sampling and drilling problems. I am truly thankful for the good working atmosphere and enthusiasm to the original MRoSA2 rover mechanics team: Mr. Jari Saarinen and Dr. Jussi Suomela from HUT, and Mr. Petri Kaarmila from VTT. Many of the novel, even strange but working ideas popped up after a day of long work with the drill, dirtying our hands inside the 'clockwork' and desperately trying to find ways to make it work.

The first project got continuation from ESA ESTEC in the form of MRoSA2 Upgrade project. This project was carried out in a relatively tight schedule during the fall 2002 and summer 2003. I was the project manager in this project. This was the time to make some ideas into reality. In the between of the first and second project, we gathered a lessons-learned memo of the drill system, and now we had a possibility to realize them to make the system even better. And we did, thanks to the HUT MRoSA2 Upgrade team of the work well done.

In the spring 2003, ESA announced the Aurora Student Competition. The idea was to create a team, which would then study and document its work, which aimed to future space technologies. We took this opportunity in the HUT Automation Laboratory, where I was studying my minor in robotics. I had the pleasure of act as a team leader in this MIRANDA project, and I want to express my gratitude to the whole team: Mr. Aleksi Kivi, Mr. Seppo Heikkilä, Ms. Sini Merikallio and our advisor Mr. Tomi Ylikorpi.

I am most grateful to Mr. Tomi Ylikorpi for the time and expertise that he has given to this thesis. Tomi was the original designer of the MRoSA2 drill when he still worked at the VTT, so it has been both useful and pleasure to work with him during the MRoSA2 and MIRANDA projects. In addition, he gave me valuable comments of my thesis' manuscript during the time of writing this thesis.

Professor Aarne Halme deserves my sincere gratitude of providing the laboratory for the late-night use of the test equipment throughout the original MIRANDA study as well as the second study, the MIRANDA-2. I want also thank the kind support of the HUT Automation laboratory staff, especially Mr. Tapio Leppänen and Mr. Kalle Rosenblad for their good work for the drill test bench.

Professor Martti Hallikainen from the HUT Laboratory of Space Technology is acknowledged for his kind support and time for my thesis and for my Ph.D. studies, and I want also express my gratitude to the laboratory for sponsoring my thesis work and conferences.

Like every enthusiastic kid, I also posed myriads of questions and information requests throughout the research and test period of my thesis work. I want to express my thanks to the kind support of information, which I got from the European Space Agency, especially from Mr. Gianfranco Visentin and Dr. Jorge Vago. I also want to acknowledge the NASA JPL Mars scientists, especially Dr. Nathan Bridges for his kind help throughout several fruitful e-mail discussions and touring me in the Jet Propulsion Laboratory, allowing me to meet some of JPL's drilling experts.

Professor Martti Lehtinen from Finnish Museum of Natural History deserves my sincere gratitude for giving me his time and effort for selecting and giving me the stones for the MIRANDA drilling tests and giving me interesting explanations of geological issues.

I would also like to thank Mr. Dale Boucher (NORCAT) and Mr. Erick Dupuis (Canadian Space Agency), who kindly introduced me their drilling tests and gave me material to support this thesis.

I want to thank my employer Space Systems Finland Ltd. for offering me the possibility to work in the highly interesting MRoSA2 project, which led me to study the Mars exploration. I am also greatful for my employer for sponsoring my trip to the Sixth Mars Conference in 2003 at Caltech, Pasadena.

I am very thankful for my preliminary examiners Dr. Jukka Piironen (Finnish Geodetic Institute) and Dr. Christopher Lee (von Hoerner & Sulger GmbH) for their reviews and good comments for the thesis.

Finally, I wish to express my fondest thanks to my wife Ulla, my parents, my sister and my friends who have supported me and provided their help, patience and encouragement needed to complete this thesis.

Espoo, March 2005

Matti Anttila

Contents

Acronyms and Abbreviations

5NM	Russian Mars Sample Return Mission
ALSD	Apollo Lunar Surface Drill
APXS	Alpha-Particle-X-ray Spectroscope
ASI	Italian Space Agency
ASTID	NASA’s Astrobiology Technology & Instrument Development Program
Aurora	ESA's new optional programme for the human and robotic exploration of our Solar System.
BMDO	Ballistic Missile Defense Organisation
BS	Brush Station
CCW	Counterclockwise
CDF	Concurrent Design Facility
CDS	Core Drill System
ÇIVA	Rosetta Lander Imaging System
CNSR	Comet Nucleus Sample Return
CO2	Carbon dioxide
COSAC	Evolved Gas Analyser, elemental, molecular composition
COTS	Commercial Off The Shelf
CPU	Central Prosessing Unit
CSA	Canadian Space Agency
DC	Direct Current
DeeDri	Deep Drill
DIBS	Drill-Integrated spectrometer
DLR	German Aerospace Research Establishment
DoF	Degree(s) of Freedom
DPU	Drill Positioning Unit
DS	Drilling Strength
DS2	Deep Space 2
DSDP	Docking and Sample Delivery Port
DSDP	Docking and Sample Delivery Port
DSS	Drilling and Sampling Subsystem
DSS	Drilling and Sampling Subsystem
DU	Drill Unit
ELIPS	European Life and Physical Sciences in Space Programme: the science programme run by ESA's Directorate of Human Spaceflight.
ERC	Earth Re-Entry Capsule
ESA	European Space Agency
ESTEC	European Space Technology and Research Centre
FDIR	Failure Detection, Recovery and Isolation
FEAE	Finnish East African Expedition
FMI	Finnish Meteorology Institute
FORJ	Fiber Optic Rotary Joint
g	Gravity, g-force factor: $9.81 m/s^2$
GC/MS	Gas Chromatographer / Mass Spectrometer
GSTP	ESA's General Support Technology Program
GUI	Graphical User Interface
Gyr	Giga year; 10^9 years.
GZU	Venera Drill type
HB	Honeybee Robotics
HDD	Hard Disk Drive
HK	Housekeeping (telemetry data)
HUT	Helsinki University of Technology
HW	Hardware
IDD	Instrument Deployment Device
IDD	Instrument Deployment Device
IFE	Instrument Front End
IR	Infra Red
ISAS	Institute of Space and Astronautical Science, Japan
ISS	International Space Station
ITT	Invitation To Tender
J2000	Julian 2000 epoch star positions
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
kgf	kilogram force, ~9.81 N
LIBS	Raman and Laser Induced Breakdown Spectrometer
MA	Matti Anttila (the author)
MAE	Materials Adherence Experiment
MASA	MArs Sample Acquisitor
MASW	MASA Drill Software
MAV	Mars Ascent Vehicle
Mb	Mega-bit: a unit of data volume equal to 2^{20} bits of information.
MEE	Mobile End Effector
MER	Mars Exploration Rover (NASA mission)
MESP	Mars Environment Survey Package
MESUR	Mars Environmental Survey Pathfinder
MET	Meteorology Package
MEX	Mars Express (ESA)
MGS	Mars Global Surveyor (NASA)
MIRANDA	MartIan Regolith Acquisition and iN-situ Drill-based Analyzer
MOD	Mars Organic Detector
MODULUS	Evolved Gas Analyser, isotopic composition
MOI	Mars Oxidant Instrument (also: Mars Orbital Insertion)
MOLA	Mars Orbiter Laser Altimeter
MPF	Mars Pathfinder
MPL	Mars Polar Lander
MRoSA	Micro Robots for Scientific Application ("Nanokhod")

MRoSA2(U)	Micro Robots for Scientific Application 2 (Upgrade project)
MRR	Material Removal Ratio
MSL	Mars Science Laboratory
MSR	Mars sample return
MUSES-C	Hayabusa Spacecraft
MVACS	Mars Volatiles and Climate Surveyor
MWD	Measurement While Drilling
NASA	National Aeronautics and Space Administration
NORCAT	Northern Centre for Advanced Technology
NSSDC	National Space Science Data Center
NTC	Negative Temperature Coefficient
OBCP	On-Board Control Procedures
OMEGA	Observatoire pour la Minéralogie, l'Eau, la Glace et l'Activité
PanCam	ExoMars rover's panoramic camera instrument
PAW	Position Adjustable Workbench
PC	Personal Computer
PDrill	Drill input power
PIP	Proposal Information Package
PSRD	Pasteur System Requirements Document
PSRI	Planetary Sciences Research Institute
PUS	Packet Utilization Standard
RA	Robot Arm
RAC	Robot Arm Camera
RAT	Rock Abrasion Tool
RCG	Rock Corer/Grinder
RCL	Rover Company Limited
RCM	Requirement Correspondence Matrix
RFI	Request For Information
RFMU	Rover Functional Mock-Up
RHU	Radioisotope Heating Units
RMS	Root Mean Square
ROLIS	Rosetta Lander Imaging System
rpm	Revolutions Per Minute
RSS	Robotic Sampling System
RSS/N	Robotic Sampling System based on Nanokhod
RTG	Radioisotope Thermal Generators
S/C	Spacecraft
SAHS	Sample Acquisition and Handling System
SCP	Specific Cutting Power
SD2	Sample and Distribution Device
SDE	Specific Drilling Energy
SDP	Specific Drilling Power
SE	Specific Energy
SHPS	Sample handling and preparation system, same as SPDS.
SMSS	Soil Mechanics Surface Sampler
SPDS	Sample Preparation and Distribution Subsystem
SPHS	Sample Preparation and Handling System
SRD	System Requirements Document
SSA/DT	Small Sample Acquisition / Distribution Tool
SSF	Space Systems Finland Ltd.
SSI	Stereo Surface Imager
SW	Software
TBC	To Be Confirmed
TBD	To Be Defined
TC	Telecommand
TEGA	Thermal and Evolved Gas Analyzer
TM	Telemetry
TRL	Technology Readiness Level
TRP	Technology Research Program
TS	Tecnospazio
TV	Television
UK	United Kingdom
US(A)	United States (of America)
USB	Universal Serial Bus
USDC	Ultrasonic/Sonic Driller/Corer
USDC	Ultrasonic/Sonic Driller/Corer
USGS	US Geological Survey
UV	Ultra Violet
VTT	Valtion Tieteellinen Tutkimuskeskus, Finnish State Research Centre
WAE	Wheel Abrasion Experiment
XRD	X-Ray Diffraction Spectrometer
XRF	X-Ray Fluorescense

1. INTRODUCTION

This thesis covers the problem of developing a Mars drilling and sampling instrument in concept level. The aim is to use current research experience and knowledge to derive an instrument, which fulfils the requirements of near-future missions.

Mars has been under study of robotic explorers for decades, but there has never been an instrument, which can acquire truly subsoil samples (if one does not take into account trenches of rover's wheels or scratches made by the scoops of robotic landers). A drill, which can be accommodated to a very small space, consumes little power, and still is able to penetrate deep layers of Martian soil and rock, is hard to make. And we are not yet even talking about the sample acquisition from unknown terrain type, let alone the requirement to use the same drill for multiple samplings and possible in-situ measurements in the borehole.

In this thesis, the problems of drilling and sampling are covered in details. Using experience of past projects, a potential solution is offered to satisfy the needs of near-future robotic Mars exploration missions.

1.1 Objective of the thesis

The objectives of this thesis are:

- To evaluate current and existing Mars drilling and sampling instruments:

An evaluation has been done to both past and currently operating instruments, and also to existing public plans of near-future missions. In addition, some instruments that have been operated in other celestial bodies than Mars have also been studied in this thesis.

- To specify the requirements for future Mars drilling and sampling instruments:

There are some plans to examine Martian soil in near-future time-scale by drilling and sampling it with various kinds of instruments. The general technical requirements for an instrument vary based on the required results. These requirements were studied focusing to the requirements of ExoMars mission's Pasteur Drill System.

- To find a solution to modify current instrument concepts to fulfil the future needs:

The focus has been especially in the ESA's ExoMars mission, which is planned for launch in the 2009 launch window. The thesis presents a new drill instrument concept, named the MASA drill.

1.2 Why Mars?

Mars is the primary place to study in a detailed manner, because it is the most Earth-like planet in our Solar System. Recent measurements show the presence of water [70], which raises the likelihood of finding traces of extinct life. In addition, Mars is also the most hospitable celestial body for humans to visit. Although the Moon is much closer than Mars, the latter offers far better conditions for astronauts to explore the surface due to the day length, greater gravity and radiation protection. Even Venus is closer than Mars, but runaway greenhouse effect has developed a very dense carbon dioxide atmosphere. This, in turn, has resulted in the escape of all of its possibly existed water, and created an infernal surface temperature of nearly 500 °C [59].

Exploring Mars will enhance our knowledge of the Solar System's history, and the formation of the planets. In case Mars has watery past, there are high chances that it has also hosted life in its history. If traces of extinct life could be found, that would naturally raise some fundamental questions and change the way that the humankind thinks of the life itself.

Even though it is said that one competent field geologist could achieve the same results in one day that a robot could do in its whole lifetime, it is not always feasible to send astronauts instead of robotic explorers. Before the astronauts can be sent to the Red Planet, a thorough research is to be done in several science areas. At the time of writing this thesis, there are two astronauts orbiting the Earth in the International Space Station (ISS). The ISS orbits Earth in about 400 km height. During the Apollo program, humans visited the Moon, which is about 400000 km away, a thousand times farther than the ISS. That is the longest voyage that humans have ever made. At the most distant point of its orbit, Mars is about 400 millions kilometres from Earth. That is one thousand times more than the distance from Earth to the Moon. The United States have their ‘Vision for Space Exploration’ program [57], which aims for a manned Mars mission. Europe has ESA’s Aurora [51] program with the same goal. But before the humans will set their feet to the Martian surface, the robots will have to do the fundamental basic research.

1.3 Planet Mars

Mars is the third closest neighboring large celestial body to our planet, right after the Moon and planet Venus. Mars, being the fourth planet from the Sun, resides with Earth in a region of the Solar System where liquid water can exist on the surface (regarding the temperature aspect), and therefore the chance that life is, or once was, present on Mars remains a distinct possibility and the key question of Mars research. Mars has been named after the Roman god of war (*Ares* in Greek history), and the planet was probably given this name because of its red color, resembling blood in the battlefields. Therefore Mars is frequently referred to as the Red Planet. Now we know that the red color is caused by rust (iron oxide) on the surface. An image of the planet is seen in Figure 1, which has been taken by the Hubble Space Telescope in August 2003 (Mars opposition) [22]. A surface view is seen in Figure 2, taken by the Mars Exploration Rover Spirit in March 2004 [23].

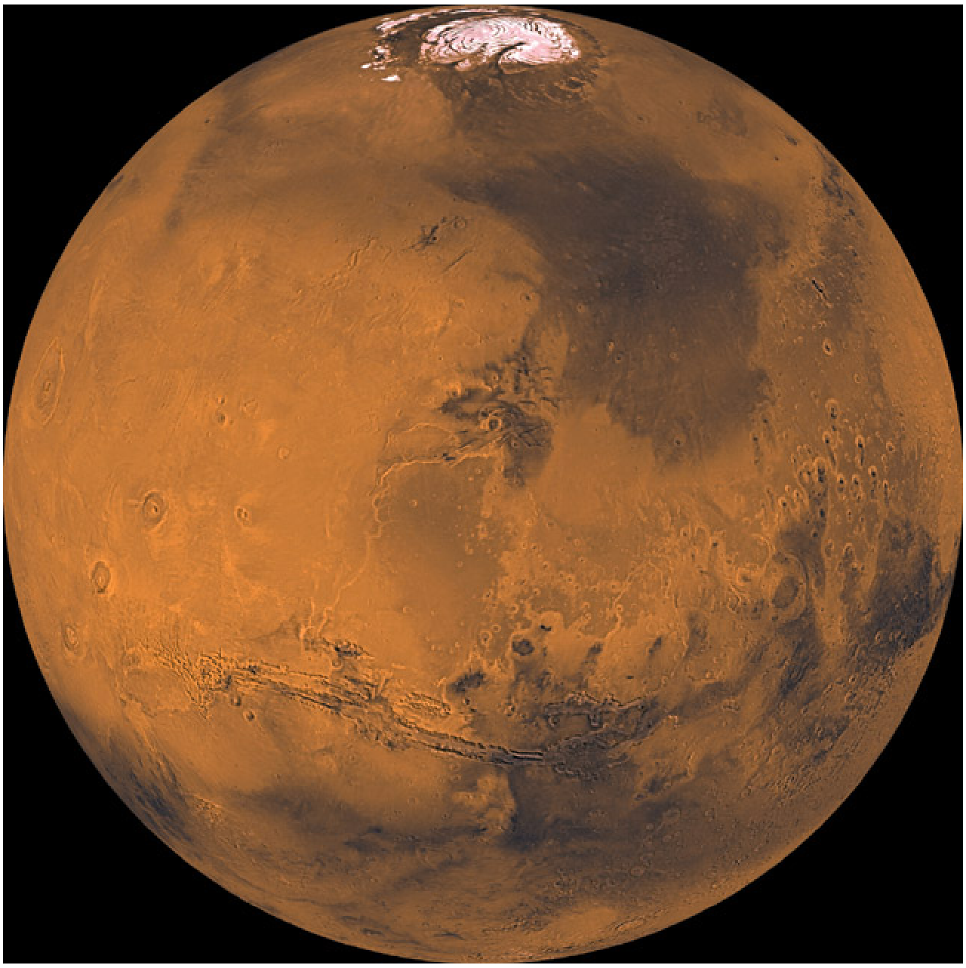


Figure 1: Planet Mars seen by the Hubble space telescope [22].

1.3.1 Environmental conditions

Mars has an atmosphere, but it is quite different from that of Earth (see Appendix III). The main constituent is carbon dioxide, with only small amounts of other gases, such as nitrogen, argon and oxygen. Even that the Martian atmosphere contains only about one thousandth as much water vapor as our air, still this amount of water can condense out, forming clouds high in the Martian atmosphere. Even some local patches of early morning fog can form in deep valleys. At the Viking Lander 2 site at Utopia Planitia [33] (Figure 3), a thin layer of water frost [60] covered the ground each winter during the mission's lifetime in 1976-1980. This frost period lasted for a third of the Martian year. The atmosphere is so thin, that it cannot support liquid water on the planet's surface. There is still some evidence that in the past Mars may have had a denser atmosphere. For millions of years ago, there may have been flowing water on the surface. Orbiters have imaged physical features, which seem to be shorelines, riverbeds and islands. These features suggest that great rivers once existed in Mars. But the surface pressure is not the only factor that affects to the existence of liquid water; Mars is cold. The average (recorded) temperature on the Red Planet is -63°C with a maximum temperature of about 25°C and a minimum recorded temperature of -140°C [61]. The average atmospheric pressure on the surface is only about 7 millibars (see Appendix III), but it varies greatly with altitude from about 10 millibars in the deepest basins to only 1 millibar at the top of the Olympus Mons mountain. Despite that the Mars' surface pressure is very low (Mars' surface pressure is equal to Earth's atmospheric pressure at 30 km height), the atmosphere is thick enough to support very strong winds and vast dust storms. These storms occasionally engulf the entire planet for several months. Mars' thin atmosphere produces a greenhouse effect but it is only enough to raise the surface temperature by 5°C; much less than can be seen on Venus or Earth. Another issue affecting Mars' surface temperature is its orbit. Unlike Earth's orbit, Mars' orbit is highly elliptical. Between aphelion and perihelion (orbit's farthest and closest point to the Sun, respectively), the average temperature variations are about 30°C. So the orbital phase, together with the tilted rotation axis, has effect to Mars' climate.

The temperature and the atmospheric pressure are both factors that must be taken into account when designing a drilling and sampling machine into Martian environment. Basically, the pressure issue is similar to when dealing with vacuum conditions, although even the thin atmosphere of Mars has some effects regarding the dust accumulation and thermal issues, in some means also to the electric charge exchange [71]. The atmosphere in Mars, despite being only about 1/150 of Earth's atmospheric pressure, is actually a good matter for thermal issues. In pure vacuum conditions the variations of shadow and light are extremely sharp, and the temperature variations are extreme and fast. This exposes the structures to larger thermal stress, possibly causing mechanical damage in shorter time than in a situation where thermal differences occur in longer time interval.

Figure 2: The surface of Mars, seen by the Mars rover Spirit [23].

1.3.2 Geological conditions

Even though Mars is a smaller planet than Earth (average radiuses are 3397 km and 6378 km, respectively), the land area is about the same for both planets. This is because more than 70% of Earth is covered with ocean. Mars has some exceptional landmarks [34] (Figure 3); Valles Marineris is a canyon system of about 4000 km long and from 2 to 7 km deep. The canyon was named after the spacecraft Mariner 4, which was the first spacecraft to visit Mars in 1965 [54]. Olympus Mons is the largest known mountain in our Solar System. The mountain peak is about 24 km higher than the surrounding plain, and the diameter of the mountain base is more than 500 km. Tharsis Montes is a huge bulge of Martian crust more than 4000 km across and 10 km higher than surrounding lowlands at its top. It is the largest volcanic region on Mars, containing 12 large volcanoes. Hellas Planitia is an impact basin in the southern hemisphere. Nearly 9 km deep and 2100 km across, the basin is surrounded by a ring of material that rises about 2 km above the surroundings and stretching out to 4000 km from the basin center.

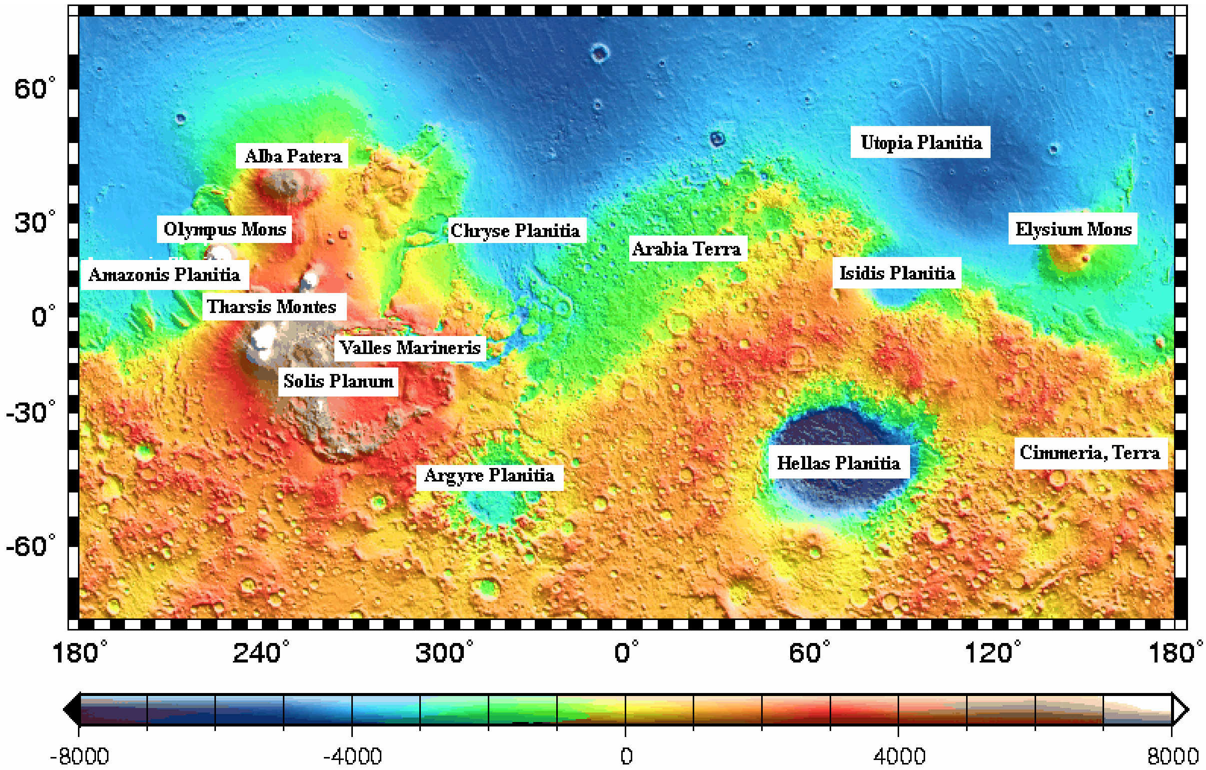


Figure 3: Global topographic map of Mars. Major surface features are labelled (Credit: MOLA Science Team) [55]. Topographic scale (in metres) is seen below the image.

Unlike the Earth, Mars lacks active plate tectonics. In this way Mars is similar to, e.g. the Moon and Mercury. There is no evidence of horizontal movement of Mars' crust, which could for example show up in a form of folded mountains. Besides having no lateral surface motion, there are no active volcanoes on Mars. This theory is still under discussion, since recent measurements of ESA's Mars Express orbiter show traces of methane in Mars' atmosphere [58]. One of the probable sources of methane could be volcanic activity. However, methane has been also detected in some earlier measurements [69].

Satellite images from Mars orbiters, such as the Viking Orbiters, MGS, Odyssey and MEX suggest that there was once liquid water on Mars. The images show valley networks, river systems, flood plains, islands and clear signs of erosion made almost certainly by running water. Just like on Earth, on Mars can be found appearances of smaller channels and networks of tributaries, forming larger rivers. Some channels on Mars may have been formed by subsurface water, which reached the Martian surface through several small springs over the planet. Ancient lakes can be seen in some areas [34], which are the lower courses for the rivers. These dry lakes may have been deposited by sediment layers. It seems that there may have been huge lakes or even oceans in Mars in its past, but this occurred only briefly and very long ago. The age of the erosion channels is estimated at about nearly 4 Gyr [34]. Valles Marineris, seen in Figure 1, was not created by running water, but it was formed by the stretching and cracking of the crust associated with the creation of the Tharsis bulge (Figure 3).

Martian and other planetary surface layer is usually called ‘regolith’. It is a layer of loose material, including soil, subsoil, and broken rock, that covers bedrock. On the Moon, Mars, and many other bodies in the Solar System, it consists mostly of debris produced by meteorite impacts and blankets most of the surface [67]. Therefore virtually every (rocky) surface in the Solar System consists of regolith

Mars has only a very weak magnetic field compared to the Earth. NASA’s Mars Global Surveyor orbiter discovered in 1997 that Mars has over eight ‘magnetic patches’, which might be the remnants of an ancient magnetic field. The axes of these patches are pointing in all different directions. Even the strongest magnetic field is roughly 1.3% of Earth's magnetic field only. The magnetic field fragments could have been formed in the past, when iron-rich Martian rocks rose to the surface at different times, and then became trapped in the surrounding rocks. The result of this may have important implications for the structure of planet’s interior and for the past history of Mars’ atmosphere, and hence for the possibility of an ancient life. The lack of a magnetic field is also a significant issue for future manned Mars missions. The cosmic rays and solar wind particles penetrate quite easily the thin Martian atmosphere, especially when there is no magnetic field protecting the astronauts.

Also seen in Figure 1 is Mars’ north pole with an ice cap. The planet has permanent ice caps at both poles composed mostly of solid carbon dioxide (regarding the ice caps’ surface layer), but recent measurements show traces of water ice (water ice traces on south polar cap: The OMEGA experiment onboard ESA’s MEX orbiter). These polar caps are formed of a layered structure with varying concentrations of water ice, carbon dioxide ice (solid CO_2 is also known as ‘dry ice’) and dust. The thickness of the ice caps varies with seasonal variation. The northern ice cap completely sublimes in Martian summer, exposing the water ice underneath the carbon dioxide layer. The southern polar cap seems not to be similar by behavior, since the carbon dioxide layer rarely disappears completely. However, as mentioned above, there are recent measurements, which show evidence of water ice also in the southern polar cap [121]. In addition to the polar ice, there possibly exists water ice below the surface in lower latitudes, based on the recent findings of large amounts of hydrogen [75]. The released carbon dioxide from the polar caps changes seasonally the atmospheric pressure by about 30% [76], as measured in the Viking 1 and 2 landing sites during 1976-1982.

1.3.3 Search for water and life

As mentioned above, the first spacecraft to fly-by Mars was NASA’s Mariner 4, which performed a Mars fly-by in July 14th, 1965. It took the first close-up photographs of Mars, and in fact, of any another planet ever visited by a spacecraft. After Mariner 4, several other probes followed, but the first ones to perform soft-landing, were the two Viking landers in 1976. At the time of writing this thesis, there have been five successful landings on Mars. Those missions will be covered later in this thesis.

All of the spacecrafts that have visited Mars, even taking measurements from orbit or from surface, have tried to find answers to two main questions among taking other measurements: has there been water in liquid form in Mars’ past? And if there was water, was there also life in some form? The recent robotic explorers, both orbiters and landers, have revealed that Mars probably was once a wet planet, and therefore possibly suitable for hosting life. But the question for life remains. A search for fossils of microbes or bigger organisms on the Martian surface or below it could provide the answer. So far there has been no trace of life, but subsoil drilling could help the scientist to resolve the mysteries of Mars’ past.

2. WORK ACCOMPLISHED

In 1998, the European Space Agency initiated the Micro Robots for Scientific Applications 2 (MRoSA2) project. The focus of the project was to develop a prototype of a Mars micro rover, which could drill and take samples from down to two-metre depth of Martial soil. The project was carried out in Finland during the years 1999-2001. In 2002, the project got continuation in the form of MRoSA2 Upgrade project (ESTEC purchase order project). The results of these projects are explained in details in Chapter 4. In brief, the MRoSA2 team developed and built a working prototype of a miniature Mars rover, capable of drilling and sampling.

It was never really meant that this MRoSA2 rover could be modified from prototype level to a real flight project. However, the aim was to study the feasibility of this concept, and especially the drill module operation in such a small, confined space. During the years 2000-2001, there were some plans to further study the MRoSA2 concept in a two larger projects: one concentrating on the drill itself, and the other one to the rover concept.

ESA announced its Aurora program [72] in 2001. The goal of the program is to create, and then implement, a European long-term plan for the robotic and human exploration of the solar system, with Mars, the Moon and the asteroids as the most likely targets. After announcing the Aurora's main objectives, ESA soon announced also Aurora's first Flagship mission, the ExoMars mission. The ExoMars mission to Mars will include a Mars lander with a rover, and the rover will include a drill. According to the preliminary plans, the drill will be quite similar to the drill onboard the MRoSA2 rover. When the original MRoSA2 project was concluded in November 2001, the drill development projects were mainly moved under the newly established Aurora program (see Appendix I).

The project team in Finland, that had built the MRoSA2 rover, was excluded from the continuation development of the drilling system, since Finland did not join the Aurora program, which is an optional ESA program. However, as mentioned above, the team got some continuation in the MRoSA2 development when ESTEC purchased upgrade work for the rover (project duration: from November 2002 to May 2003).

During the original MRoSA2 project (1999-2001), the team performed some testing of the system (VTT Automation performed drilling tests, and SSF & HUT performed systems and functional testing). It was actually then when the author of this thesis began documenting the test results and a 'bug list' also for academic purposes, not only because it was mandatory regarding the project work. The MRoSA2 Upgrade project did not include testing, other than the normal systems tests before final delivery [17]. However, the author had then possibility to perform multiple systems testing for the drill module and document improvement possibilities that were out of the scope of the project then, but which could be accomplished in possible later projects. During the Aurora Student Competition (2003), the author gathered a team from HUT to perform the actual drilling tests. This competition project, the 'MIRANDA' project, concluded the drill tests, since for the first time the team had adequate hardware to perform wide-range drilling tests to rocks and sand. After this test, the author modified the existing MIRANDA hardware for additional testing. These tests formed the MIRANDA-2 project, peformed by the author. In addition, the author has been involved in some additional drilling studies described below in Chapter 2.3.

The following chapters describe the author's work regarding the topic of this thesis.

2.1 MRoSA2 and MRoSA2-Upgrade projects

The MRoSA2 activity was an ESA funded GSTP project, issued originally in 1998 [12],[13], and conducted during the years 1999-2001 [2]. The acronym MRoSA2 stands for 'Micro Robots for Scientific Applications 2'. 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. The MRoSA2 project is a key issue to this thesis, since the drill module (developed originally by VTT Automation in Finland) is one of the predecessors for the upcoming ESA's ExoMars rover's drill.

Figure 4: The MRoSA2 rover and author of this thesis as a size-reference [32].

The author of this thesis acted as a systems and software engineer in the MRoSA2 project, concentrating to the drill functions and operational issues. Later on, in the MRoSA2 Upgrade project, the author served as the project manager and technical engineer. The goal of the ESA funded upgrade project was to upgrade the rover-drill-combination (Figure 4) from a single-function level to drilling and sampling readiness level in laboratory conditions.

During the MRoSA2 project in 2001, the author conducted several reliability and drill-function tests, which are documented in Chapter 5.1. Before these functional tests, VTT Automation conducted several drilling performance tests. These tests are documented in Chapter 5.1.1. Wider drill functional tests were conducted by the author in 2002-2003 during the MRoSA2 Upgrade project, and those tests are documented in Chapter 5.2.

2.2 MIRANDA drill 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 team gathered a team, and the author of this thesis acted as a team leader and engineer in the team. The team designed and built a drilling test bench during 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.

Regarding the topic of this thesis, the author started another drill test project by using the existing MIRANDA hardware. This project, called the 'MIRANDA-2', aimed to analyze the temperature variations in the drill bit and in the drilled material during drilling and sampling. These tests were performed from May to October 2004. The existing drill test bench was modified to fit the new project's requirements. The MIRANDA 1 and 2 tests, including the results, are explained in details in Chapters 5.3 and 5.4.

2.3 Other studies

In addition to the tests conducted during the MRoSA2, MRoSA2 Upgrade, MIRANDA and MIRANDA-2 projects, described in the previous chapters, the author has been involved in other studies that are relevant to this thesis.

In 2002, the MRoSA2 project team received a Request For Information (RFI) [6] from NASA Jet Propulsion Laboratory (JPL). This semi-informal RFI was part of a usual 'scientists-ask-scientists' information exchange, in which JPL Mars engineers wanted to learn about other ongoing Mars projects. During that time, the NASA's Mars Science Laboratory (MSL) 2009 mission was in definition phase. It was yet undecided, whether the MSL lander would include a drill or not. The MRoSA2 team received a few possible MSL mission plans, and we made a brief feasibility study about the MRoSA2 drill concept onboard the MSL lander [56].

In addition, after the MRoSA2 project, the author listed some known problems of the system with possible solutions (published in ASTRA2002 conference at ESA ESTEC in 2002 [1]). The publication was taken as reference documentation to the ExoMars / Pasteur System Requirements Document [63].

2.4 Summary of the author's work

Table 1 below summarizes the author's role in different projects that are relevant to this thesis.

Table 1: Summary of the author's participation to the projects relevant to this thesis.

Project or study	Duration	Team	Author's role	Notes
MRoSA2	End of '99 – Nov '01	SSF, VTT, HUT, RCL, ESTEC	Systems Engineer & other self-study for this thesis.	Some tests that were not focused for project work, but for this thesis.
MRoSA2 Upgrade	Nov '02 – May '03	SSF, HUT, ESTEC	Project Manager & other self-study for this thesis.	Several tests that were not focused for project work, but for this thesis.
MIRANDA	Mar '03 – Jul '03	HUT Student Team	Team Leader and engineer.	Test results used in this thesis.
MIRANDA-2	May '04 – Nov '04	HUT	Project Leader	Main focus was this thesis.
Others	Several: 2002 -	SSF, HUT	Author, Co-Author	As listed in Chapter 2.3

3. PLANETARY SAMPLING

The reason for scientific space-related studies is to learn about ourselves and the surroundings. Whether it is our history, the history of planet Earth, and the history of the Solar System or even the whole universe. Among the results of these studies and observations, we hope to discover new techniques, processes, and even something to commercialise. There are still several things to learn about the formation of our solar system and the planets in it. Planet Mars has been one of the key targets under scientific studies for hundreds of years, but not until the time of telescopes and space probes has the humankind improved its knowledge of it significantly. There are several reasons to study our Solar System, especially Mars, for example:

- To learn about the planets and the Solar System.
- To find out whether there has been water on Mars.
- To find our whether there has been life in some form on Mars.
- To find important resources which future human missions could utilize.

While telescopes and remote sensing by orbital instruments could deliver useful scientific information about the planets and other celestial bodies like moons, comets, asteroids and other objects, they still cannot achieve similar results than in-situ analysis methods, not to mention sample return to Earth.

Both of these methods, remote sensing and in-situ analysis have their benefits and drawbacks, and they rather support each other than compete against each other. In fact, achieving comprehensive scientific objectives for exploring planets, moons, and asteroids requires orbital global mapping, in-situ analysis by robots, and sample return and analysis. This approach, providing data from in-situ measurements and from orbit, has successfully been used in for example the NASA's Viking 1 and 2 missions, and is currently used in Mars by MER rovers and orbiting satellites. These missions are explained further in this chapter.

Sample return allows the best possible analysis for celestial samples, but it poses several new challenges. Getting the sample back from an asteroid or a planet is challenging, but even the task of acquiring the sample is difficult. 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 2), if one does not count solar wind samples taken by the Genesis spacecraft (the return capsule was damaged during landing, but some of the samples could still be retrieved [120]). The Moon has been sampled by the manned U.S. Apollo program and by the Russia's robotic Luna program, and several Lunar meteorites have been studied.

Table 2: All-time sample-return missions [64,66,100,110].

Mission	Mission type	Sampling method	Sample mass	Mission timeline (month/year)
Apollo 11-12, 14-17	Manned	Hand, rake, drill etc.	Total 381.7 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 point	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 '25143 Itokawa'	Bullet / dust gathering	~1 g	05/'03 – 06/'07

3.1 Sampling methods

The optimum strategy for taking samples depends on many factors, but mostly it depends on the required size and nature (or form) of the target object. In this thesis, the emphasis has been given to sampling soil and rock samples from surface or within a few metres depth from the surface. One factor that affects greatly to the sampling operation is the environment and target celestial body. These factors can be divided into:

- Gravity
- The material form of the sampling location (e.g. solid rock, hard soil, porous/spongy soil, liquid etc.)
- Possible atmosphere
- Temperature
- Solar radiation

The gravity and the local terrain type are the most dominant factors. However, in extreme conditions, like on the surface of Venus, the temperature is one the most critical factors. The gravity, or rather the lack of gravity, is a challenging factor. This issue was faced when the SD2 drill was developed to the Philae lander of ESA's Rosetta mission [62]. Philae is going to land on a comet Churyumov-Gerasimenko in 2014 and perform drilling and sampling there. However, since the comet has virtually no gravity at all, the lander must attach itself to the comet by harpoons. Philae's drill needs counterforce to sustain the drilling operation. The main focus of this thesis is to study a drilling device in Martian conditions, where there is significant gravity ($0.37\ m/s^2 \approx 0.38\ g$). The maximum drilling force must be limited to be less than the weight of the drilling platform (e.g. the rover) in local environment, to maintain the efficiency of the drilling and to avoid lifting the platform from the surface.

While there are several possible sampling methods proposed for different kinds of missions to planets, comets and asteroids, this thesis will consider mainly the methods that are potential options at the Martian surface.

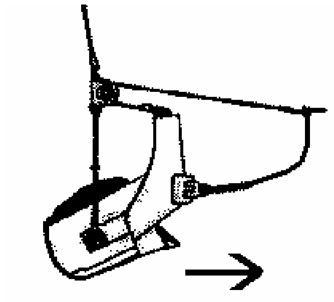
Basically, the possible methods to sample robotically the Martian surface or subsurface are:

- Claw, scoop or trowel
- Tongs/pincers
- Drag lines and nets (throwable net etc.)
- Drillers (deep drillers and surface drills) and corers
- Penetrators
- Drive tubes and penetrators
- Passive/adhesive surfaces
- Brush sweeper
- Gas jets

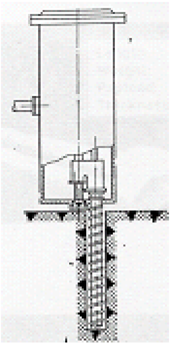
In addition to these sampling methods, there are several ways to actually reach the sampling location. For example, the Viking lander was a stationary lander, and it took samples from its surroundings by scooping. The scoop was attached to a boom, i.e. robotic arm. All these methods have their benefits and drawbacks. Some of them are suitable only for surface sampling, and some are possible methods to access subsurface material and retrieve it for analysis. Also the sample handling includes several kinds of tools, ranging from brushing to percussion tools. However, these are not covered in this thesis.

a) Viking Scoop (Image: NASA)

b) Tongs/pincers (MEE image: ESA)

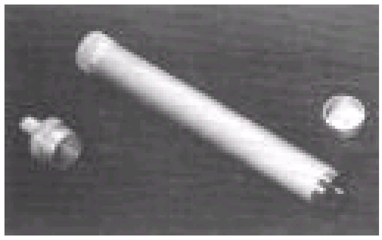


c) Drag-lines, buckets or nets



d) Driller and corer (Luna 16 & 20 drill image: [74])

e) Penetrators and moles (Deep Space 2 image: NASA)



f) Drive tubes from Apollo missions (Image: NASA)

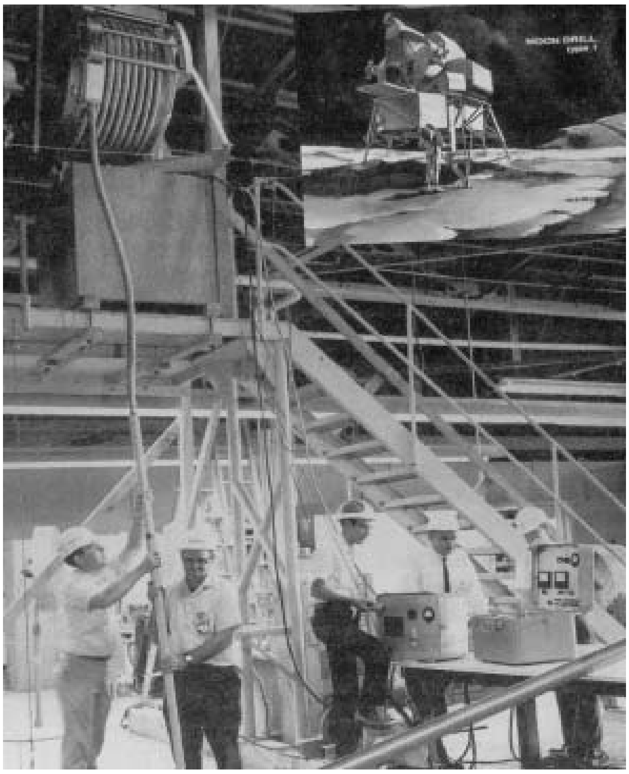
Figure 5: A brief overview of some possible sampling methods.

Figure 5 above shows six possible sampling methods. Method a), the scoop, has been used during the Viking 1 and 2 missions to Mars in 1976-1982 and during the Venera missions to Venus in 1980's. The Viking lander's sampling arm created a number of deep trenches as part of the surface composition and biology experiments on Mars. The digging tool on the sampling arm (at lower center) could scoop up samples of material and deposit them into the appropriate experiment. Some holes were dug deeper to study soil which was not affected by solar radiation and weathering. Viking sampling mechanism will be explained in Chapter 3.2.2.

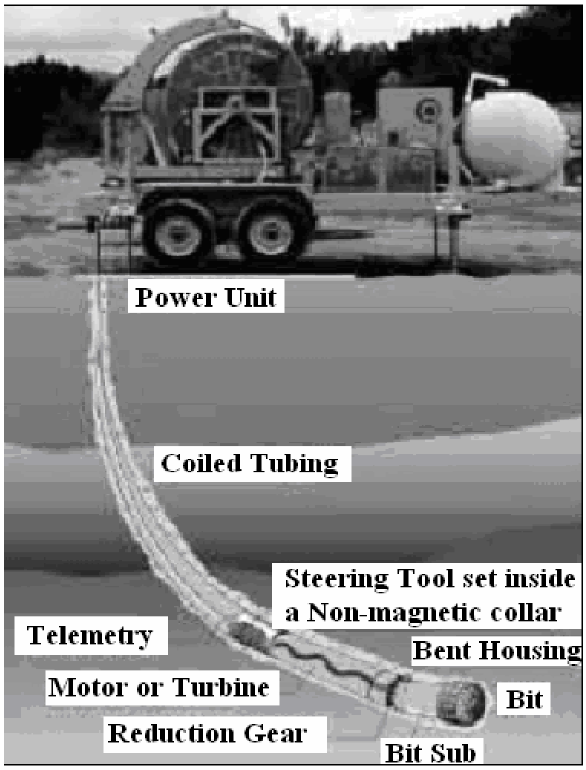
Tongs/pincer (MEE) shown in Figure 5b were developed for the SSA/DT project (see Chapter 3.4.6). The Surveyor Lunar lander (see Chapter 3.2.1) carried a "lazy-tongs" (Figure 8) mechanism to dig lunar soil. The tongs' end-effectors were quite different to those in the figure b), and the scoop was attached in an end of a robot arm (see Figure 8). Drag-line buckets or nets (Figure 5c) have been proposed for example for a sampling mission to Moon [74], although none of them have been flown or assigned to future missions yet.

Method d), the drill, has been used so far in Luna, Apollo, Venera and in ongoing Rosetta mission. Image shows the Luna 16&20 drill. Rosetta's SD2 drills more than 20 cm into the surface, collects samples and delivers them to different ovens or for microscope inspection (see Chapter 3.3.5). The first drill that has operated in another celestial body than Earth was the Russian Luna 16 drill. The drill was attached to a robotic lander that returned its sample back to Earth. Following that, there were the Apollo 15-17 missions, 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 landers had a robotic driller too. These missions will be discussed later in this thesis (Chapter 3.2.3). 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 metres depth. The drill was not 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, e.g. when the drill gets stuck. However, it is not possible 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.

Besides of several small drill devices, such as the Luna, the ALSD or the Venera drills, there have been plans to develop huge drills, which would be capable to reach tens of metres depth, even kilometres. NASA had plans in 1960's to equip post-Apollo manned missions with a colossal coil-drilling device (Figure 6).



a)



b)

Figure 6: a) Northrup Corporation's post-Apollo lunar drill engineering model, on test stand at Marshall Space Flight Center demonstrates deployment of coiled drill string and core stem. (NASA MT 6-9401) [41]. b) Los Alamos developed a coiled-tubing drilling unit for the earth-bound drilling (Image: Los Alamos Laboratories).

As known, there were no post-Apollo manned Moon missions, so the coiled drill was never flown. There was also not any technical reference for the drill system, so it remains unknown whether this kind of coiled drill (or the more recent study shown in Figure 6b) could be scaled down for robotic missions. NASA has also some newer plans for coiled drill strings (see Chapter 3.4.8).

A penetrometer (Figure 5e) is basically a stick that is pushed down to the soil. The soil properties can be analyzed by several methods by using a penetrator, and different instruments in penetrators may reveal for example temperature, moisture, adhesion and electric properties. There are several different kinds of penetrometers, and one classification can be made by the penetrating method; impact or active and slow pushing force. A mole is like a penetrometer, but it is (usually) connected to the lander (or other platform) by a tether instead of rigid structure as penetrometer is. The Beagle-2 mission (Chapter 3.2.2) to Mars had a mole, but unfortunately the landing was unsuccessful.

There have been several penetrometer instruments onboard planetary landers. One of the first was the penetrometer used in Lunokhod Moon rovers (see Chapter 3.2.1). In addition to penetrometer instruments, there have been plans and attempts to use penetrating spacecrafts, which lands like a dart to target body (comet, planet surface etc.). These surface penetrators have been designed to survive an impact of possibly tens or hundreds of g's, measuring and telemetering the properties of the penetrated surface back to orbiting spacecraft or directly to Earth. So far no penetrator spacecraft have been successfully operated. An example of a penetrator spacecraft is the twin Deep Space 2 penetrators, which piggybacked to Mars aboard the Mars Polar Lander and were to hit into Martian soil on December 3, 1999. The faith of these two penetrator spacecrafts is unknown, since they were never heard from.

Drive tubes (Figure 5f) are generally used to extract a soil sample for density analysis or for extracting whole core sample from adhesive soil. Three models of drive tubes were used in Apollo flights. Early tubes were sometimes hard to drive into the compact lunar regolith and did not always retain the core when removed. By the time Apollo 15, a new, thin-walled, larger diameter core tubes were designed and worked well. During Apollo 16, it took 5 minutes to get a single core tube and 11 minutes for a double core tube. Robotic spacecrafts have used drive tube designs in their drill sampling tool heads. The drill bit contains a sample container, which extracts the core sample from the bottom of the borehole. There have been some studies to drive tubes for cometary [77], Mars surface and lunar sampling, down to a depth of about 10 cm. Required power would be between 0.5 and 1 W and sampling efficiency ranging from 1.2 to 6.6 J per sample (1.9 cm^3 sample). This kind of drive tube is shown in Figure 7.

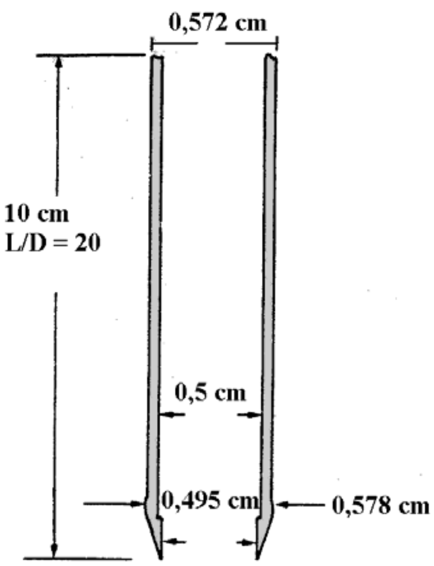


Figure 7: A drive tube design. 'L/D' means 'Length-per-Diameter' –ratio (Image:[77]).

In addition to the methods explained above, there are several possible ways to collect planetary surface or subsurface material, ranging from hand-picking (astronauts) to blowing material to containers ("gas jets" [74]). Examples of these methods are e.g. passive/adhesive surfaces (sticky material), sweeping by brush and using augers to drill surface material. These are not relevant to the topic of this thesis and are not explained further. Analysis of these methods is explained in [74].

3.2 Review of past in-situ surface analysis and sampling missions

Over the last decades, starting from the 1960's, robots and astronauts have conducted in-situ sampling of the celestial bodies; the Moon, planets, comets and an asteroid. This chapter will summarize these past missions and give a brief overview of the future missions that are either ongoing or in a study-level only. The main focus of this chapter's literature study has been finding relations between past missions' sampling methods and the needs of future missions.

While there have been missions incorporating environmental sampling in different forms, the emphasis has been given to soil and rock sampling, analysis and methods to access subsurface samples. Therefore those missions, which have included for example solar wind sampling (NASA's Genesis mission), comet dust sampling (NASA's Stardust mission), atmospheric sampling while flying/falling (some of the Venera missions [40]), Galileo Probe (NASA), Huygens (ESA) etc. have not been studied here.

There is plenty of literature available of drill studies, mostly regarding the Russian and NASA's Moon missions. Information about Russian missions to Venus is harder to find, but it is worth studying too, since the Russians have built the only working autonomous drillers to celestial objects (to Venus and to the Moon). There are many references in the literature for proposed plans to retrieve Martian samples by robotic spacecraft. References from [42] through [46] describe designs and implementations of drilling and sampling devices, which are related to the study area of this thesis. These missions are described in the following chapters. In brief, these related projects are:

- The Russian robotic Lunokhod rovers on the Moon.
- The drill used on Russian robotic Luna landers on the Moon [45].
- The drill used by American astronauts during the Apollo missions to the Moon [46].
- The robotic Viking landers on Mars.
- The Sojourner rover on Mars.
- The Beagle-2 mission to Mars.
- The Mars Exploration rovers on Mars.
- The past, unsuccessful Russian projects to Mars: M-71, Mars 2-3, Prop-M and 5NM.
- The Russian robotic Venus landers: Venera mission.
- The Small Sample Acquisition and Distribution Tool (SSA/DT [42,43])
- The SD2 tool in the Rosetta comet mission [62].

The following chapters describe past sampling projects to the Moon, Mars and Venus.

3.2.1 Sampling missions to the Moon

The Moon, as the closest celestial body of the Earth, is obviously the first target to be studied in the history of in-situ analysis of celestial bodies. The Moon has been visited by several spacecrafts. Some of them have been orbiters while others have landed on the surface. Not all of these Moon missions are relevant regarding this thesis, so only some of them are covered here. These missions are NASA's Surveyor and Apollo missions and Soviet Union's Luna missions. These missions represent soil analysis techniques and lunar drilling and sampling technology.

US robotic Moon program and the Surveyor landers

The Moon was an obvious target of United State's space program. The reason was not only scientific, but also, and in some cases mostly, political. The Soviet Union had launched their Sputnik satellite on orbit in October 1957, and US had strong pressures to reach the space too. During the early years of the U.S. space program, the Moon studies took their shape. The first lunar mission consisted of the Able probes, later called the Pioneer probes (1958-1959), launched by the U.S. Air Force Ballistic Missile Division, the Army and later on the Space Technology Laboratories of NASA. The Pioneers were not successful, since only some of them reached even halfway of their target. The next program was the Ranger program (1961-1965). It consisted of impact probes to the Moon, which took series of photographs before crashing to the lunar surface. This program was fairly successful with only some failures in the early days.

The Surveyor program (1966-1968) consisted of seven Moon landers. Unlike the Rangers, these probes were supposed to soft-land on the Moon and take photographs and perform some scientific experiments, preparing the manned Apollo program. NASA launched the Surveyor 1 Moon lander in May 1966. The spacecraft landed successfully to the Moon, in the Ocean of Storms on June 1966 (however, Russian Luna 9 was the first spacecraft to soft land on the Moon on the 3rd of February 1966). The lander took more than 11000 photographs of the lunar surface over a month-long period. The second spacecraft (Surveyor 2) failed, but Surveyor 3 successfully landed on the Moon in April 1967. It also took photos but, in addition, it also included a remote scooper arm to determine the density of lunar soil. Experiments by the Surveyor 3 lander showed that the lunar soil had the consistency of wet sand [73]. Surveyor 4 failed, but Surveyors 5 to 7 successfully landed on the Moon in 1967-1968, returning vast amounts of photographs and data on the Moon that were critical to designing experiments for the Apollo missions.

Surveyor 3 and 5 – 7 were successful and they had also a robot arm with scoop and a chemical element analyser in their scientific tool kit. The objectives included examining of lunar soil below the surface and to identify mineral composition in scientifically interesting sites. Surveyor 5 found basalt revealing some history of lunar melting. Also the determination of adequate bearing strength in the lunar soil was important for planning the Apollo program. Surveyor 7 was the second US lander, which had a soil mechanics surface sampler. The device (Soil Mechanics Surface Sampler, SMSS) was a bucket digger on a pantograph arm (the "lazy tong" design) of varying length (see Figure 8), which it used in several kinds of tests on the Moon. Acting on commands from Earth, Surveyor used its scoop to pick up small rocks and weigh them to determine their density (the size was determined through the TV camera or by the scoops volume). The scoop dug many trenches, one 75 cm long and 23 cm deep, whose sharp edges showed of a slightly cohesive soil. Surveyor 7 tried unsuccessfully to reach a large rock just out of reach, and it even tried to chip off a piece of nearby rock by raising and dropping the arm like a hammer. Surveyor also had an alpha-scattering instrument to measure the composition of lunar soil nearby the lander. Later scientists concluded that much of the lunar soil was chemically similar to volcanic basalt.

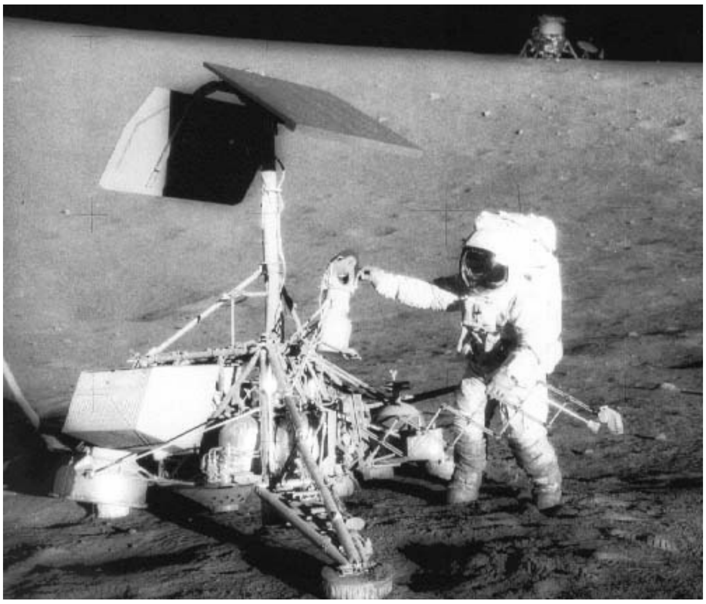


Figure 8: Apollo 12 crew visited The Surveyor 3 lander in November 1969. Astronaut Alan Bean lays his left hand on the scoop device giving a scale to it (Image: NASA).

In addition to these three US lunar missions, NASA launched also the Lunar Orbiter mission (five orbiters during 1967-1968), the Explorer mission (three probes; two of them successful, 1967-1968), the manned Apollo program (covered later in this chapter), the Clementine orbiter mission (joint mission of the Ballistic Missile Defence Organization, BMDO and NASA; 1994) and the Lunar Prospector orbiter (1998-1999). Of these eight missions, only the Surveyor and Apollo programs have included in-situ experiments on the lunar surface.

The Soviet Union's Luna missions: Lunar drilling, sample retrieval and the Lunokhod rovers

The Soviet Union conducted its long Luna program starting in 1950's. The first Luna spacecraft flew already in 1959 and the last one, Luna 24, in 1976. The mission was designed to gather information about the Moon and its environment, not only for scientific purposes but also to be used in the planning of future Soviet lunar missions including manned missions to the Moon, which was never accomplished. The series included flyby, lunar-orbiting, and soft-landing missions. The three Luna missions that are of interest regarding this thesis are the Luna 16, 20 and 24 landers, which drilled the lunar surface and returned samples back to Earth. Also of particular interest are the Lunokhod 1 and 2 rovers, which were delivered to the Moon by Luna 17 and 21 landers, respectively. These rovers conducted soil mechanics experiments, although they didn't have a drill. It is also interesting to take a quick review of the Luna 13 lander, which also conducted soil experiments. These missions are explained in chronological order in below.

The Luna 13 spacecraft was launched toward the Moon in December 21, 1966. It performed a soft landing on December 24, 1966, in a region called Oceanus Procellarum. The spacecraft opened its petals, erected its antennas, and begun radio transmissions to Earth only four minutes after the landing. Luna 13 lander Figure 9 was equipped with a mechanical soil-measuring penetrometer (Gruntomer), a dynamograph, and a radiation densitometer for obtaining data on the mechanical and physical properties of the soil and the cosmic-ray reflectivity of the lunar surface. Luna 13 ended its operations in less than seven Earth days. The lander carried two manipulators, which were actuated by torsion springs. Each actuator had six degrees of freedom. The first arm carried a small quantity of Cesium-137 to study the density of the terrain, while the second carried a wedge shaped penetrometer [92].

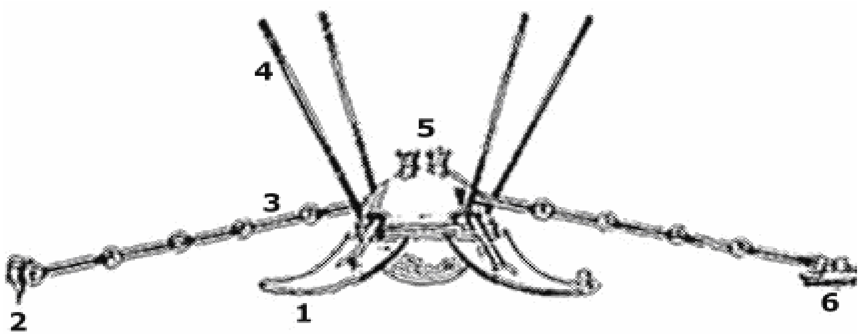


Figure 9: Luna 13 lander (Image: Astrolink.de). 1: petal, 2: mechanical soil examiners, 3: extendable arms, 4: antennas, 5: TV cameras, 6: radiometer. The radius of the ball-shaped chassis is roughly 0.5 metres.

Luna 16 spacecraft (original manufacturer's designation: 'Ye-8-5') was the first-ever robotic spacecraft to successfully land on the Moon and also taking samples and returning them back to Earth. It was launched in September 1970 from the Soviet Union, and after less than eight days of travel it soft-landed in its target area in Sea of Fertility. At the landing, the mass of the Luna 16 was 1880 kg. An automatic drill (see Figure 10) began its work 51 minutes after landing, and it took 7 minutes to drill down to 350 mm of lunar surface. The drill elevated the sample and lifted it up to the ascent vehicle, which sat on the top of the Luna 16 lander. Two hours and 31 minutes from landing, the ascent vehicle launched off from the Moon, and after four days journey it returned to Kazakhstan and delivered its cargo. Later analysis of the sample (mass 101 g) showed dark basalt material that had close resemblance to soil recovered by the US Apollo 12 mission.

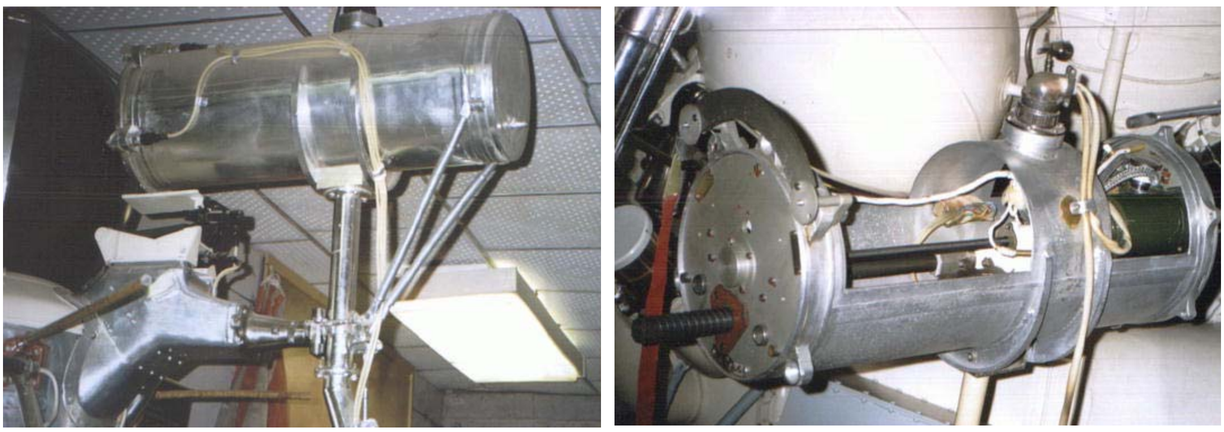


Figure 10: The Luna 16 drill module (left) and the drill without its casing (right). The metallic tube is about 70 cm long *(Image: NPO Lavochkina museum, Chernov).*

Luna 20 followed concept similar to that of the Luna 16 spacecraft. Not long after landing, Luna 20 lowered its drill down to surface and began drilling. The drill was slightly improved from Luna 16 and it consisted of an arm-mounted drill with a cylindrical hollow container, which collected the core sample as the drilling proceeded. The rock was hardest encountered on the Moon so far, and the ground operators had to shut down the drill from time to time to avoid overheating. The return flight was flawless, and the sample collected by Luna 20 was determined to be formed from ejected material scattered from the formation of the crater Apollonius C. It is thought to be lunar bedrock 100 million years older than any moon rock yet returned to Earth. The 55 g soil sample differed from that collected by Luna 16 in that the majority (50-60 %) of the rock particles in the newer sample were ancient anorthosite (which consists largely of feldspar) rather than the basalt of the earlier one (which contained about 1-2% of anorthosite). It seemed that a significant amount of soil had dropped during the sample delivery from the drill head to the return capsule [100].

The drill tool in Luna 20 was a thin-walled tube (see Figure 10 for similar Luna 16 drill, where the drill is visible in the left side of the aluminium tube) including helical threads on its outer surface and sharp teeth at its cutting end. The drill had two different mechanisms; one for collecting hard core samples from rocks, and the other one to collect loose soil sample. The drill rotational speed was 500 rpm and it took about 30 minutes for the entire length (see further in this paragraph a note regarding this claim) of the drill to penetrate to the lunar soil [66]. The drill motor travels on a pair of rails while the long drill rod (seen between the lower sections of rail) penetrates the Moon. As the drill is retracted, the sample is coiled tightly inside the hollow and thin inner tube (Figure 12b) of the drill rod before being transferred to the return capsule. The protective shield next to the capsule protects the drill head and the packing device from direct solar heating while in the rest position. The drill casing had thermal insulation and the casing was gas-tight to avoid adhesion or sticking of the metallic parts before the drilling began (the casing was opened just before the drilling started). Hermetically sealed casing allowed use of oil vapour lubricants, which would evaporate in lunar vacuum without gas-tight container. The drill had two motors. In nominal operation only one was used, but in case the drilling progress was halted (drill got stuck), the standby motor was used to overcome the situation. Depending on the sources, Luna 20 drill penetrated a total of 250 mm and returned its sample back to Earth in February 1972. According to [66] the drilling operation proceeded without incident to a depth of 100-150 mm. Some sort of hard material had been hit that overheated the drill motor three times during the seven minute drilling operation. Further drilling was abandoned after about 30 minutes due to fear of damaging the sampling mechanism. The undersized sample, about 55 grams, was returned to Earth.

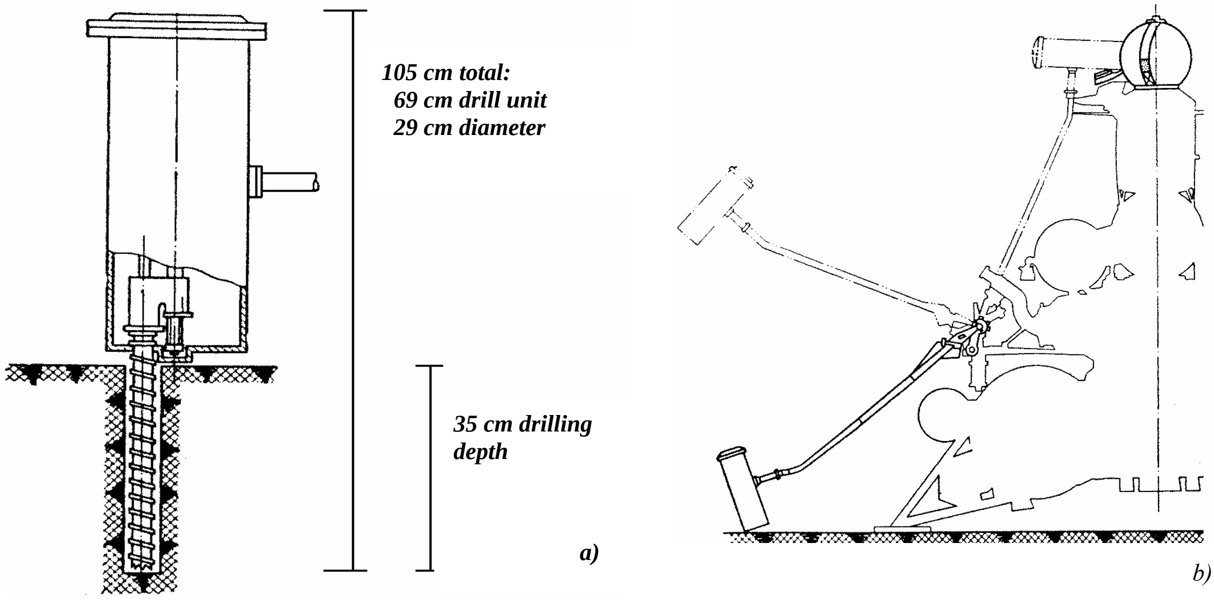
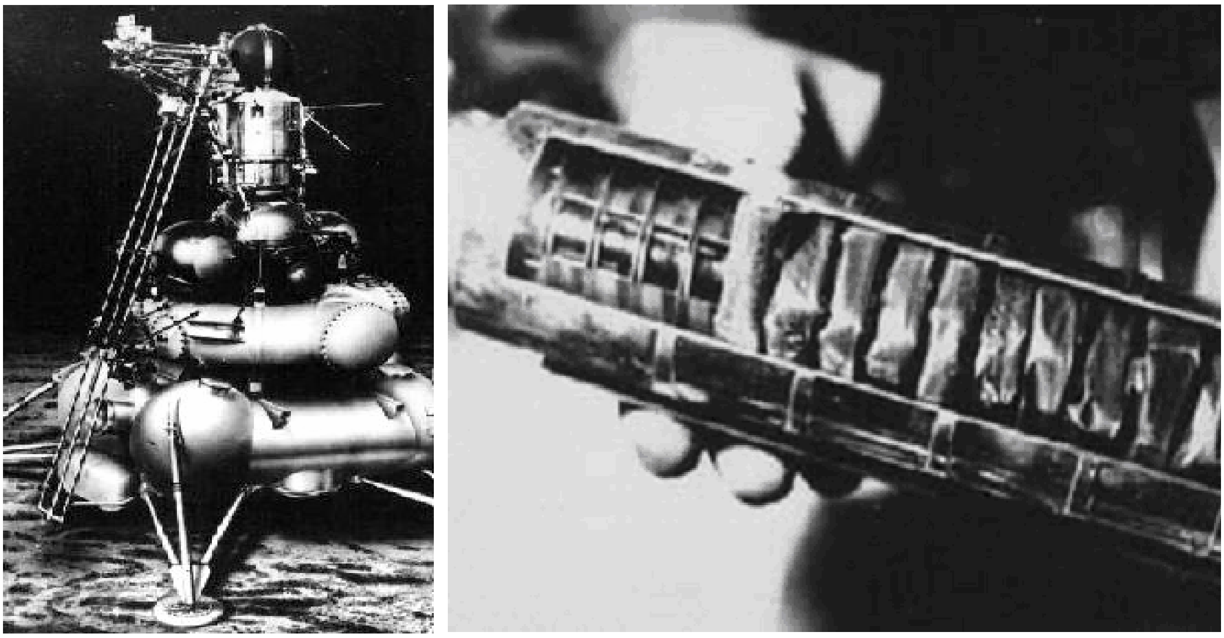


Figure 11: The Luna 16 and 20 drill and operation principle [74].

After Luna 20, other Luna missions followed, but Luna 24 was the third and the last successful sample-return mission. Luna 23 had modified drill system, as had the Luna 24 lander, but Luna 23 failed to drill and return the sample. Luna 24 returned its sample back on August 1976. Luna 24 recovered the heaviest sample so far (on the Luna mission): 170.1 g. Luna 24 (Modified E-8-5) had a rail-mounted drill (Figure 12 a) instead of a robot arm mounted. The objective of the drill was to drill down to 2.5 metres. Achieved depth was 160 cm. Study of the soil indicated a layered structure, as if laid down in successive deposits. Tiny portions of the sample were shared with NASA in December 1976. Shown in the Figure 12 b) is the tightly coiled soil sample, still in the protective tubing into which it was inserted while on the Moon

The Luna 16 and 20 drills had a mass of 13.6 kg and they were 69 x 29 cm of size. The maximum power of the drill (without the robotic arm and sample handling system) was 140 W. Average drilling speed varied between 8…24 cm/min to lunar regolith (core diameter 2.6 cm). Consumed energy was 42…54 kJ / 35cm sample [78]. Estimated drilling moment was 0.2…0.3 Nm [74].



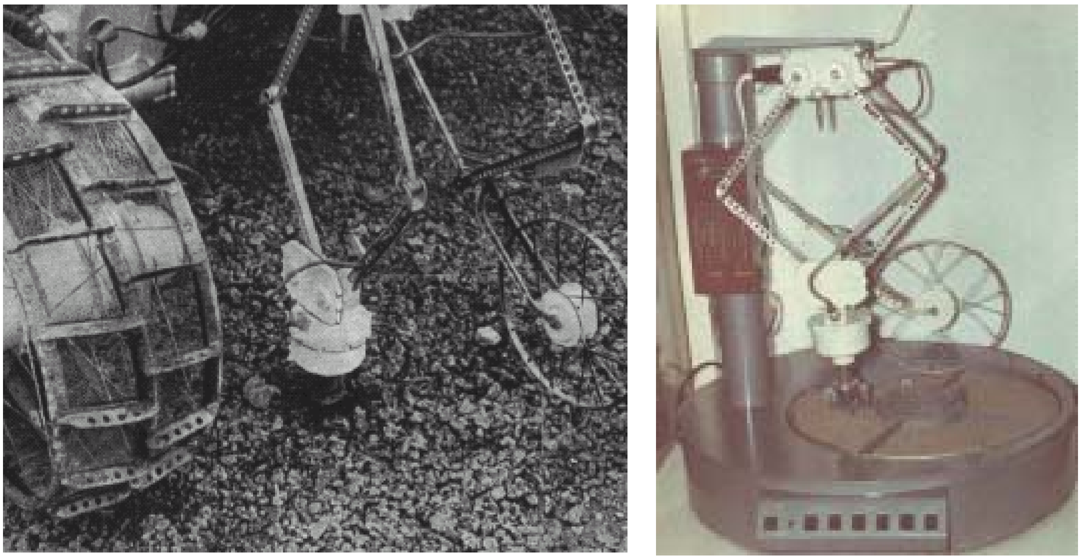
a) *b)*

Figure 12: a) Luna 23/24 rail-mounted drill. b) Luna 24 sample coiled inside the drill rod's inner tube and placed in a container. Note how the thin tube was dented when it was coiled (Images: NASA).

The Soviet Union built two mobile vehicles, the Lunokhods, which landed on the Moon in November 1970 and in January 1973. The Lunokhod 1 and the Lunokhod 2 were teleoperated Moon rovers that carried television cameras and instruments to measure the physical and chemical properties of the lunar soil. They were launched by Luna 17 (carried Lunokhod 1) and 21 (carried Lunokhod 2) landers in November 1970 and January 1973, respectively.

The Luna 17 spacecraft soft-landed on the Moon in the Sea of Rains on November 15, 1970. The spacecraft had dual ramps on opposite sides of the lander by which the payload, Lunokhod 1, descended to the lunar surface. The redundant system was due to possible big rocks or other natural obstacles, which could have prevented driving onto the lunar surface. The Luna 21 spacecraft landed on the Moon and deployed the second Soviet lunar rover, Lunokhod 2, on January 15, 1973. The primary objectives of the missions were to collect images of the lunar surface, examine ambient light levels to determine the feasibility of astronomical observations from the Moon, perform laser ranging experiments from Earth, observe solar X-rays, measure local magnetic fields, and study mechanical properties of the lunar surface material. Lunokhods were a lunar vehicle formed of a tub-like compartment with a large convex lid on eight independently powered wheels. Lunokhods were equipped with a cone-shaped antenna, a highly directional helical antenna, four television cameras, and special extendable devices to impact the lunar soil for soil density and mechanical property tests. An x-ray spectrometer, an x-ray telescope, cosmic-ray detectors, and a laser device were also included. The vehicle was powered by a solar cell array mounted on the underside of the lid.

Lunokhods were intended to operate through three lunar days but actually operated for eleven lunar days (one lunar day is one month; 14 days of daylight and 14 days of night). The operations of Lunokhod 1 officially ended on October 4, 1971. Lunokhod 1 had travelled 10.54 km and had transmitted more than 20000 TV pictures and more than 200 TV panoramas. It had also conducted more than 500 lunar soil tests. Lunokhod 2 operated for about four months, covered 37 km of lunar terrain, and sent back 86 panoramic images and over 80000 TV quality images. Many mechanical tests of the surface, laser ranging measurements, and other experiments were completed during this time. On June 4 it was announced that the program was completed, leading to speculation that the vehicle probably failed in mid-May 1973 or could not be revived after the lunar night of May-June 1973. The Lunokhods performed soil mechanics analysis experiments by using their “PROP” cross-country capability evaluation instrument (penetrometer) [68]. The instrument was a part of the Lunokhods self-propelled chassis. The purpose was investigation of mechanical properties of the lunar soil along the rover’s route.



a) *b)*

Figure 13: The “PROP” cross-country capability evaluation instrument [68].

The PROP penetrometer is shown in Figure 13. Image a) shows the instrument, which was situated in the rear panel of the Lunokhod rover (in ground tests in Russia), and image b) shows the instrument test bench. Maximum penetration force of the instrument was 230 N with a maximum depth of 100 mm. The angle of swing of the levers could reach up to 90°, and maximum pushing force was 5 N [68]. PROP-F was designed during 1983-1987 for Phobos-2 surface station, and it also included a penetrating densitometer.

The Apollo missions

The United States’ Apollo missions in the 1960’s and 1970’s included total of six successful manned Moon landings. These six flights returned total of 2196 individual rock and soil samples weighing a total of 381.7 kg [64]. During the first Moon landing, Apollo 11 mission gathered 58 samples weighing total of 21.5 kg. The last flight, Apollo 17 mission, collected as much as 741 samples weighing 110.5 kg.

The difference between the amounts of rock samples is due to the length of the missions, but also because the experience was gained throughout the Apollo program. Since there was no prior experience on collecting lunar samples, the main focus on Apollo 11 was to collect at least some lunar material and return it to Earth. In later missions, the astronauts had a wider range of tools, and they covered longer distance during their stay on the Moon.

The sampling strategy of the first Moon landing mission was simple; to retrieve some samples back to Earth. Shortly after saying the legendary words ("*That's one small step for man, one giant leap for mankind*"), Neil Armstrong scooped a couple of rocks, bagged them and put it in a pocket of his suit. Besides of that contingency sample (which was collected rapidly in case they had to leave quickly for some reasons), they collected 21.5 kg of other samples. The sampling strategy evolved in later five missions. With increased mobility (using the lunar rover), astronauts gathered more samples with smaller average weights. These samples represented varying local conditions (surface, subsurface, varying minerals etc.) and several different tools were used.

The sampling tools that were used during the Apollo missions were: contact soil sampling device, contingency soil sampler, core tube, drill, extension handle, hammer, lunar rover soil sampler, rake, scoop, tongs, trenching tool, brush-scriber-lens, gnomon and weight scale [41]. Figure 14 illustrates the use of the Apollo Lunars Surface Drill. This is of particular interest, since some of the phases for the drilling are very difficult to perform robotically.

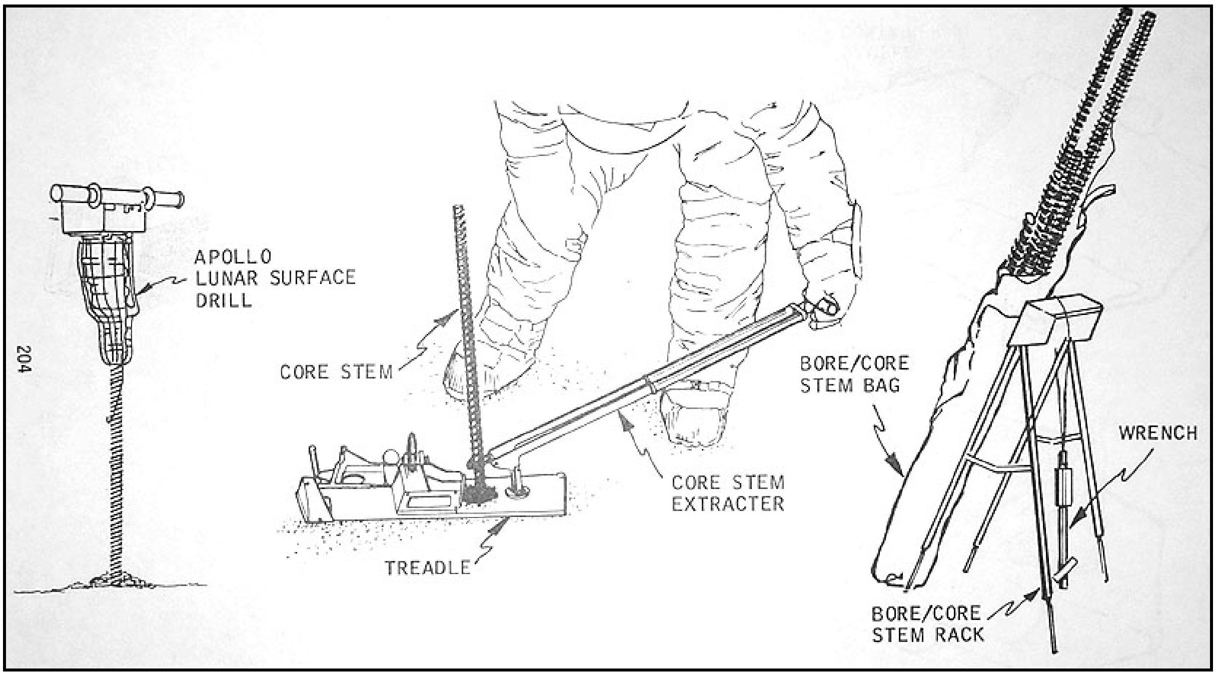
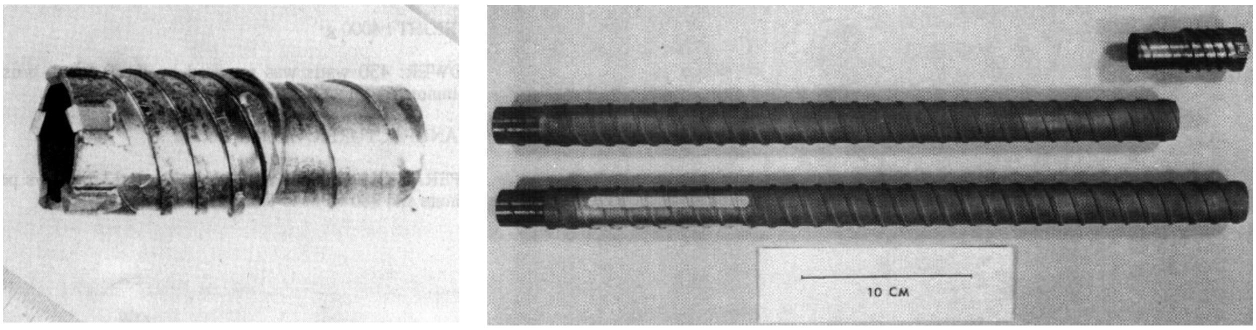


Figure 14: The Apollo lunar surface boring and coring hardware [29] (Image: NASA).

The drill (Apollo Lunar Surface Drill, ALSD) was used to drill hollow tubes into the lunar surface. These tubes were used for emplacement of probes for the heat flow and neutron probe experiments, as well as to obtain deep core tubes of the regolith for geology experiments back on Earth. The deepest penetration achieved on a hand-driven core tube was 70 centimetres, which required about 50 blows with a hammer [41]. For sampling at greater depths, the Apollo 15-17 crews used a battery-powered drill. This allowed sampling to depths of 1.5 to 3 metres, which was reportedly achieved easily on Apollo 16 mission, but with much more difficulty on Apollo 15 and 17. These boreholes are still the deepest drilled holes outside Earth. The ALSD had rotary percussive power head. The drill rod consisted of fiberglass tubular sections reinforced with boron filaments (each about 50 cm long). A closed drill bit, placed on the first drill rod, was capable of penetrating the variety of rock including about one metre of vesicular basalt (40% porosity). As lunar surface penetration progressed, additional drill rod sections were connected to the drill string. The drill string was left in place to serve as a drill hole casing [79].

The ALSD mass was 13.4 kg without the drill strings and caps. The size was 57.7 x 24.4 x 17.8 cm. The electric power was enormous 456 W (24 V DC, 19 A) [151]. That is much more than is available in modern robotic drill missions for a drill motor. It took up to 15 minutes to drill a hole, depending on the target material. The core stems came in sections. After the first two sections were assembled and drilled in so that about 15 cm remained above the surface, the drill was detached from the drill string with a wrench (Figure 14) and the second pair of core stems were assembled and attached (Figure 15). Then the drill was attached to this new section and the drilling continued until the third and fourth pairs had to be attached in a like fashion. The holes were to be within 15º of vertical, as visually determined by the astronaut once the probes were inserted [80]. The drill rods were left in place.



a) *b)*

Figure 15: a) The Apollo drill bit (6 cm long) close-up, and b) the drill stems and a bit [65].

The lower tube in image b) is a standard-length tube while the upper stem (shorter one) is designed to accommodate the bit. Note the helical threads to connect the tubes. The drill bit (close-up in figure a)) has five tungsten-carbide teeth. The narrow end (right side of the bit) is typical of the threaded joints between the stem sections (Images: NASA).

Basically drill performed well during the lunar surface activities. However, the following problems related to drilling operations were encountered during the first drilling-related mission, Apollo 15 [81]:

- Penetration of the surface to the full depth with the bore stems was not achieved.
- Releasing the bore stems from the drill adapter was difficult.
- Bore stem damage occurred near the first joint.
- Removing core stems from the drilled hole in the lunar surface was difficult.
- Separation of core stem sections was difficult.

These are basically the same type of problems that are common in terrestrial drilling also, and the MRoSA2 and MIRANDA tests (see Chapter 5) revealed similar problems. One fundamental problem during deep drilling is the friction of the compacted soil in the borehole. This affects the rotary movement of the drill string and requires additional power for drilling. During the Apollo drilling tests, it was discovered that interference from the compacted material in the drill flutes can be reduced and core stem removal eased by pulsing the power head when at the bottom of the hole without upward and downward motion of the drill stem. According to the NASA's Apollo drilling tests [81], the best results are obtained when the power head is pulsed just before the power head is removed to add each core stem section. The tendency to auger, as reported by the Apollo 15 astronauts on the Moon, is also reduced by pulsing the power head before each new core stem is added. To assure maximum core return and minimum core disturbance for those missions (without having the benefit of some of the experience from later Apollo ground tests), the crew did not pulse the power head. In addition, the core stem string was left in the ground for several hours before the crew returned for its final removal. The core stem string was removed with considerable physical effort, but still a very complete core was recovered. A mechanical assist (modified jacking mechanism shown in Figure 14) was mounted on the treadle for easier core removal from difficult formations.

3.2.2 Robotic sampling missions to Mars

By the time of writing this, there have been 38 Mars missions [91] by the United States, Russia, Japan and the Europe. About two thirds of them have failed. Mostly these missions have been fly-by missions (the early missions), or attempts to place spacecraft to an orbit around Mars. The most important missions regarding the topic of this thesis are the landers, which have performed in-situ analysis on Martian surface. While some of them have not been successful, some of them are also worth of reviewing. There have not been actual drilling missions on Mars, if one does not count rock abrasion devices and soil scooping.

The selected missions for analysis in this chapter are the NASA's Viking landers, the Beagle-2 lander and NASA's Sojourner and Mars Exploration Rovers (MER). Also some early Russian landers and concept designs are reviewed. These missions are explained in below.

The Viking landers

NASA sent two Viking Missions; Viking 1 and 2 to Mars in 1975. Each of them consisted of an orbiter and a lander (Figure 16). The landers landed safely to Mars on July 20, 1976, and September 3, 1976. The primary objectives of the mission included obtaining high-resolution images of the Martian surface, characterising the structure and composition of the atmosphere and surface, and search for evidence of life. The Viking landers took surface samples and analysed them for composition and signs of life, studied atmospheric composition and meteorology, and deployed seismometers. The Viking 2 lander ceased communications on April 11, 1980, and the Viking 1 lander on November 13, 1982 [91].

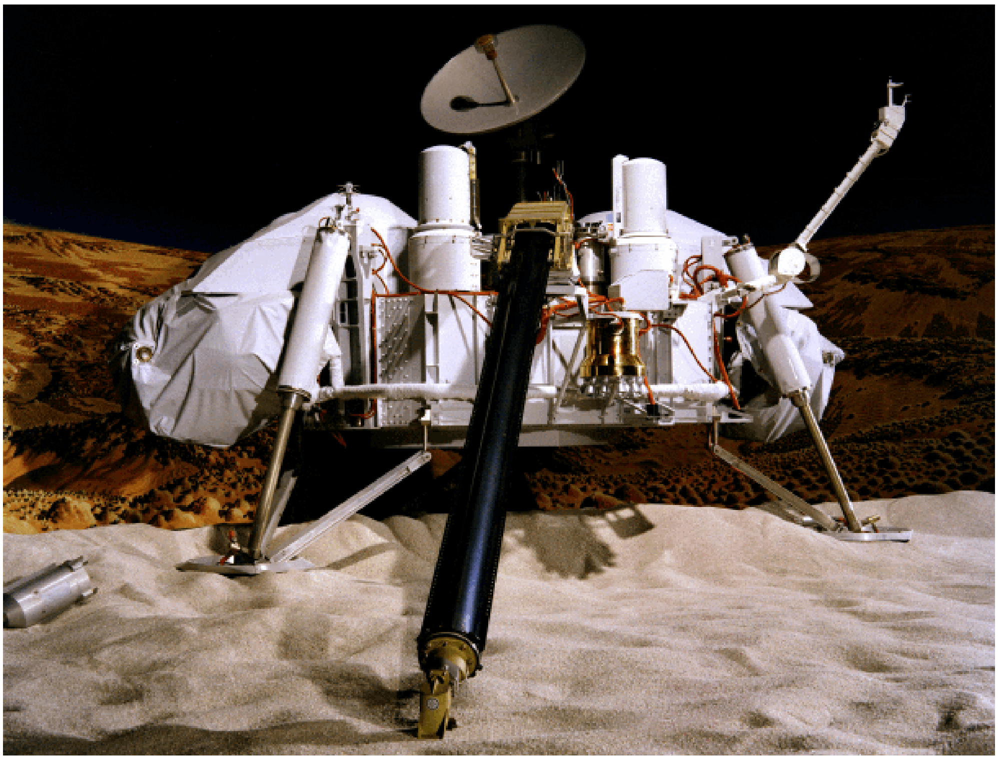


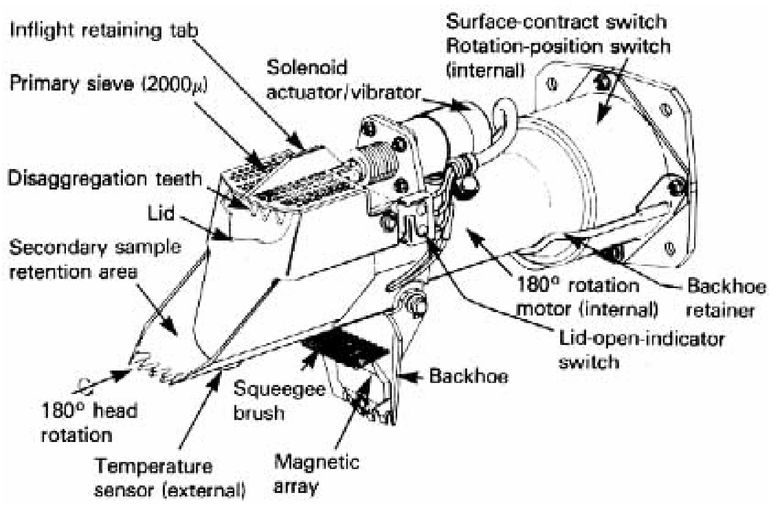
Figure 16: Viking lander and its extendible boom and scoop (Image: NASA).

According to the images and soil properties measurements, the surface material at both landing sites can best be characterised as iron-rich clay [60]. Measured temperatures at the landing sites ranged from 150 to 250 K, with a variation over a given day of 35 to 50 K. Seasonal dust storms, pressure changes, and transport of atmospheric gases between the polar caps were observed. The biology experiment produced no evidence of life at either landing site.

Viking landers had a six-sided chassis with alternate 1.09 m and 0.56 m long sides. The landers stood on three extended legs, which were attached to the shorter sides. The distance of the footpads was 2.21 m in an equilateral triangle shape. Payload instrumentation was attached to the top of the base. Electric power was provided by two radioisotope thermal generator (RTG) units, containing Pu-238. Each RTG unit 0.28 m tall, 0.58 m in diameter, had a mass of 13.6 kg and provided roughly 30 W of continuous power at 4.4 V voltage. Rechargeable batteries were also onboard to handle peak power loads.

Primarily interesting payload instrument regarding this thesis is the surface sampler arm of the lander. An extensible arm and scoop system, shown in the middle of Figure 16, was programmable to acquire samples of soil and rock for analysis on board the landers and to affect the local environment for visual inspection. The lander's chemical and biological investigations all used samples of surface materials excavated by the surface sampler. In addition, as the experience with lunar Surveyor spacecraft demonstrated (see Chapter 3.2.1), there was much to learn about the surface simply by digging in it. During the Viking mission, digging was part of the physical properties and magnetic properties investigations.

The surface sampler (Figure 17) consisted of an instrument attached to the end of a three-metre retractable boom. The boom housing, supporting the boom, could be rotated. The instrument's collector head was basically a scoop with a movable lid and a backhoe hinged to its lower surface. A motorized rotator acted as a mechanical wrist to permit manipulation of the collector head by allowing 180° rotation angle. To fill the scoop with Martian soil, the lid was first raised and then the boom was extended along or into the surface. Once the scoop was full of samples, the lid was closed. The top of the lid had a sieve formed of holes (2 mm diameter). When the sample-full collector head was positioned over one of the inlets for the soil study instruments, it was inverted 180° and the sieve vibrated. This allowed particles smaller than 2 mm to drop down to the inlet of the instruments. Samples coarser than that could be delivered to the X-ray fluorescence spectrometer. The gas chromatograph-mass spectrometer and the biology instruments had their own filters to control the size of material introduced into their sample processing assemblies [76].



a)

b)

Figure 17: a) Viking sampler arm, which is mounted on the end of the Extendible Reel Stored Boom. b) A trench that was dug by the sampling scoop. The depth of trench is approximately 10 cm (Image: NASA).

The surface sampler was also used to dig small trenches, by lowering the backhoe to place the sampler head on the surface, and then retracting the boom. Maximum digging force was 133 N as shown in Table 3. After excavation, the soil could be scooped up for sampling and for analysis of instrumentation such as magnets and temperature sensor.

Table 3: Viking lander's Extendable Reel Stored Boom parameters.

Parameter	Value	Note
Mass	11.3 kg	
Dimensions	614.8 mm x 233.7 mm x 342.9 mm	Full length when extended is 3 metres.
Power	30 W max	
Sampling energy	Estimated 4.3-8.6 kJ / cm^3	Very conservative estimation for energy/sample is estimated by assuming full power during whole sampling period taking typically 24-28 min [74]
Sampling depth	Surface	
Sampling force	Shear: 20 N, digging: 133 N, scraping: 88 N	

Although the Viking landers did not carry a drill system onboard, it is very interesting to study the soil scooping mechanism. One method of comparing different kind of instruments is the energy-per-sample ratio. As can be seen from the Table 3, the estimated [74] energy needed for 1 cm^3 soil sample of soil is in a range of 4 to 9 kJ. The scooping method is also productive way to achieve some means of subsoil investigation, since the sampler arm could dig trenches of few tens of centimetres.

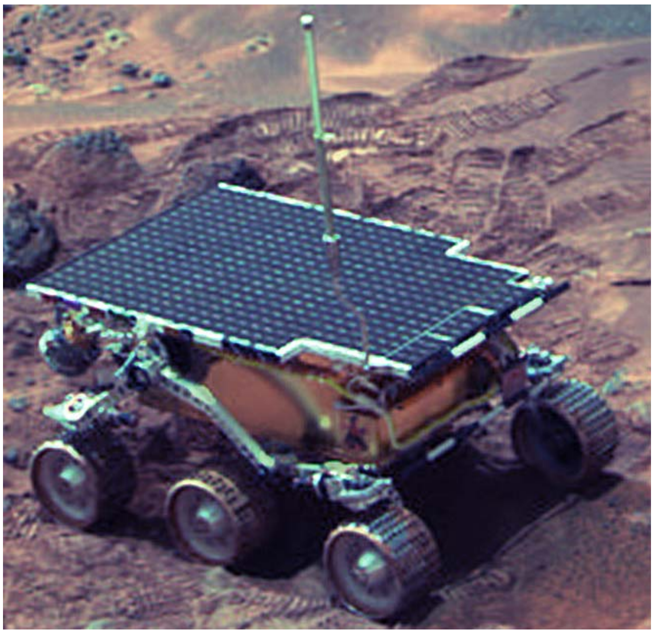
Pathfinder lander and Sojourner rover

The Mars Pathfinder mission consisted of a stationary lander and a surface rover. They landed on Mars in July 4, 1997. Although the mission had the primary objective of demonstrating the feasibility of low-cost landings on and exploration of the Martian surface, there were also high hopes for the robotic mobility and soil analysis techniques. The mission's scientific objectives included atmospheric entry science, long-range and close-up surface imaging, rock and soil composition and material properties experiments. Along with these objectives, a meteorology packet was included in the lander surface station. Mars Pathfinder mission was formerly known as the 'Mars Environmental Survey Pathfinder' (MESUR).

The 10.5 kg rover, 'Sojourner' (Figure 18 a), is the main point of study here, since it has the closest resemblance of the ESA's ExoMars rover, although it was much smaller in size and in performance. The dimensions of the Sojourner were 280 mm (height), 630 mm (length) and 480 mm (width). Ground clearance was 130 mm mounted on a "rocker-bogie" suspension [28]. Maximum power consumption was 13 W.

The main experiments of the Sojourner were Alpha Proton X-ray Spectrometer (APXS), Rover Imaging Cameras, Materials Adherence Experiment (MAE) and Wheel Abrasion Experiment (WAE). The objective of the MAE was to determine the rate of dust deposition on the Martian surface. The rate of deposition is an important quantity in the evaluation of the use of solar cells for long-term missions on Mars, because dust covering will affect the performance of the solar cells. The WAE was designed to study the abrasive wear of the Martian soil on various types of metal plates attached to one of the rover's six wheels. The experiment consisted of thin (20 - 100 nm) films of nickel, aluminium and platinum over black anodised aluminium strips attached to the center of the tread of the middle left rover wheel (Figure 18 b). Film reflectivity was then measured over time by a photovoltaic sensor. Changes in reflectivity indicated the amount of abrasion on the different films due to rolling wear. At times all other wheels were locked and only the abrasion wheel was spun in the regolith, providing a test of wear under harsher conditions [28]. Wear characteristics of the different metals indicated the types of soils encountered by the rover wheels. This information, combined with terrestrial ground simulations, allowed determination of the types of materials comprising the Martian regolith.

There was no specific sample scooper or other type of robotic arm instrument. However, the WAE was also a method to manipulate Martian soil. It was somewhat similar experiment to the Viking lander's trench digging method, but instead of robotic arm, the rover used it wheel to dig a trench. Out of the six wheels, five were set to drive forward slowly while one was locked in position. During this 5-wheel drive, the one locked wheel caused friction with the soil, developing a shallow trench and exposing subsoil regolith. Then the rover used its cameras and APXS instrument to analyse the exposed soil.



a)

b)

Figure 18: a) The Sojourner rover on Mars, imaged by Pathfinder lander. b) Wheel Abrasion Experiment (Images: NASA).

The Mars Exploration Rovers

NASA sent two (identical to each others) Mars Exploration Rovers (MER) to Mars in 2003 (Figure 19). They landed on different sides of Mars in January 2004. The main objective among the mission's scientific goals is to search for signs of past water and characterise a wide range of rocks and soils that might hold clues to past water activity on Mars. The rovers will also perform their contributions in pursuit of the overall NASA's '*Follow the Water'* Mars science strategy. Understanding the history of water on Mars is important to meeting the four science goals of NASA's long-term Mars Exploration Program: to determine whether life ever arose on Mars, to characterise the climate of Mars, characterise the geology of Mars and to prepare for human exploration [93]. The spacecrafts were targeted to sites on opposite sides of Mars that appear to have been affected by liquid water in the past. The landing sites are at Gusev Crater, a possible former lake in a giant impact crater, and Meridiani Planum, where mineral deposits, such as hematite, suggest that Mars had a watery past. The MER rovers are interesting devices regarding the topic of this thesis, since they resemble the ESA's plans for ExoMars rover. Even that the MER's do not carry a drill with them, there are basically two methods that the rovers can use for manipulating Martian soil or rocks: the 'wheel digging' method, and the Rock Abrasion Tool (RAT).

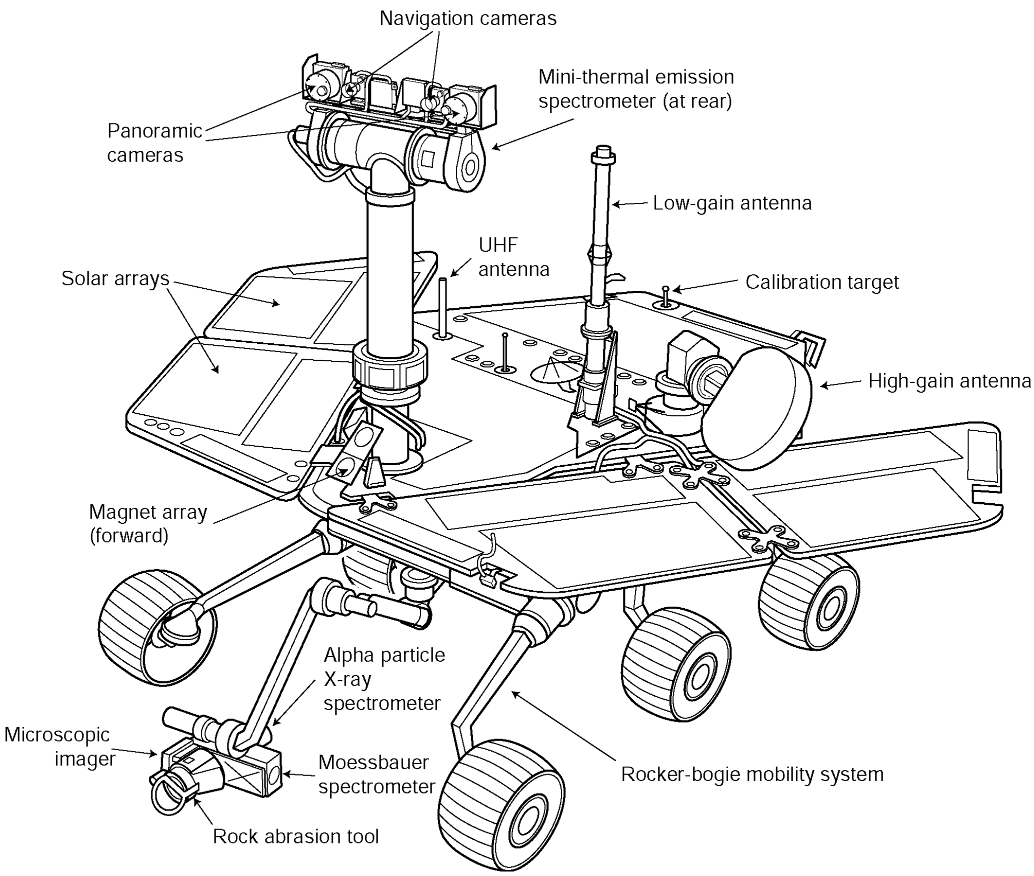


Figure 19: Mars Exploration Rover. Height of the mast from the ground is 1.4 metres (Image: NASA).

The Instrument Deployment Device (IDD), "robot arm", contains instruments to analyse and manipulate the environment. The instruments are Alpha Particle X-ray Spectrometer (APXS), Mössbauer spectrometer, microscope imager and Rock Abrasion Tool (RAT). The RAT is the most interesting instrument regarding the topic of this thesis. However, it is worth to take a brief look at the IDD itself also, since the ExoMars missions Pasteur drill calls possibly for a robotic arm too. The IDD is about one metre of length when extended and it contains five actuators (Figure 20). The design of these actuators is subject to several primary requirements based on the MER mission as a whole. The requirements for the IDD actuators are then [90]:

- IDD must withstand launch loads and landing loads of approximately 42 g's (due to the Mars Pathfinder airbag-style landing).
- IDD must survive rover driving and manoeuvring loads of approximately 6 g in Mars.
- It must operate within a temperature range of –70ºC to +45ºC (203 K to 318 K) and a non-operational temperature range of –120ºC to +110ºC (153 K to 383 K).
- IDD must be as low mass as possible and allow the IDD to stow in a very confined launch volume.
- Perform throughout the duration of the 90-sol primary MER mission (a relatively short lifetime for all mechanisms involved).

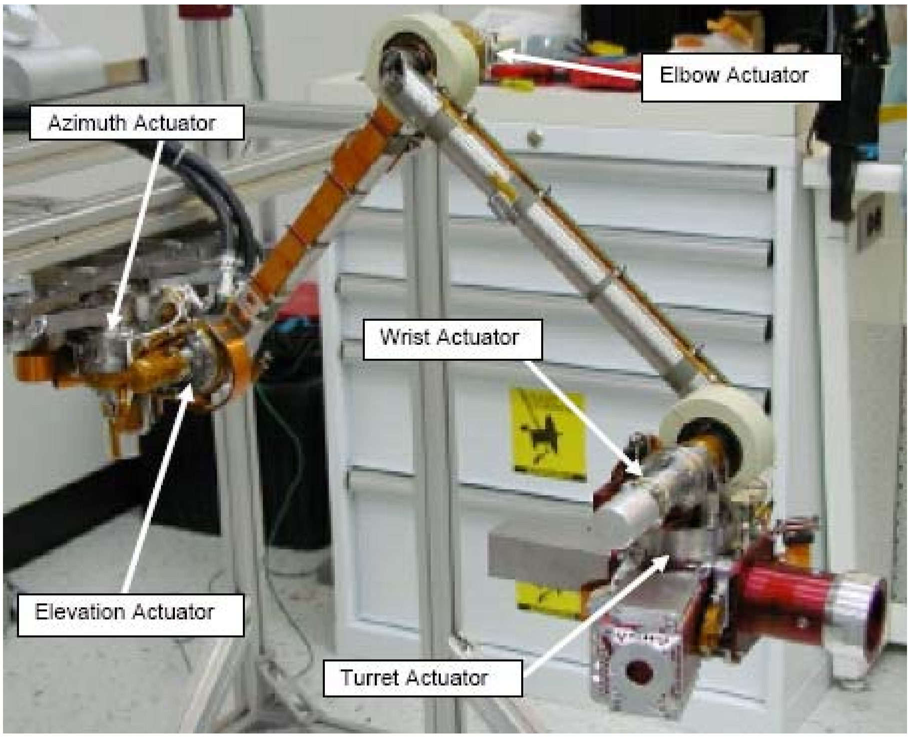


Figure 20: MER IDD robot arm (Image: Alliance Spacesystems, Inc.) [90]

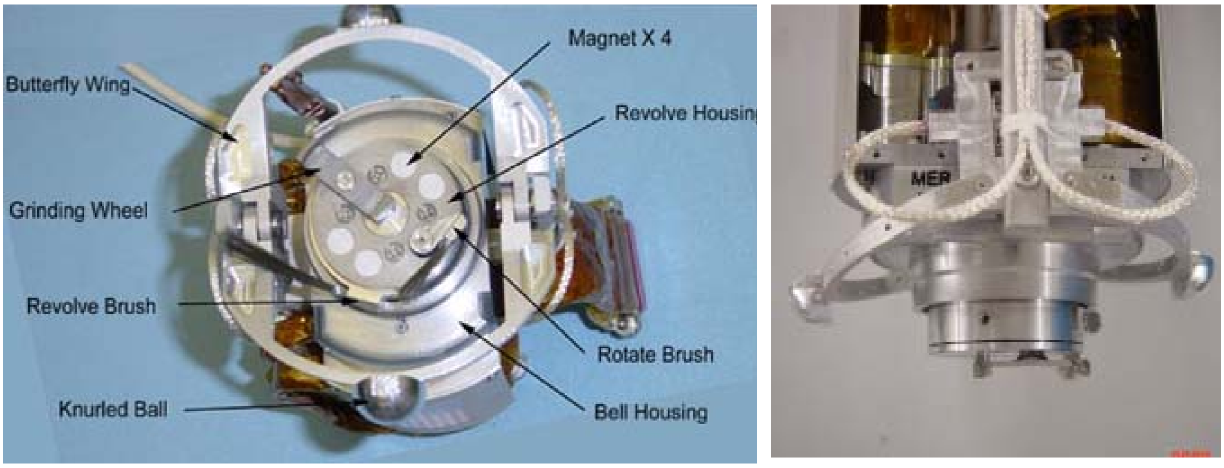
Both rovers are equipped with the Rock Abrasion Tool (RAT), which have been designed, developed, and operated by Honeybee Robotics, a US based company. The RAT is an electric-powered device containing a grinding wheel designed to remove dust and weathered material from the surface of a rock to expose a fresh surface. After the RAT has finished its work, the fresh rock surface can be studied by the other instruments of the IDD (Figure 20).

The RAT is mounted on the IDD, the 'robot arm', which places the RAT against the target rock. RAT is 10 cm of length and has diameter of 7 cm. It weighs 685 g and uses 11 W of average operational power (Table 4).

Table 4: The Rock Abrasion Tool properties [101].

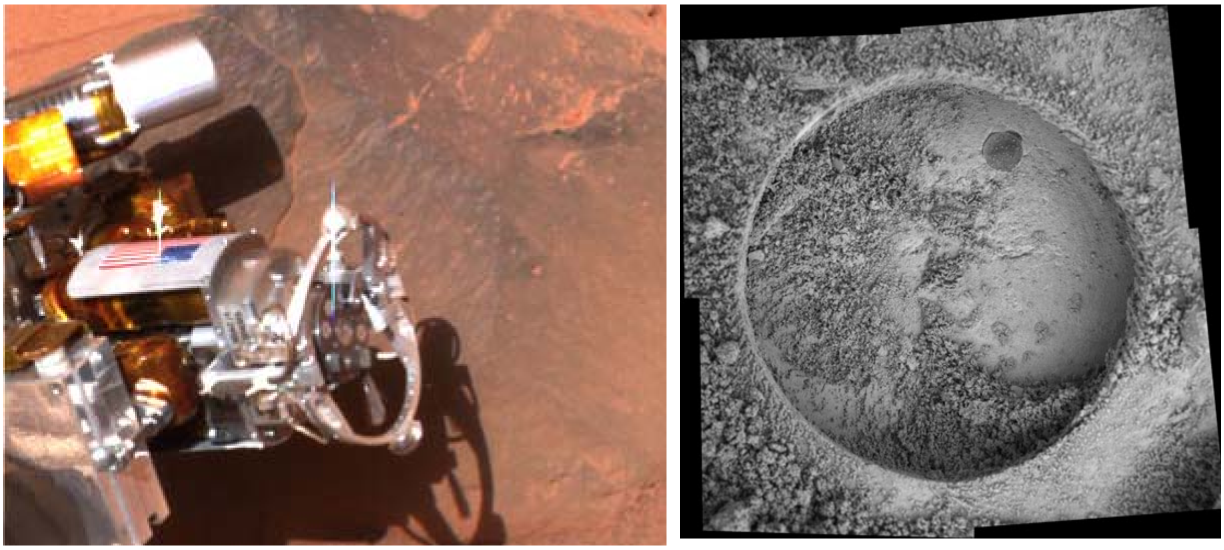
Parameter	Value	Note
Mass	685 g	
Dimensions	100 mm (length) x 70 mm (diameter)	
Grinding area	45 mm in diameter, depth 5 mm nominal maximum depth	Possible to go deeper by grinding several holes to the same target.
Power	11 W required for operation	Max 30 W-hour allowed per day
Operation time	2-4 hours	depending upon depth required & rock hardness
Force	Required preload: 20-100 N, F from IDD: 10-100 N, contact to rock: ~5 N	
Contact to rock	Grinding wheel single contact area: 13 mm^2	Two contacts in RAT, total 26 mm^2; 3000 rpm speed; Each contact area is covered with 3800 diamond particles, 125-125 µm in size.
Grinding position:	±15° pitch and yaw, with respect to target.	

RAT instrument, consisting of 188 parts, uses two diamond matrix wheels (shown in Figure 21 a), and each of these two wheels has two teeth which cut out a circular area as the instrument's head rotates at high speed (max 300 rpm). In addition, the grinding wheels can also slowly revolve around each other, sweeping the two circular areas over the cutting region (45 mm diameter). Like in all moderate-power drills and grinders, penetration into the rock is slow and designed to minimize alteration of target's petrologic fabric, chemistry or mineralogical composition. Temperatures values and motor currents are monitored during the grinding operation, because they can be used to get information on the rock properties. According to [101], grinding operations take about 2 hours for dense basalt. A unit price for RAT device is 875 thousand US dollars in a delivery of four units (2 flight models (Opportunity's RAT seen in Figure 22), 2 spares, totaling 3.5 million USD [101]). Time from design to delivery was 27 months.



a) *b)*

Figure 21: a) RAT main parts. b) Side profile (Images: Honeybee Robotics).



a) *b)*

Figure 22: a) RAT imaged in Mars. b) Grinding made by MER Opportunity's RAT instrument. The target rock is called 'Tennessee' and it was made on June 14, 2004. Hole depth is 8.12 mm and diameter is 45 mm. (Images: NASA/JPL/Cornell/USGS).

Although the RAT is the main sample preparation device, the MER rovers can also use the 'wheel digging' method. This method was explained in previous chapter about NASA's Sojourner rover. Similarly, the MER's can dig a trench using their wheels.

Past unsuccessful Mars soil analysis missions

There are several unsuccessful missions to Mars ranging from the 1960's. The Russians had their Mars program in 1960's and 1970's, when total of 16 Mars probes were sent to Mars [102]. However, none of these probes were complete success, and the same fate was faced by later Phobos probes in 1988 and the ill-fated Mars'96 probe (last Russian's lander to Mars, which was co-built in Finland). It is a pity that none of these early-days' landers succeeded in their operation, since they carried interesting soil analysis packages and could have brought important information from Mars. The Russian's landing attempts of 1960's and 1970's were in chronological order: Sputnik 24 (1962), Cosmos 419 (1971, it is not known whether this craft contained a lander also [103]), Mars 2 (1971), Mars 3 (1971), Mars 6 (1973) and Mars 7 (1973). In addition to these landing attempts, there were two Phobos landers in 1988, which failed to perform the landing operation. In 1999, Mars Polar Lander (MPL) and accompanying Deep Space 2 probes failed in their landing attempts. In addition to these Russian and NASA's missions, ESA sponsored and UK built Beagle 2 failed in its landing attempt in 2003.

Among of these failed landing missions, a few of them are worth to study in some details. Missions that are relevant to this thesis are explained in chronological order in below. Also some never-flown missions are explained.

Russian projects: M-71 Mars 2 – 3 and M-73 Mars 6 - 7

The M-71 was a spacecraft type that was built for 1971 Mars launch window. M-71 was used in three missions: Cosmos 419, Mars 2 and Mars 3. Cosmos 419 failed to leave Earth orbit, but Mars 2 and 3 managed to get to Mars. The Mars 2 and Mars 3 missions consisted of a bus/orbiter module and an attached descent/lander module [30]. Mars 2 was launched on May 19, 1971. The spacecraft released the descent module 4.5 hours before reaching Mars on November 27, 1971. The descent system malfunctioned and the lander crashed to Martian surface at 45° S, 302° W.

Mars 3 probe (launched May 28, 1971) intended to conduct of a series of scientific investigations of the planet Mars and the space around it. The descent module was released on December 2, 1971 about 4.5 hours before reaching Mars. Through aerodynamic braking, parachutes, and retro-rockets, the lander achieved a soft landing at 45° S, 158° W and began operations. But only after 20 seconds of operations after landing, the instruments stopped working for unknown reasons. Orbiter data was sent back for many months. Scientific objectives of the Mars 3 lander was to perform a soft landing on Mars, return images from the surface, and return data on local meteorological conditions, atmospheric composition, and mechanical and chemical properties of the Martian soil. Mars 3 was the first spacecraft to make a successful soft-landing on Mars. The lander was similar in appearance than the Luna 13 lander in Figure 9.

The Mars 2 and 3 landers were equipped with two TV cameras with a 360° view of the surface as well as a mass spectrometer to study atmospheric composition; temperature, pressure, and wind sensors. The landers had also devices to measure mechanical and chemical properties of the surface, including a mechanical scoop to search for organic materials and signs of life.

Mars 6 and Mars 7 were part of the Russian Mars 1973 program, and thus the spacecraft type was designated to be M-73. Mars 6 was launched in August 5, 1973 and it has similar concept than the Mars 2 and 3 crafts. Mars 6 landed on Mars in March 12, 1974, but the contact was lost during the final approach of the descending. Mars 7, launched four days after Mars 6, experienced problems with its retro-rockets and was unable to land on Mars.

All of these Mars landers, 2-3 and 6-7, carried a small micro-rover called PROP-M, which was intended to use for analysis of Martian soil-properties.

The PROP-M Mars Rover

The Russian Mars landers carried a small, walking robot, "PROP-M" [68]. Because it did not have its own power source, it was tethered to the lander. The tether was 15 m of length and it also carried the communication line. The robot carried two instruments: a dynamic penetrometer and a radiation densitometer (called "GEOHI" RAS). The rover was onboard Mars-2 and 3 (1971), and later Mars-6 and 7 (1973) landers, which all unfortunately failed. The "ski-walking" rover is shown in Figure 23.

Mass of the rover was 4.5 kg, and dimensions were 215x160x60 mm. Travel speed was one metre per hour, and the rover consumed 5 W of power. Russian Lavochkin Association produced the rover.

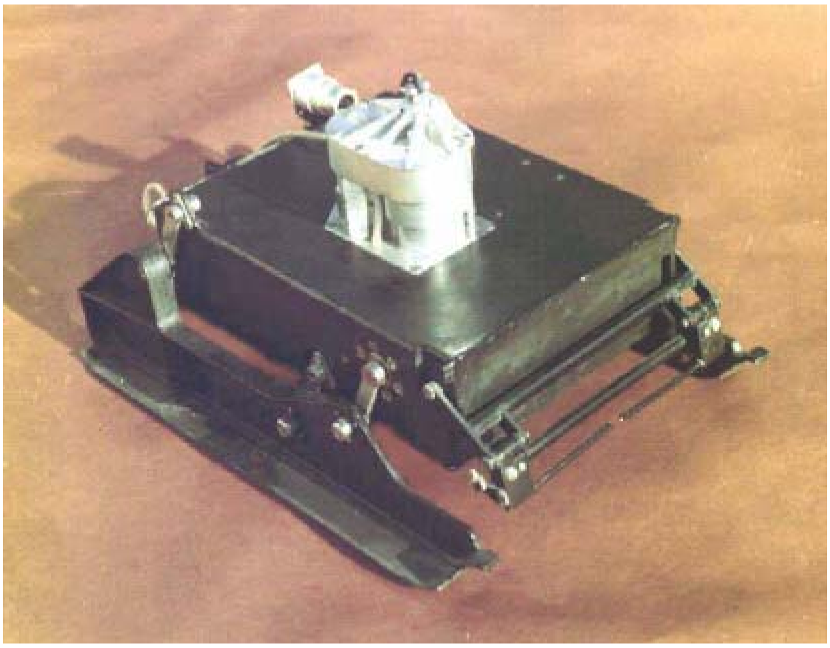
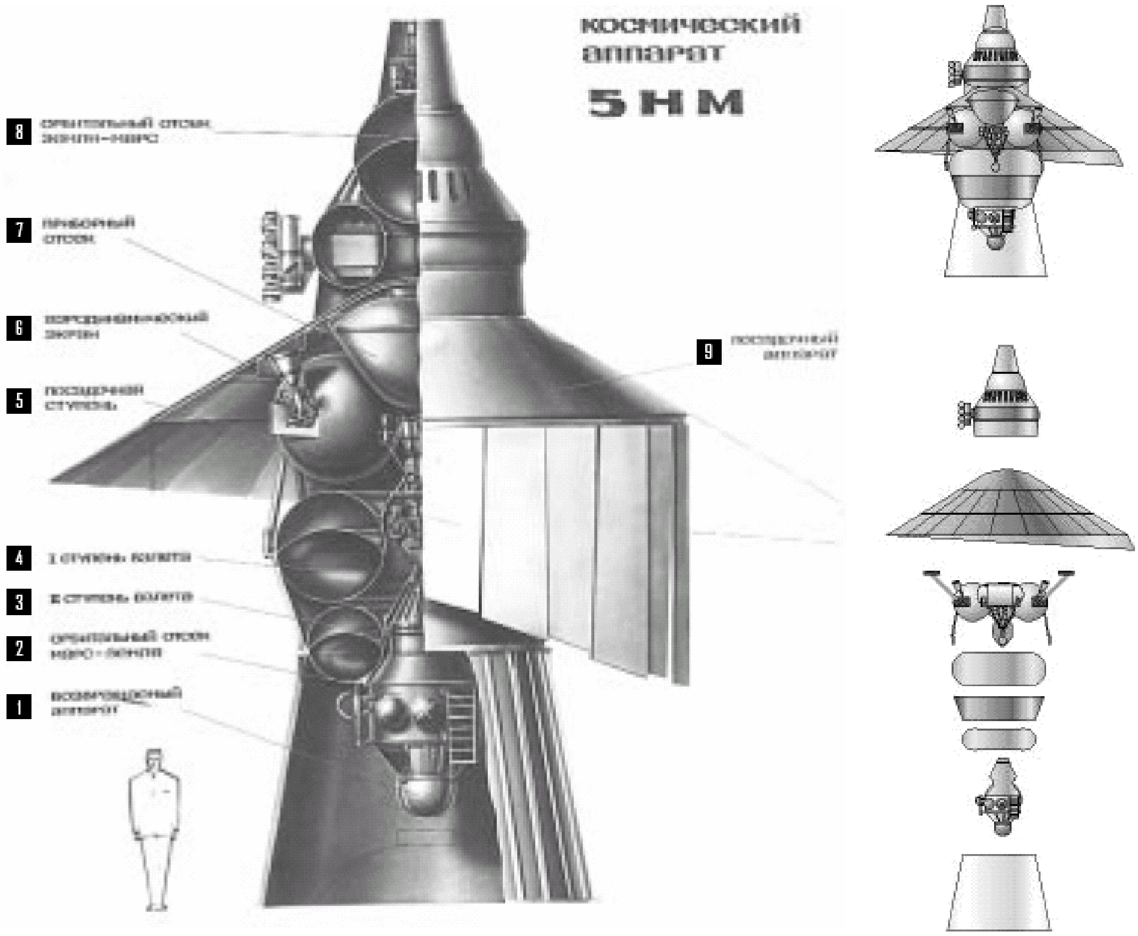


Figure 23: The PROP-M ski-walking rover (Image: RCL).

As shown in Figure 23, the main frame of the PROP-M was a squat box with a small protrusion at the center of the body. The rover had two wide flat skis, one extending down from each side elevating the frame slightly above the surface. Also seen in the picture are the obstacle detection bars in front of the rover. The rover was supposed to be lowered to the surface after landing by a manipulator arm and to move in the field of view of the TV cameras. Then the rover was planned to stop every 1.5 metres to make measurements. The traces of movement in the Martian soil would also be recorded to determine material properties.

Project 5NM: Mars sample return attempt

The Project 5NM was the first mission that was supposed to bring Martian soil sample back to Earth. Mission 5NM was to have been launched on September 1975 and it was to have reached Mars on September 1976. However, the mission was cancelled because of the high risk of failure of the probe during three years in space and of the risk of bio-contamination if the re-entry capsule broke on entering Earth atmosphere. The system consisted of orbiter and a lander. The mass of the lander was impressive 16000 kg and it had a foldable aeroshell screen with a central solid area with a diameter of 6.5 metres. At the perimeter of the solid cover, 30 petals were attached. After the spacecraft entered an interplanetary trajectory, the petals were opened, creating an aerodynamic cone with a diameter of 11 metres. The instrument module system included the velocity meter, which worked on the Doppler principle, altimeter, radio system, the program timing device, and the power system [25]. The spacecraft is shown in Figure 24.



a) b)

Figure 24: Project 5NM Mars Sample Return mission [25].

The 5NM Spacecraft designed to deliver the samples of the Martian soil to Earth: Figure a): (1) returning capsule, (2) orbital Mars-Earth module, (3) second stage, (4) first stage, (5) landing stage, (6) aeroshield cover, (7) instrument module, (8) orbital Earth-Mars module, and (9) lander [25]*. Figure b): Top, cross section. Below, exploded view showing each stage (Image: Mark Wade [122]).*

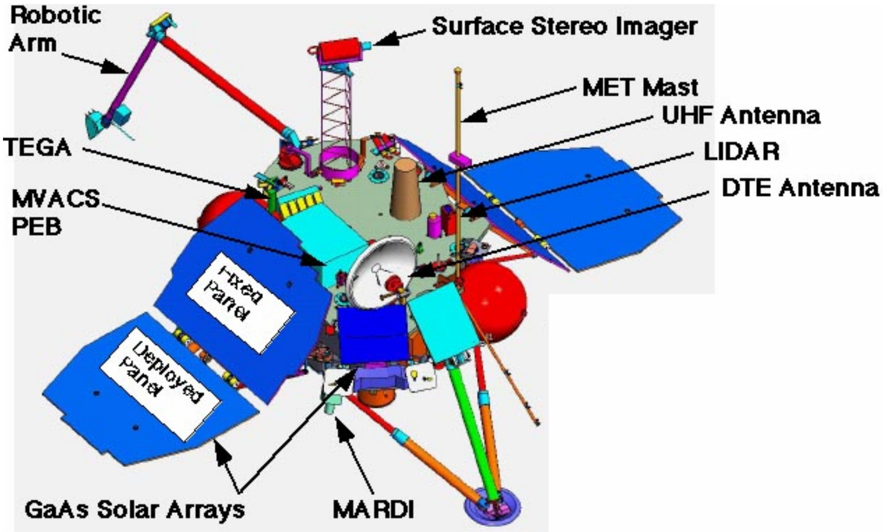
The landing site would be surveyed using panoramic cameras. The lander's robot arm would be commanded to scoop up some soil from a desirable location and insert it in a return capsule. Unfortunately more information about the sampling system was not available or found.

Mars Polar Lander and Deep Space 2 probes

The Mars Polar Lander (MPL) mission was part of the NASA's Mars Surveyor program and the objective was to study Martian volatiles (such as water ice and carbon dioxide) and Mars' climate history. The southern polar region was assumed to be the best place to conduct these studies in the frames of this mission. Attached to the spacecraft's cruise stage were two Deep Space 2 (DS2) Mars microprobes/penetrators, which would separate from the cruise stage prior entering the Martian atmosphere and penetrate into the Martian surface about 100 km from the MPL's landing point.

Lander mass was 290 kg and it landed on Mars in December 3, 1999. However, the retro-rockets were shut down too early by a computer error (design fault in the software), and the lander crashed to the surface. The two DS2 probes (named 'Scott' and 'Amundsen') were successfully separated prior MPL's atmospheric entry, and made their way to the surface. However, they too were unable to establish any contact with Mars orbiters or Earth ground stations.

The MPL payload (see Figure 25a) was called 'Mars Volatiles and Climate Surveyor' (MVACS), consisting of four major science elements: a Stereo Surface Imager (SSI), a Robotic Arm with Camera (RAC), a Meteorological package of pressure, temperature, wind, and water vapour sensors, and a Thermal and Evolved Gas Analyzer (TEGA).



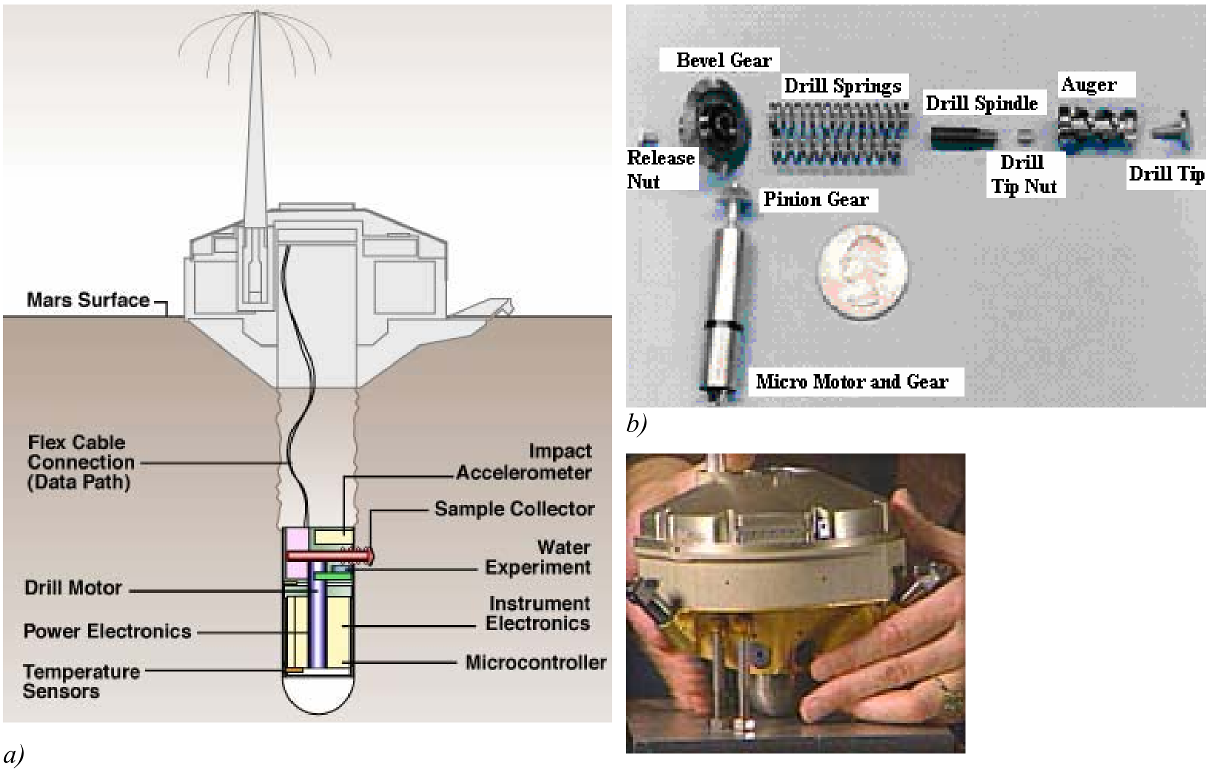
a)

b)

Figure 25: a) NASA's Mars Polar Lander. b) Fully extended robotic arm (Images: NASA).

Robotic Arm (RA) & Robotic Arm Camera (RAC) had a two-metre arm (Figure 24 b) with articulated end member, camera, and temperature probe. The RA could dig trenches, acquire samples of surface and subsurface materials and support operations of the RA Camera. The arm was about as strong as a human arm, and the scoop had additional teeth to aid in digging. The RAC was supposed to image the surface and subsurface at close range to reveal possible fine-scale layering and to characterise the fine-scale texture of the samples and trench sides. The lightweight RA also supported a climate probe for measuring surface and subsurface temperatures (the Elbow Temperature Sensor, ETS). ETS was part of the MET package, but it was located on the elbow of the Robotic Arm. ETS would have provided additional temperature measurements, and allowed surface temperature measurements to be made anywhere by moving the Robotic Arm.

The primary scientific objectives of the Deep Space 2 (DS2) Mars microprobes (Figure 26 a) were to search for the presence of water ice in the soil and to characterise its thermal and physical properties. DS2 penetrators included a small drill, which would have brought approximately 0.1-gram soil sample inside the probe. The sample would then be heated in 10° C increments, and measurements of the amount of water vapour released at each stage of heating would be made using a tunable diode laser, giving information on the water-bearing minerals within the sample. The tunable diode laser was set so that its light was at the point in the spectrum where water absorbs light. When the impact occured, an accelerometer measured the rate at which the probes came to rest. This information would have been used also to determine the hardness of the soil and to determine possible soil layers at the impact place. The DS2 probe had temperature sensors, which would have estimated the heat conductivity of the soil.



a)

b)

c)

Figure 26: a) Deep Space 2 microprobe schematics. b) Motor / Drill assembly. c) Scale-reference for DS2 (Images: NASA).

The drill had a tiny motor, which would have driven a small drill bit out the side of the probe's forebody. After sample acquisition, bits of soil engaged by the drill tool would have fallen into a small heater cup, which was sealed by firing a pyrotechnic device which closes a door. The drill mechanics is shown in Figure 26 b), and the DS2 probe in Figure 26 a) and c) [123].

Beagle 2

The United Kingdom developed Beagle 2 (Figure 27), a 72 kg probe (with a 32 kg lander), for inclusion on the ESA's 2003 Mars Express mission. Mars Express was launched on June 2, 2003 with Beagle 2 onboard and it reached the red planet on December 25, 2003. As Mars Express performed a successful orbit insertion, Beagle 2 landed in Isidis Planitia basin on Mars [36]. Unfortunately the lander was never heard of after it separated from the Mars Express. Beagle 2 was supposed to use "hit, bounce, and roll" airbag landing technology to that employed by NASA's Mars Pathfinder in 1997.

The primary scientific purpose of the Beagle 2 was to search for life from Mars [8]. The lander carried several tiny instruments that were to search for organic material on and below the surface of Mars, and to study the inorganic chemistry and mineralogy of the landing site.

Beagle 2 lander is stationary; it cannot move unlike the rovers, but it has a robotic arm called Position Adjustable Workbench, PAW (see [36]). PAW can move in a radius of 0.75 metres and it contains several soil analysis instruments. Also included in the PAW is the 'mole', called 'PLanetary Underground TOol' (PLUTO). The PLUTO can dig its way down to 2 metres and it is connected to the PAW by a tether, which supports the power and communication. PLUTO can move at most 3 metres in any direction and its purpose is to return a 0.24 cm^3 sample back to the lander, which in turn analyses it. Included in the Beagle 2 payload is also a rock corer/grinder instrument (RCG). It has basically two purposes; to remove any dust from nearby rocks that they can be analysed by PAW's X-ray and Mössbauer instruments, and to obtain core samples from rocks. The RCG has rotating chipping bit that produces a flat surface of 30 mm in diameter. Sampling of the rocks is performed by using a hammering and rotating action to obtain cores about half a centimetre long.

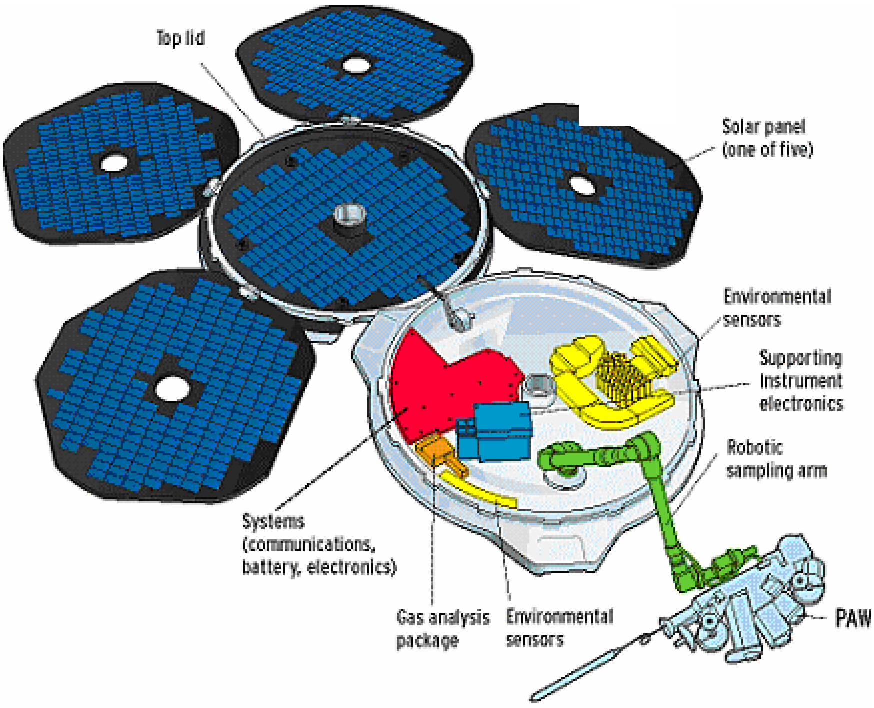
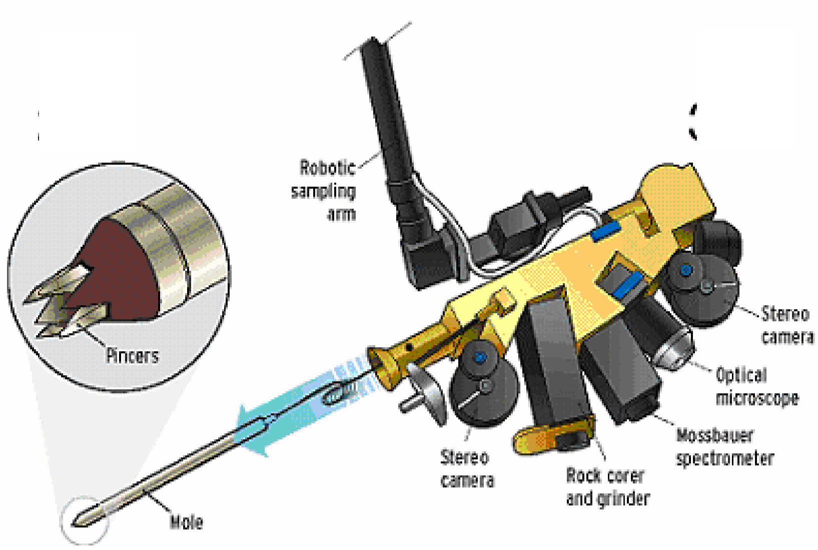
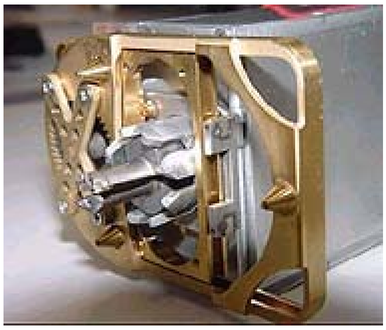


Figure 27: The Beagle 2 Mars lander and its instruments [35].





a) (left)

b) (above)

Figure 28: a) The Beagle 2 PAW. b) Rock corer/grinder (Image: [38])

The RCG, situated in Beagle 2 PAW, is shown in Figure 28 b). The inner axis of the RCG contains a device called the Micro End Effector (MEE). It is consisted of a pair of forceps, which can grind and sample the target rock. The RCG can produce a borehole up to 10 mm deep. Repeated boring produces a flat surface of 30 mm in diameter for the investigations of the X-ray spectroscope and the microscope camera. The RCG weighs 154 g and its dimensions are 30 x 60 x 100 mm. RCG uses 6 W of power in operation [36].

3.2.3 Venera and Vega missions to Venus

Venus is the nearest planet to Earth, and due to their similar sizes, Venus is often called the 'sister planet' of Earth. The Soviet Venera (*Venera* is Russian name to Venus) program aimed to study the planet Venus. The program included 16 probes, three of which failed. Venera 1 was the first probe from Earth to pass by Venus (although radio contact was lost already after a week after launch) and Venera 3 was the first probe to land on Venus' surface (Venera 3 also failed to maintain radio communication). The Venera spacecraft from 9 to 14 consisted of both an orbiter and a lander. Number 13 and 14 were identical, as were the 15 and 16 (launched 1983).

Venera 13 and 14 were launched in October 30 and November 4, 1981, respectively. They were identical spacecraft consisting of a bus and an attached lander. They were also the first Venus landers, which contained a drilling apparatus. After launch and a four-month cruise to Venus, the descent vehicle separated and plunged into the Venus atmosphere on March 1, 1982. As the spacecraft flew by Venus, it acted as a data relay for the lander, and then continued on into a heliocentric orbit. The landers had instruments to conduct chemical and isotopic measurements, monitor the spectrum of scattered sunlight, and record electric discharges during its descent phase through the Venusian atmosphere. The spacecraft utilized a camera system (see Figure 25), an X-ray fluorescence (XRF) spectrometer, a soil/rock drill and surface sampler, a dynamic penetrometer, and a seismometer to conduct investigations on the surface.

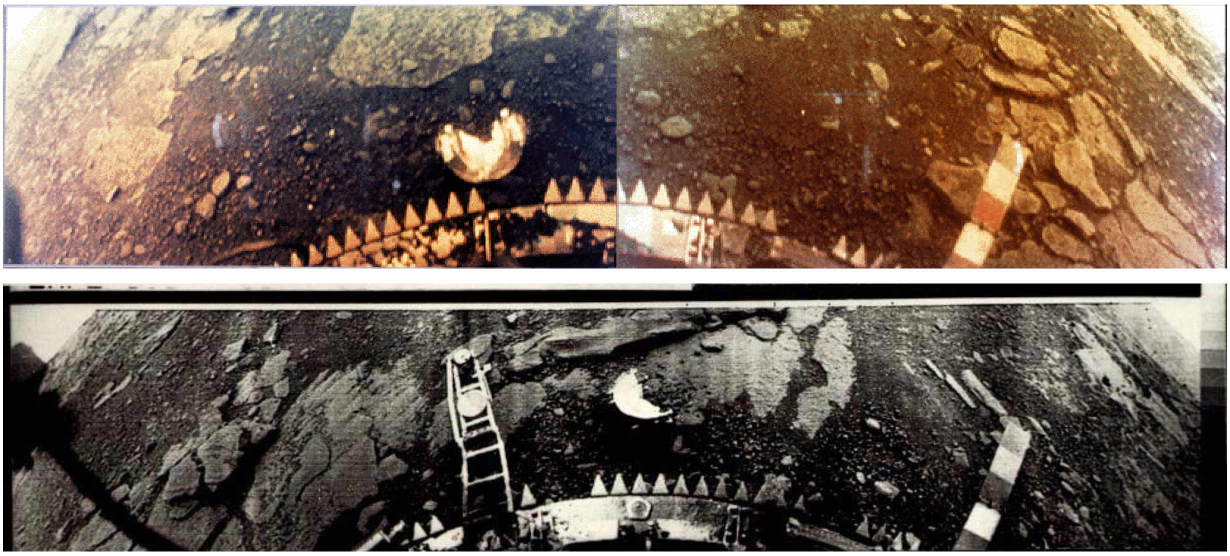


Figure 29: Venera 13 lander's images from the surface of Venus [30]. Venera 13 lander touched down on the Venusian surface on the 1st of March 1982 in the region known as Phoebe Regio. Venera 13 survived on the surface for 127 minutes. The above photographs were taken from its two opposite-facing cameras. The upper image is approximate true-colour image. The black-and-white bottom frame shows the lander's testing arm. The surface is made up of flat, platy rocks and soil. Parts of the lander and semi-circular lens covers can be seen in both images. The images seem to be curved due to the panoramic lens of the camera.

In addition to the drilling device, the Venera landers 13 and 14 were equipped with a penetrometer (Figure 30) attached to the outside of the lander body. The purpose was the determination of physical and mechanical properties of soil and electric resistance of the soil surface layer of Venus. The penetrometer instrument used a 'one-fold impact' action, as it was spring-loaded and could be used only once. Its overall dimensions were 360×145×120 mm and its mass was 2.1 kg.

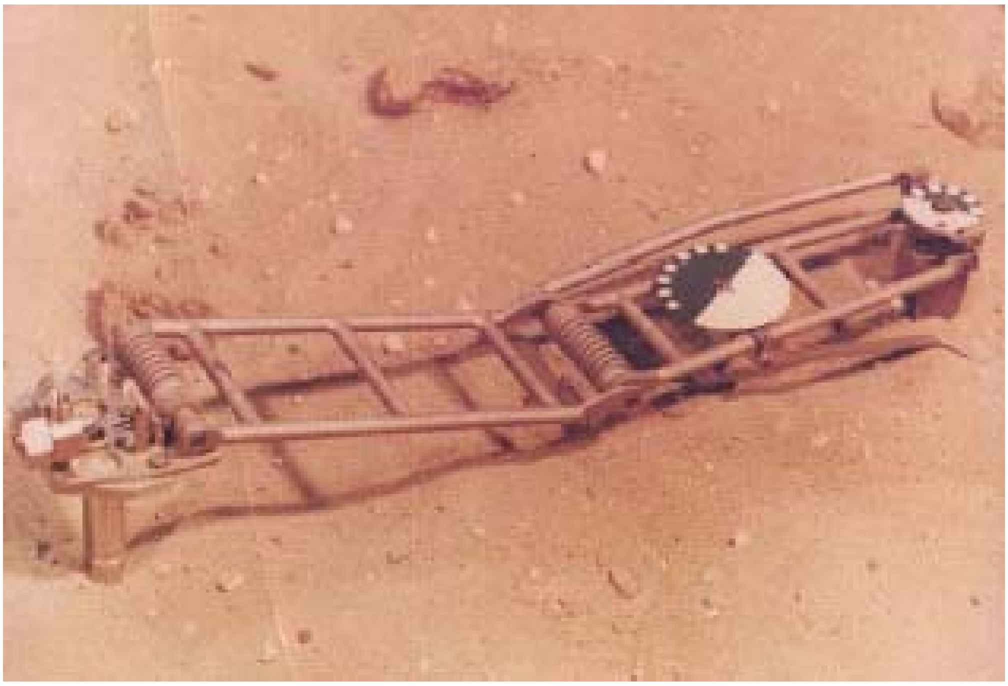


Figure 30: Venera 13 penetrator arm [68].

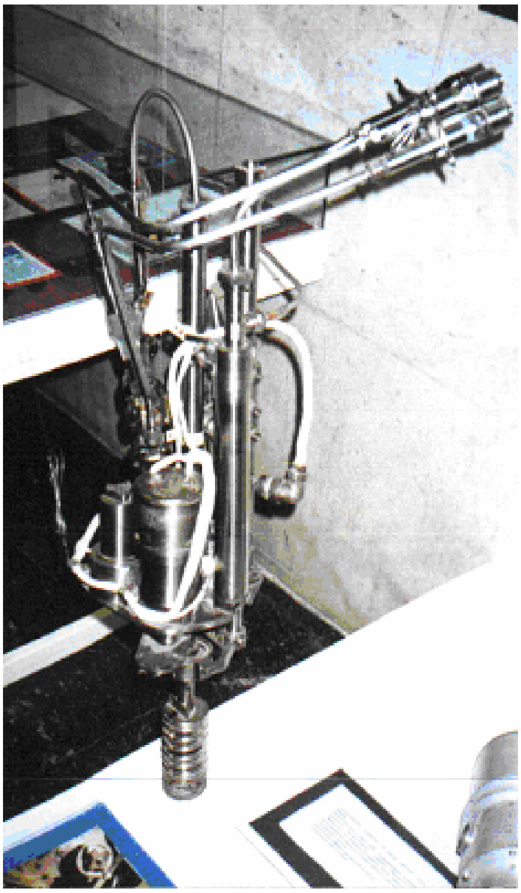
Venera 13 and 14 landers were the first of Venera series' landers that carried a drill system (as shown in Figure 31) [39]. Both of the landers were equipped with a complex device, which bored and scooped a soil specimen and fed it into an airtight container of the lander. The soil sampling mechanism had a hard task to conduct: the system had to operate in 500°C temperature and in a surrounding pressure of 100 bar of mostly carbon dioxide, i.e. under conditions that were many times harsher than any terrestrial or space-based drilling had to operate before. The drill had to be able of coping also with specimens whose assumed physical and mechanical properties were specified over a very broad range, and to transport the samples to the analysis chamber while reducing the pressure of the gases on the soil specimen.

The drill, named 'GZU Drill', was capable of drilling 30 mm into igneous rock by using maximum of 90W of electrical power. The same electric motor was used both for drill rotary movement and constant speed of feeding the linear movement. The soil sample volume was 1-6 cm^3 and it took total of 200 seconds to carry out the boring and sampling operation. Due to the high operation temperature, the machine parts were designed to fit and properly work in only the Venusian temperature. The high temperature caused significant thermal expansion and it was not feasible to make a drill, which would be able to operate in both room temperature and in 500°C, therefore the latter temperature was chosen [125]. The mass of the drill was 26.2 kg and it was roughly half metre in height.

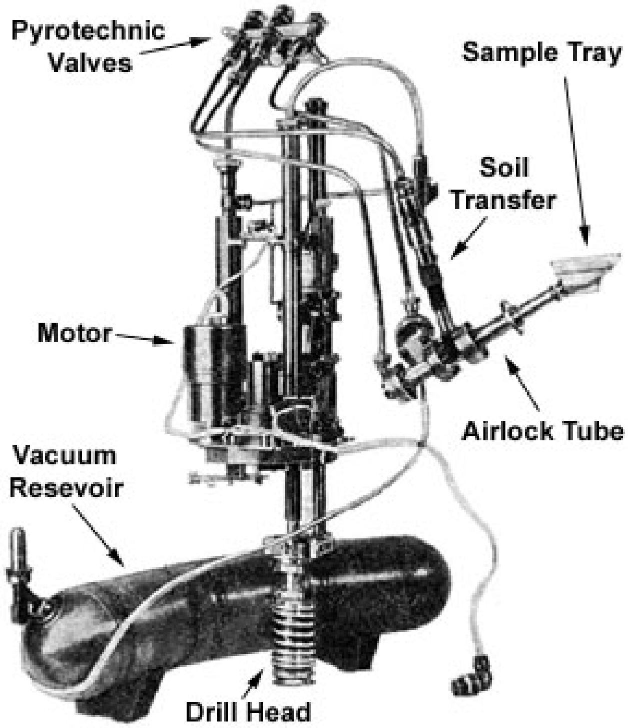
The drill is shown in Figure 31. The telescoping drill head lowers to the surface and the drill starts rotating. After two minutes, set of pyrotechnic charges break a series of seals that allow the high-pressure atmosphere to rush into an assembly of tubes. Soil is sucked from the interior of the drill head and carried in stages, into a soil transfer tube and onto a sample container. The sample container is driven through an airlock by pyrotechnic charges and into the X-ray fluorescence (XRF) spectrometer chamber. Before the analysis begins, a large vacuum reservoir then lowers the chamber pressure to about 0.06 bar and the temperature of the specimen is dropped down to about 30°C [125].

In addition to the elemental analysis of the soil sample, information on the speed and movement of the drilling rig, drill penetration depth, and magnitude of electric current consumed by the motor during drilling were recorded and used to determine the physical and mechanical properties of the surface. The Venera 13 and 14 results showed that the surface characteristics correspond to compacted ash material such as volcanic tuff [124]. The composition of the Venera 13 sample determined by the XRF spectrometer put it in the class of weakly differentiated melanocratic alkaline gabbroids. Venera

14 soil sample was determined of showing it to be similar to oceanic tholeiitic basalts. The Venera 13 and 14 landers measured temperatures of 462°C and 465°C and surface pressures of 88.7 bar and 94.7 bar, respectively.



a)



b)

Figure 31: a) and b) Venera and Vega sampling drill [40].

The Soviet Vega 1 and Vega 2 probes encountered Venus on June 11 and 15 of 1985, respectively. Vega 1 and 2 landers were identical to the Venera 13 (and 14) design. Vega landers carried similar drilling device than the GZU Drill, but the sample analysis equipment were slightly updated. Instead of the XRF spectrometer, Vega 1 and 2 had 'BDRP-AM25' X-ray spectrometer. However, Vega 1 mission was partially unsuccessful, since the drill was not used due to the malfunction, which deployed the drill already during the decent phase. Vega 2 landed successfully on Venus and the surface sample was found to be an anorthosite-troctolite (a rock type, which is found also in the lunar highlands but is rare on Earth).

3.2.4 Summary of past missions

It is notable that most of the sampling methods of these missions are relatively simple in mechanical and functional ways. There have been only three successful missions incorporating drilling device; the Russian Luna missions (three drilling operations which incorporated two different drilling devices), the Apollo (several drilling experiments during different Moon missions) and the Venera sampling drill (three drilling operations). There has not been any actual drilling done on Martian soil.

Table 5: Drills and subsoil retrieval systems of past and ongoing missions.

Instrument	Mission	Mass kg	Dimensions mm	Power W	Depth mm	Efficiency / notes
Luna 16/20 drills	Luna 16, 20	13.6	690 x 290	140	350	~30 min / 350 mm, core drill diameter 26 mm.
Luna 23/24 drill	Luna 23, 24	>10(1)	~3000 x 500 x 500	>100(1)	2500	~1600 mm achieved by Luna 24; Luna 23 did not drill.
Apollo drills	A 11-12, 14-17	13.4(2)	577 x 244 x 178	456	3000	5-15 min / 200 mm
Viking scoops	Viking 1 - 2	11.3	614.8 x 233.7 x 342.9	30	~200(3)	Estimated 4.3-8.6 kJ / cm^3, typical duration 24-48 min
DS2 micro drill	Deep Space 2	< 0.05	< 11 cm^3	0.9	< 10	(Nominal: 5 min drilling time.) Mission failed.
Philae SD2 drill	Rosetta	4.8	150 x 760	4-12	230	Still en route to its target.
Beagle-2 RCG	MEX / B-2	0.2	30 x 60 x 100	6	10	Mission failed; never tested on Mars.
MER RAT	MER - A / B	0.7	100 (length) x 70 (diameter)	11	5-10 (4)	Nominal max. depth 5mm
Venera GZU drills	Venera 13-14, Vega 1-2	26.2	~500 mm height	90	~35	Worked only in Venusian conditions; drill time: 120 sec.

Table notes: "NK" = Not known by the author. (1)Luna-23/24: Power and mass is estimated by the author, based on the Luna-16/20 properties. (2) ALSD: mass does not include drill strings. (3) Scooping depth is not actually limited mechanically, but the value 200 mm is a practical limit. (4) RAT can perform multiple abrasion operation next to each other, and then it can use the just-created depression to perform another abrasion operation, thus exceeding its nominal 5 mm depth limit.

While there are several past, ongoing and planned drill-related projects, this thesis concentrates on already-flown drills, selected near-future concepts, 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 5, there have been four different working drilling instruments in space, not counting 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 and Luna 23/24 drill were clearly the best in depth performance. However, the ALSD cannot be counted because it does not include any autonomous functions, which are needed in robotic missions. Similarly, the Luna23/24 deep drill is far too big to be included in for example the ExoMars mission. 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 16/20 and SD2 drills. Despite the fact that Luna 16/20 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 centimetres. The objective of future drills is to be able to drill down to more than one metre. The MRoSA2 concept is one possibility to achieve this.

In the following chapters, some additional drill devices (concepts and prototypes which have not flown) are explained, and an in-depth explanation is given of the MRoSA2 drill. The drills that have flown already give an important contribution for the future missions' drill designs, but none of them is suitable for deep and autonomous drilling in Martian conditions, especially when the drill must be small and light.

3.3 Future sampling missions and plans

While there are plenty of mission plans to sample different celestial bodies, some of those plans are closer to the topic of this thesis. The most essential future missions are ESA's ExoMars rover and NASA's Mars Science Laboratory rover. Both of them are planned to be launched in 2009 launch window. The ExoMars mission is the most important topic regarding this thesis, so it is reviewed more detailed below.

3.3.1 The ExoMars mission and the Aurora program

European Space Agency's ExoMars mission is an ambitious mission to launch an orbiter and a rover to Mars. Even though there have been three working rovers on Mars before (NASA's Sojourner, MER-A and MER-B), ESA has never before landed a rover to any celestial body.

ExoMars mission belongs under ESA's Aurora program. Aurora's goal is manned Mars landing in about 2030, and in the mean time the aim is to develop robotic technologies that support the long-term goal. Aurora includes different kind of missions, called Arrow missions (supporting smaller projects) and Flagship mission (major milestones). The ExoMars mission is the first Flagship mission to be assessed. Its aim is to further characterise the biological environment on Mars in preparation for robotic missions and later human exploration. Data from the mission will also provide input for broader studies of exobiology, i.e. the search for life on other planets, not only on Mars.

Figure 32: An artist's view of the ExoMars rover. The rover is approximately 1.5 m of height and weighs about 220 kg (Image: ESA).

The ExoMars mission consists of a Mars orbiter, a descent module and a Mars rover. The Mars orbiter will have to be capable of reaching Mars and putting itself into orbit around the planet, like ESA's Mars Express orbiter that reached Mars' orbit in December 2003. On board the orbiter will be a Mars rover within a descent module. After their release and landing on the surface of Mars, the orbiter will transfer itself into a more suitable orbit where it will be able to operate as a data relay satellite, and possibly containing some science experiments. The orbiter's main purpose is to act as a data relay for the ExoMars rover, but its life may be extended to serve future missions, such as the MSR (Mars Sample Return) mission.

The Mars descent module will deliver the rover to a specific location by using an inflatable braking device or parachute system. Both systems are sufficiently robust to survive the stresses of atmospheric entry and their landing accuracy will be sufficient for this mission.

The rover will use conventional solar arrays to generate electricity and it will be able to travel a few kilometres on the surface of Mars. The semi-autonomous vehicle will be capable of operating autonomously or under instructions of the ground controllers by using onboard software and it will navigate by using optical sensors. Included in its approximately 40 kg payload will be a drilling system, a sampling and handling device, and a set of scientific instruments to search for signs of past or present life.

The payload, or the instrumentation, of the ExoMars rover is called “Pasteur”, after the past biologist Louis Pasteur. The aim of the Pasteur payload is to characterise possible organic compounds and traces from Martian soil. The Pasteur payload consists of the following instruments [51]:

- Panoramic Camera (PanCam)
- Close-up Imager
- Drill System
- Sample Preparation & Distribution System (SPDS)
- Optical Colour Microscope
- Raman and Laser Induced Breakdown Spectrometer (LIBS)
- Mössbauer Spectrometer
- APX Spectrometer
- Mars Organic Detector (MOD)
- Gas Chromatographer/ Mass Spectrometer (GC/MS)
- Life Marker Chip
- Mars Oxidant Instrument (MOI)
- X-Rays Diffraction Spectrometer (XRD)
- Mars Environment Survey Package (MESP)

The drill system is in the highest interest regarding this thesis. The payload, especially the fundamental parts of the drilling and sampling system, is further explained in Chapter 6.1.2.

3.3.2 NASA’s Phoenix lander

Following the failure of the Mars Polar Lander (MPL, see Chapter 3.2.1), an identical lander that was to be launched in 2001 was put into permanent storage. The Phoenix Lander (2007) will carry a suite of instruments originally designed for both the failed Polar Lander as well as the postponed 2001 lander [10]. The Phoenix lander targets the northern Martian plains between 65°N and 75°N, where water ice might be protected from solar UV radiation by a thin layer of regolith. Lander’s robotic arm and microscopic imager will be capable of digging up to a metre into the soil in order to search for water in the frozen tundra. The robotic arm will be quite similar in operation than the previously explained MPL’s robotic arm.

Figure 33: Phoenix lander. (Image: Univ. of Arizona)

3.3.3 NASA's Mars Science Laboratory mission

NASA is developing a new kind of Mars rover for the 2009 Mars launch window. The mission is called Mars Science Laboratory, MSL (formerly known as Mars Smart Lander). The scientific object of the MSL mission is to explore and quantitatively assess local Martian regions on the surface as a potential habitat for past or present life. The mission will use a wide variety of instruments carried on a rover platform that is expected to remain active for one Mars year (687 Earth days).

The MSL rover is envisioned to have a 1.5 to 2-metre long robotic arm (shown in Figure 34), which carries a suite of tools for abrading (to remove outer layer of rock) and coring (to acquire samples) rocks and regolith suitable for scientific evaluation [104]. The corer/abrader tool will be autonomously operated on Mars.

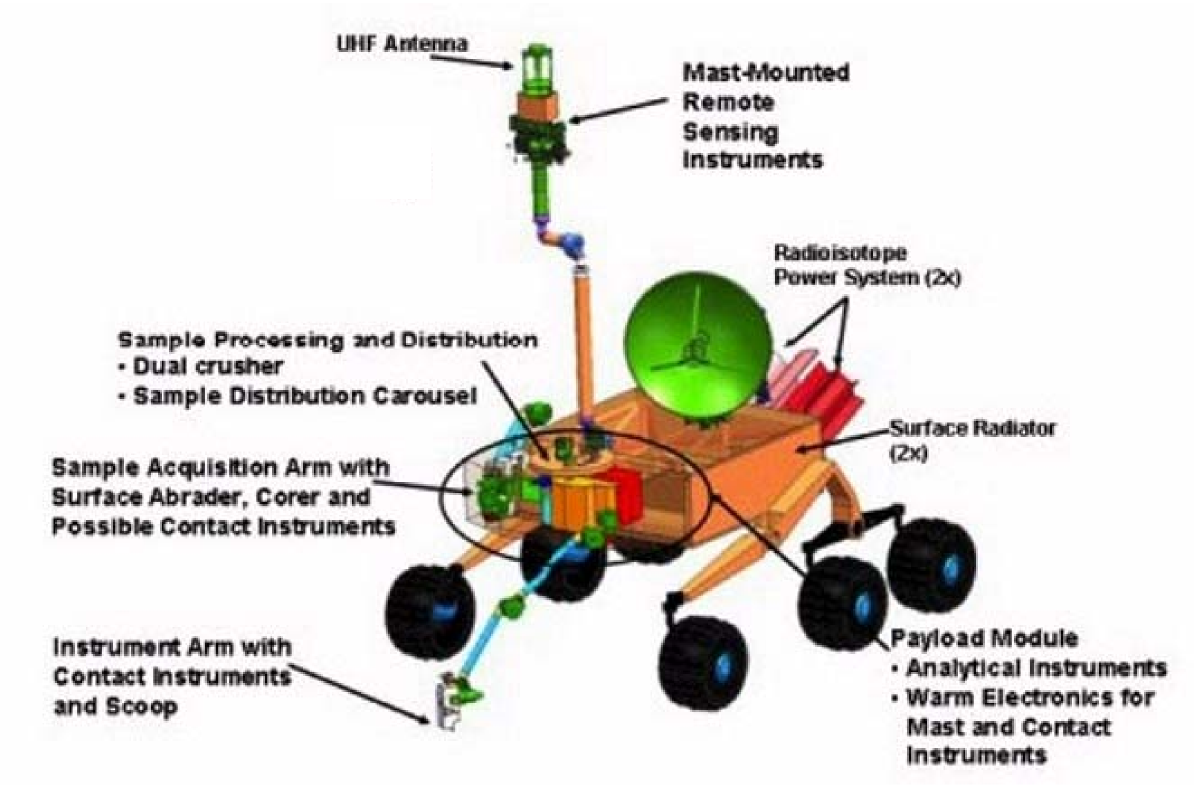


Figure 34: An early development model of NASA's MSL rover (Image: NASA).

The roughly four-kilogram Corer/Abrader is supposed to be attached on a turret, along with other instruments, at the end of the robotic arm. One of the requirements is, that the the Corer/Abrader tool must not require excessive force to be applied by the robot arm to hold it in contact with the target. This requirement is to due to the mass limits for the robot arm.

As explained, the MSL rover will not carry any actual drill instrument, as envisioned onboard ESA's ExoMars rover. NASA has preliminary plans to include a deep driller in its 2018 and/or 2020 mission, which would incorporate a drill capable of 3-10m of penetration [105]. The requirements set to the Corer/Abrader tool are explained in more detailed manner in Chapter 6.1.3.

3.3.4 Mars Sample Return mission

The major space agencies have been studying about robotic sample return mission to Mars for decades. There have been several different plans, consisting of novel ideas and different kind of sampling strategies. But basically the mission curriculum is always the same. While it is not objective to explain a Mars Sample Return (MSR) mission in detailed manner in this thesis, it is useful to go through the principle. The MSR mission is one of the goals to further develop planetary sampling and drilling systems.

ESA has plans [94] to conduct a MSR mission in next decade within its Aurora program. MSR would be the second major cornerstone mission in Aurora program, following the ExoMars (see Chapter 3.3.1). The mission objective is to return Martian soil samples to the Earth. The mission comprises four major modules: the Mars orbiter (which also delivers the lander), the Earth Re-Entry Capsule (ERC), the Descent Module (DM) and the Mars Ascent Vehicle (MAV). The DM will include a drill system, which could be similar than the MRoSA2 drill (drill box and drill string visible below the DM in Figure 35).

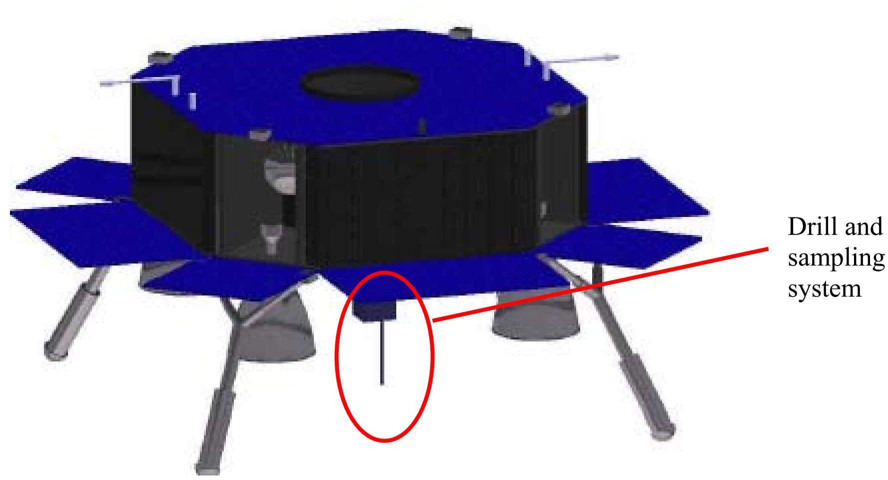


Figure 35: ESA's concept of MSR mission's Mars Descent Module (Image: ESA).

The four modules are basically the key elements of a future manned Mars mission also. All four modules, mentioned above, will be transferred to Mars. The Mars orbiter and ERC will be placed into a circular orbit around Mars at an altitude of about 500 km. Then the DM and MAV will perform an atmospheric entry and a soft landing to Mars. The drill system of the DM will be used to collect soil samples. The samples will be stored in a container, which is launched by the MAV. After rendezvous with the Mars orbiter, the container is transferred to the ERC. One part of the Mars orbiter acts as carrier vehicle, performs a Mars escape manoeuvre and returns the ERC to the Earth. The ERC is deployed by the carrier prior to arrival to Earth's atmosphere. Finally the ERC lands on Earth.

3.3.5 Other drilling or sampling missions

While there are and have been several other missions than the ones described in previous chapters, only the most relevant missions have been described here. Those missions are ESA's Rosetta mission and JAXA's Hayabusa mission. Rosetta comet spacecraft's Philae lander contains an interesting drill device, the SD2 drill, which is worth of more detailed study. Hayabusa mission demonstrates a new type of sampling method, so that mission is also explained briefly in below.

Some other missions, that include soil analysis in celestial bodies, such as the ESA's Huygens mission to Titan and BepiColombo Mercury Surface Element (cancelled), are interesting also. However, these missions are not so relevant regarding this thesis, so they have not been studied here.

<ins>Rosetta mission: The SD2 instrument onboard the Philae lander</ins>

Rosetta is ESA's interplanetary spacecraft, which was launched in 2004 on a 10-year journey from Earth to Comet 67P/Churyumov-Gerasimenko [62], where a 'Philae' lander will land on a comet. This will be the first time to try landing on a comet. The lander, named Philae (see Figure 36), contains several instruments, including a sampling drill 'SD2' (Drill Sample and Distribution System). The SD2 system consists of an integrated drill and sampler tool. The instrument will drill and collect samples, and delivers samples to a carousel equipped with ovens for distribution of samples to the analysis instrumentation. The main characteristics of SD2 are presented in Table 6.

Table 6: Philae SD2 characteristics [62]:

Drill parameter	Value
Drilling depth	230 mm
Sample dimension	3 mg or 20 mm^3
Carousel (containing 26 ovens)	Diameter 126 mm, height 90 mm
Tool box dimensions	Diameter 150 mm, height 760 mm
Total mass (including electronics)	4.8 kg
Power	1 W (stand-by), 4-12 W during drilling
Operating temperature	-150°C operating, -170°C non-operating

The SD2 drill will produce samples to three different experiments: COSAC (Evolved Gas Analyser, elemental, molecular composition), MODULUS (Evolved Gas Analyser, isotopic composition) and ÇIVA/ROLIS (Rosetta Lander Imaging System) [62].

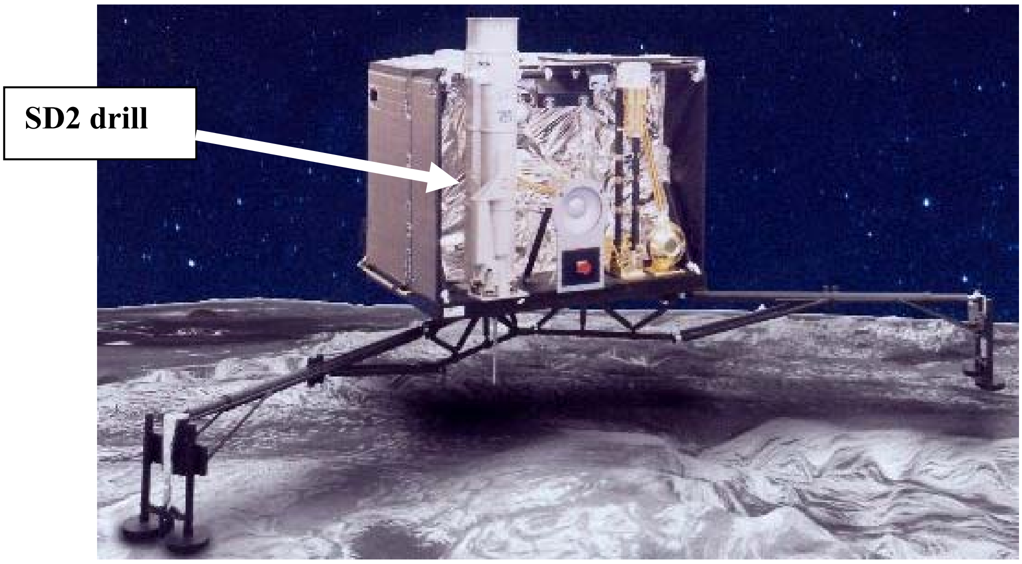
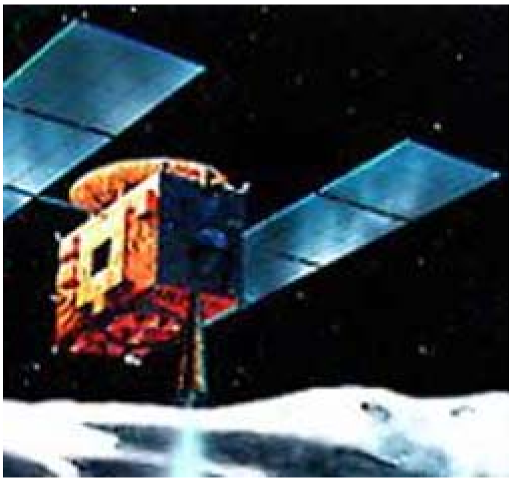


Figure 36: The Philae lander. SD2 drill is in the front section of the lander. The height of the lander is slightly over one metre.

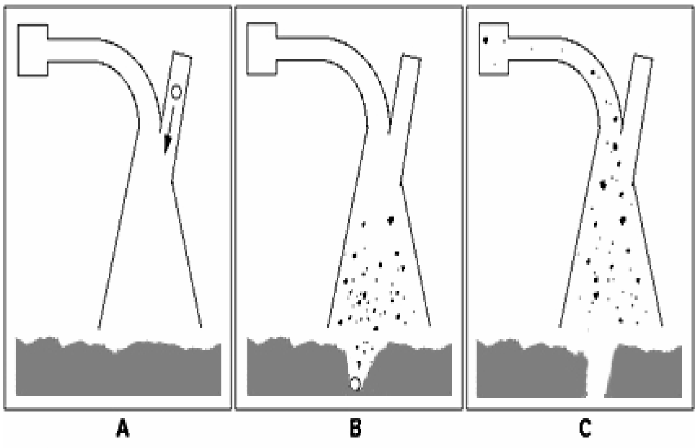
Japan's Hayabusa mission (MUSES-C)

Hayabusa, also known as 'MUSES-C', is an asteroid sample return mission. The target asteroid is 25143 'Itokawa'. Mission's primary goal is to acquire and verify technology which is necessary to retrieve samples from small celestial bodies and to bring back them to the Earth.

The spacecraft will carry a funnel/horn (Figure 37 a) that will be brought up to the asteroid surface as Hayabusa makes a close approach in November 2005. During the approach, a small pyrotechnic charge will fire a bullet into the surface, causing fragments of the impact to spread out. This material will be captured by the horn and funnelled into a sample container (Figure 37 b).



a)



b)

Figure 37: a) The Hayabusa spacecraft. Note the 40 cm diameter horn on the nadir side of the S/C bus. b) Operation principle of the sample collecting system: A: The 10-gram projectile is fired at 300 m/s velocity to the surface of an asteroid. B: As the projectile (bullet) collides with the asteroid, it produces surface ejecta. C: Sample material is being collected (Images: ISAS).

The Hayabusa will try performing several sample extractions from several different locations to obtain a mix of data and to get the best achievable scientific return. On each of the sampling attempts, the Hayabusa will begin its approach at some distance from the asteroid, move in to collect the sample, and then return back to the same distance. Prior to each sampling run, the spacecraft will drop a small target plate onto the surface from about 30 m altitude to use as a landmark to ensure the relative horizontal velocity between the spacecraft and asteroid surface is zero during the sampling. The time for each of the contacts with the asteroid surface is planned to be on the order of one second and the sample collector system is designed to comply with to every kind of surface composition. After sampling, the samples will be stored in the re-entry capsule for return to Earth in 2007 [106].

3.4 Instrument prototypes and concepts for Mars soil sampling

While there are several planetary drill projects ongoing around the world, not all of them can be discussed here. The author of this thesis is aware of some very interesting projects, which are similar with the MRoSA2 drill concept (discussed in Chapter 4) or in other way fundamental to the topic.

In addition to already flown space drills, there have been concept studies for different kind of drills, especially regarding robotic Mars and Moon missions. Some examples of these concepts are the Core Driller System [74], Deep Driller (DeeDri) [53], Sample Acquisition and Handling System (SAHS), Honeybee Robotics' drill / core samplers [115], Ultrasonic/Sonic Driller/Corer (USDC) [113] and NASA's Mars Drill. It is not possible to include all known concepts and prototypes, but these devices are good examples of the broad spectrum of drills under study. The MRoSA2 drill system is explained in Chapter 4.2.3. These prototypes and concepts might have evolved after the author of this thesis has referred them, so every piece of information is presented as "best knowledge" of the author. A summary of these concepts and prototypes is given in Chapter 3.5.

3.4.1 Core Drill System

The United States had plans to explore Mars after the Apollo program. Unofficial goal was to continue manned Spaceflight after Moon landings in a form of Moon bases and eventually manned Mars mission. Before astronauts could land on Mars, a series of robotic probes would have been launched. These probes would have been the pathfinders for manned missions by imaging possible landing areas, detecting important minerals and helping in finding possible water ice as well as other useful resources. As known, there hasn't yet been a manned Mars mission. However, NASA had plans to conduct Mars Sample Return (MSR) mission as a precursor for manned mission and the first studies for MSR had been done already during the Apollo flights (Ironically, there hasn't been a MSR mission yet either). In 1980's there were more studies conducted, and a concept of Core Drill System (CDS) was developed. It must be emphasized, that this concept is just one among the others, but it represents well the past level of technical readiness regarding planetary drilling systems.

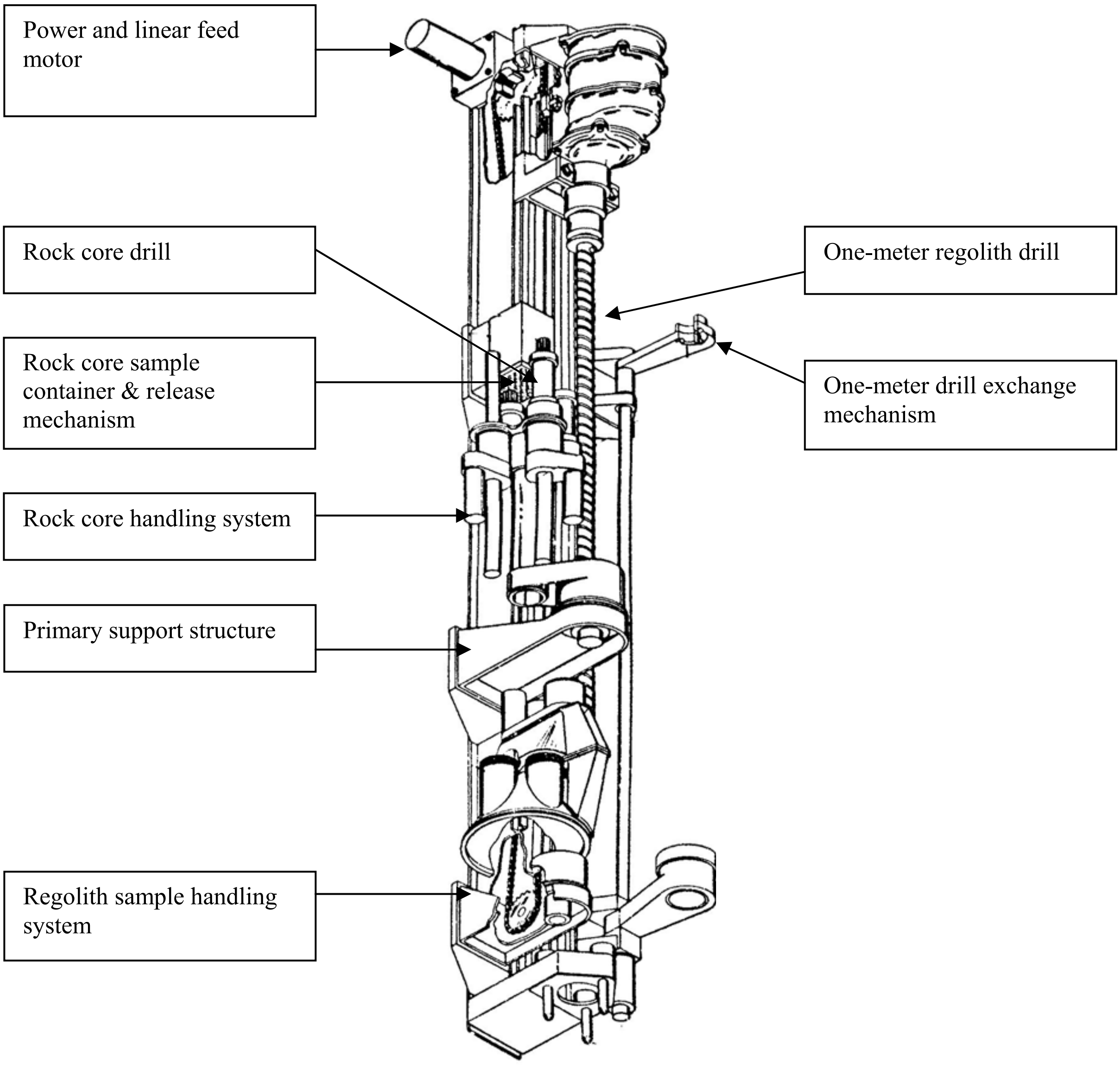


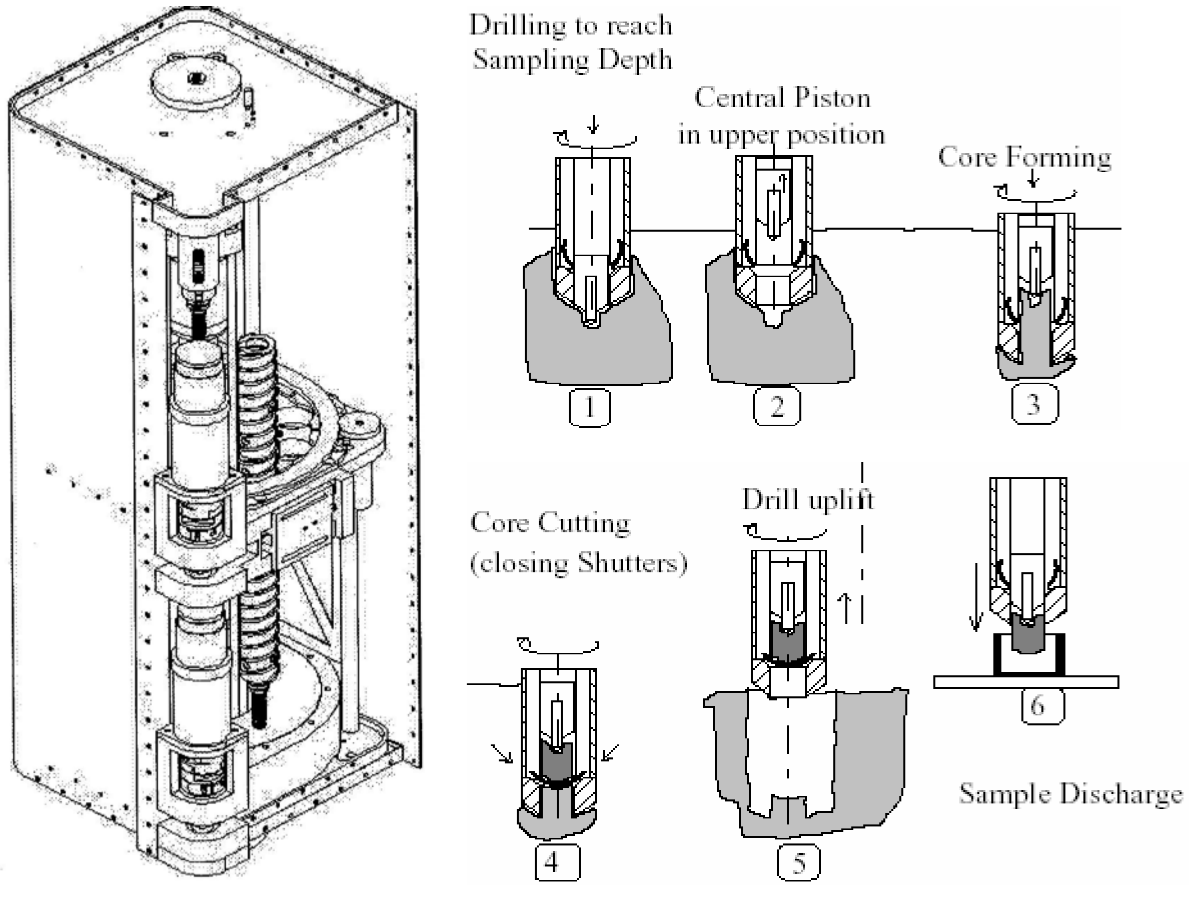
Figure 38: The layout of the Core Drill System [74].

The mass of the CDS was 41.2 kg and its dimensions were 1765 x 142 x 140 mm. Power consumption was relatively high, 236 W and it could drill down to one metre. Penetration speed was 50 cm/min in regolith, or 5 cm/min to rock. Sample core diameter is 1.9 cm and it requires approximated 65 kJ per one-metre sample, so calculated efficiency is about 2.28 kJ/cm^3 [74].

3.4.2 DeeDri

The Deep Driller (DeeDri) project is focused on the design, realisation and test of the drill to be sent to Mars. The project is funded by the Italian Space Agency (ASI) for the NASA Mars Exploration Mission. Within this program a core sampler mechanism has been developed. The purpose of the instrument is to collect Mars surface and subsurface soil samples and release them to the scientific instruments or storage system on the planetary rover or a lander. Italian companies, Tecnospazio and Galileo Avionica, have developed a prototype of the core sampler mechanism. According to the references [53,136], the DeeDri concept has gone through several design updates. The sampling depth of these models varies from 0.5 metres to 3 metres, which makes the instrument, or its variant, suitable in general for example to the ESA's ExoMars mission. However, under the 'DeeDri' name, there are several totally different designs, such as the 1-metre drill [53] and a 2.5-metre Multirod drill [53]. This brief concept introduction deals with the 2.5-metre design. The concept is close to the MRoSA2 concept (Chapter 4.2.3), and this instrument is particularly interesting regarding the topic of this thesis. The apparent similarity of the DeeDri Multirod drill and the MRoSA2 DSS is not a coincidence; the two drill design teams shared partly the same personnel. Thus the DeeDri Multirod drill can be considered not only as a 'big brother' of the original MRoSA2 DSS, but also as a revised and improved version that takes advantage of lessons learned with the MRoSA2 DSS [150].

The DeeDri drilling tool prototype consists of a hollow steel tube equipped with an auger thread on outer surface and a drill tip at the lower end of the tool. The drill makes a hole 35 mm in diameter (MRoSA2 drill hole diameter is 17 mm). The central part (piston) of the tool can be withdrawn so to form a volume to allow sample core to be collected inside this opening (Figure 39b). The core sample collected is 14 mm in diameter and 25 mm in length [53]. The mechanism allows collecting not only core samples but also powder-like samples. The achievable drilling depth of the DeeDri drill is 1-3 metres. The drill can support direct borehole science by installing inside specific dedicated scientific instrumentation (e.g. the DIBS system [135]).



a) b)

Figure 39: a) The DeeDri Multirod drill module (height in picture: 540 mm) for 2.5 metre drilling depth [53]. The sampling procedure is shown in figure b) [53] (Images: Tecnospazio).

3.4.3 Sub-surface Sample Acquisition and Handling System

The 'Sub-surface Sample Acquisition and Handling System' (SAHS) is a robotic system which includes a drill capable of drilling up to 10-metre under the Mars surface as well as sample handling equipment for extraction, preliminary screening, and distribution of the Mars samples [52]. The

Northern Centre for Advanced Technology (NORCAT) has developed this drill, also called 'CanaDrill' [137] that could be used in some future Mars mission to collect samples from below the Martian surface. The SAHS was especially identified one possible drill for the NASA's Mars Science Laboratory (MSL) 2009 mission [134]. To prepare soil and regolith samples for scientific analysis, this drilling and sampling system would classify them by composition, then polish and even grind them. The samples would then be fed into a scientific instrument for analysis through various types of tests. Samples might be taken either from the Martian surface or by digging a hole in the soil.

Unfortunately there was not much technical information available about this design. The SAHS seems very interesting concept. However, it was not possible to compare it technically with other drill designs. In addition, according to the latest plans [128], there will not be a deep driller onboard the NASA's MSL mission.

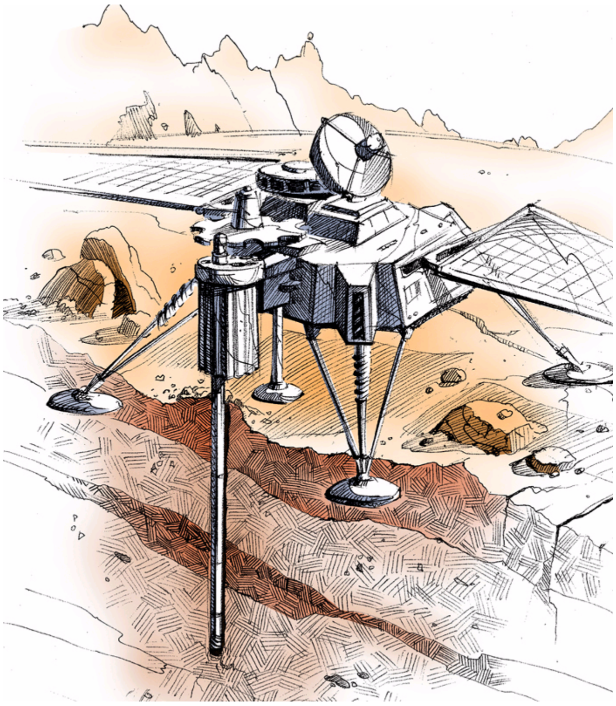


Figure 40: An artist's concept of the SAHS drilling system (Image: CSA).

3.4.4 Honeybee Robotics' drills

Honeybee Robotics (HB) is a privately held company in U.S. It has some interesting driller machine prototypes, as well as the RAT (explained in Chapter 3.2.2). Besides the RAT, the author has taken a brief look of some of the drillers and samplers, which are introduced in below:

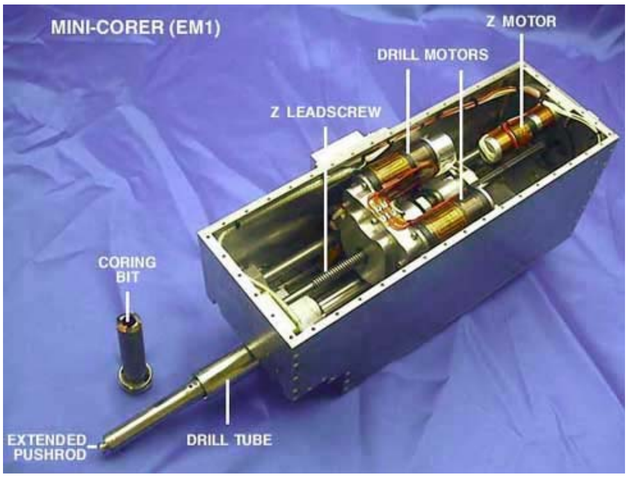
<u>Core samplers</u>

The HB's 'Miniature Rock Coring and Rock Core Acquisition and Transfer System' (Mini-Corer) was originally designed as a portion of the NASA's Mars Sample Return Athena Payload 2003. The purpose of the instrument is to obtain small rock core samples from the surface rocks and deliver them to other instruments in the lander's (or rover's) payload. The Mini-Corer is capable of obtaining two cores (length 25 mm, diameter 8 mm) from the same borehole of hard rocks [115]. The Mini-Corer, seen in Figure 41, is 15 cm x 10 cm x 30 cm of size and 2.7 kg of mass. It consumes about 36 kJ energy when drilling to 25 mm into hard basalt (operation time ~6 minutes).

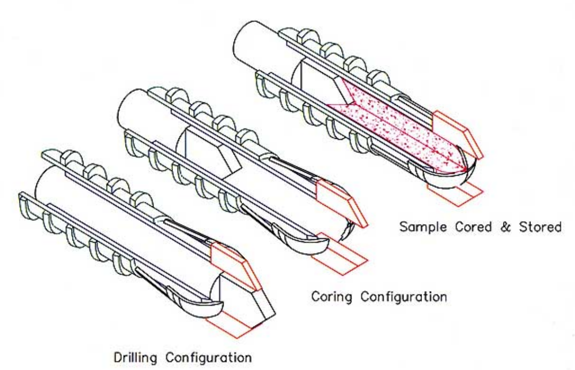
In addition to the Mini-Corer, HB has developed other samplers, such as the "touch-and-go-sampler" systems [116].

One-meter drill and ten-meter drill

The most relevant HB drilling systems regarding this thesis are the 1-meter drill and the 10-meter drill (seen in Figure 41c and d). The Mini-Corer, seen in Figure 41a, contains interesting mechanics, but the achieved depth is too low for deep drilling.



a)



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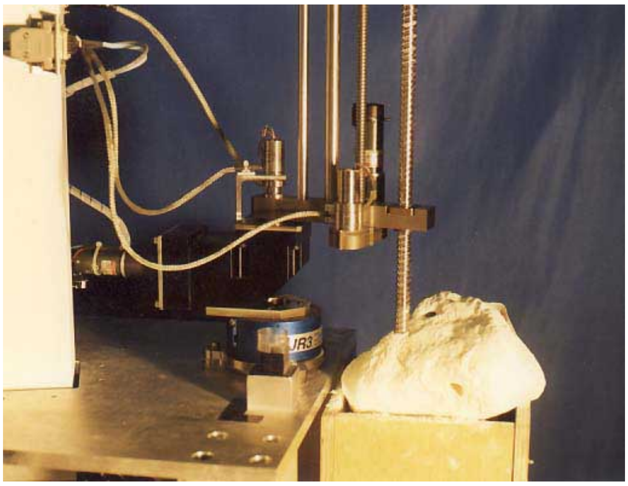

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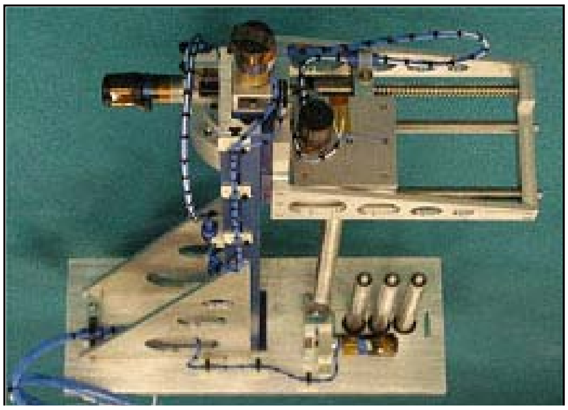


d)

Figure 41: a) The Mini-Corer. b) Athena corer drill head, used in 10-meter drill [114] c) One-meter drill. d) 10-meter dill (Images: Honeybee Robotics).

The 'One-Meter Drill' prototype was developed and tested at HB to demonstrate the performance requirements necessary to meet the late NASA's 'ST/4 Champollion' mission objects. The cancelled Champollion project was supposed to drill cometary surface, but the drill is also possible to use in Martian conditions. The drill was designed to acquire samples from one metre below the surface, without cross-contamination and to accommodate the different sample volume requirements by each instrument onboard the lander. The drill has a sample chamber that can be adjusted from 0.1 cm^3 to 0.5 cm^3 volume. The 'One-Meter Drill' (also known as 'SATM', 'Sample Acquisition & Transfer Mechanism') is under further development with the JPL Exploration Technology program [7].

ESA's Rosetta mission's Philae lander was introduced in Chapter 3.3.5. Originally the mission was supposed to carry two landers. One was supposed to be built by a collaboration of the French and Americans (named 'Champollion'), and other built by the German DLR space agency, originally named "Roland" for "Rosetta Lander" (later named ‘Philae’). NASA cancelled the Champollion project in 1999, but DLR went on to complete Roland, which was renamed Philae not long before the Rosetta launch.

The HB’s ‘Ten-Meter Drill and Sample Retriever’ (Figure 41d) development has been funded by NASA for potential use on a future Mars mission. This sample acquisition system will consist of several automatically fed and attached drill strings, capable of drilling down to 10 metres depth [107].

3.4.5 Ultrasonic/Sonic Driller/Corer (USDC)

NASA JPL has developed an ultrasonic/sonic driller/corer (USDC) to enable collecting samples from various planets or small celestial bodies (e.g. asteroids) using low axial load and low power. The drill does not rotate, but ultrasonic and sonic vibrations are responsible for the drilling action. The vibrations are generated by piezoelectric material in the upper section of the drill (see Figure 42). The drill head has a mass of 400 g and it requires axial load at the level of 3-10N and can be operated by power in a scale 3-25 W. The USDC has demonstrated 25 mm deep holes in granite from a 4 kg platform, and 15 cm and 15 mm diameter in sandstone [113]. Unfortunately no specific sampling energy values were found by the author of this thesis.

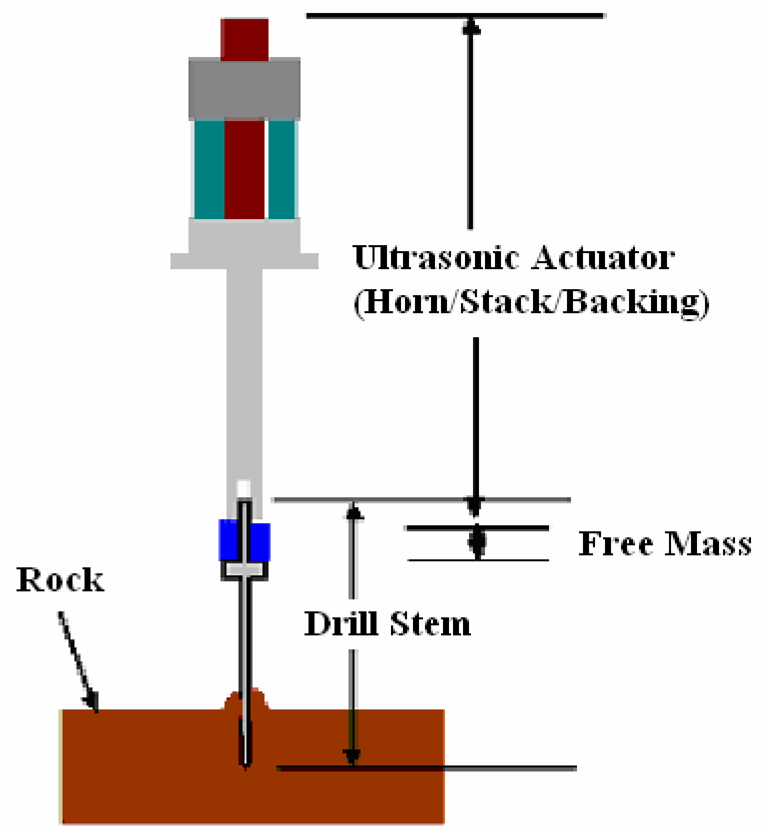


Figure 42: Principle of the USDC driller (Image: NASA JPL).

3.4.6 Small Sample Acquisition and Distribution Tool

The ‘Small Sample Acquisition and Distribution Tool’ (SSA/DT) [42,43] is not only a drill, but also a subsurface tool intended to gather surface samples and deliver them to the lander’s instruments. ESA funded work to develop and test a small device equipped with different tools for surface sampling, for planetary and cometary in-situ investigation missions. The SSA/DT (Figure 43 a) was developed in 1995-1997 in an ESA/ASI (ASI is the Italian Space Agency) project [108] by Tecnomare (Italy) and VTT (Finland). In addition, the German DLR undertook testing of the drill tool.

The SSA/DT is able to use different tools (seen in Figure 43b and Figure 44). Micro End Effector (MEE) tool was designed by University of Hong Kong to collect soil samples from the surface of comets or Mars. As can be seen from Figure 43b, the MEE tool is very capable of collecting loose soil with its claws. It was used as a drill with the claws staying closed whilst rotating in one direction. When rotated in the opposite direction the claws opened allowing the sampling operation. The "Inverted Cheese-Scraper" is able to take core samples of surface rocks. Unfortunately the author found no further information of this tool. The characteristics of the SSA/DT are shown in Table 7.

Table 7: The main characteristics of the SSA/DT [42]:

Instrument parameter	Value
Degrees of freedom (DoF)	3
Tool exchange	Automatic
Ground clearance / reach	Operate from 0.3m above surface
Mass	1.76 kg
Power	5 W
Sampling ability	Few grains (0.2 cm^3)
Coring tool depth	1-2 cm (*estimated by author*)

a)

b)

Figure 43: a) SSA/DT shown in the center of image. The MEE tool is taking a sample from the sand. MEE is shown also in figure b) (Images: ESA).

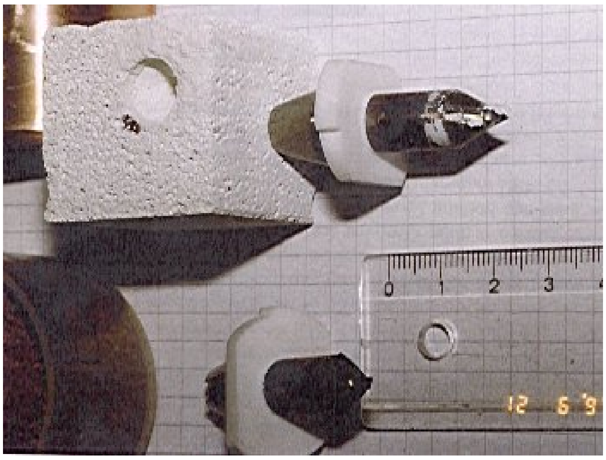


Figure 44: SSA/DT tool called "Inverted Cheese-Scraper (Images: ASI/ESA).

3.4.7 Sampling tools for the CNSR mission

The Rosetta mission (see Chapter 3.3.5), was originally known as the Comet Nucleus Sample Return (CNSR) mission. In 1985 ESA initiated a program to study a mission to return samples back from a comet (ESA SP-1070, 1984). This mission's focus was later changed several times and the original sample return mission was cancelled. However, some activities were conducted under the CNSR project to study the sampling and drilling problems. For example, a drilling/coring tool was developed to the Comet Nucleus Sample Return (CNSR) mission during 1990-1995.

The "Comet Nucleus Sample Return Sampling & Anchoring devices" project was ESA funded work, intended to develop and test corer tool, surface tool and anchor in preparation of the (later) Rosetta mission. The 'Corer Tool', seen in Figure 45a, is able to drill and collect a core (100 mm diameter, 1400mm length) from soft and hard material under comet conditions (cryogenic temperatures and zero gravity). The 'Surface Tool' is able to collect soft and medium hard material with harder grains (150 mm diameter, 600 mm length). In addition to the sampling tools, an anchoring device was developed to penetrate inside soft and hard materials and withstand reaction forces due to drill operation (length 1300 mm, mass 3.4 kg). These instruments were tested in vacuum at -160°C.

Figure 45: CNSR corer tool (left), tuff core sample (center) and sample container with bottom shutter (right), which would be located inside the corer tool. (Images: ASI/ESA).

3.4.8 NASA's Mars Drill

NASA's Johnson Space Center (JSC) and the Baker Hughes Company have been developing an autonomous Mars drill since 2001 [109]. The drill uses an electrically-powered down-hole "tractor" unit, which is lowered on the end of a cable, locked to the sides of the hole and pushed down from there. This drill is intended to bore holes from few metres to kilometres in depth (limited by cable length and available time/energy). In addition, the system will be capable of providing hole stabilization as required. The drill advances by drilling first only a thin tubular hole. The created core is then broken off and lifted to the surface by cable. This method saves energy by reducing the bored area. The object is to develop the device to be low in mass (~20 kg) and relatively low in electrical power (~60 W) [110]. The drill, being part of NASA's Astrobiology Technology & Instrument Development Program (ASTID), takes the form of a down-hole unit attached to a cable so that it can, in principle, be scaled readily to reach significant depths (possibly hundreds of metres or even kilometres [111]).

3.5 Chapter summary

Chapter 3 has introduced the topic of planetary sampling, concentrating to the issues that are relevant to this thesis. Several historic missions have been studied, as well as many existing instrument concepts and prototypes. Briefly said, none of these instruments are compliant with the ExoMars Drill System requirements, which are presented later in this thesis. In general, there are three main issues that dominate this non-compliancy: size, drilling depth and power. The closest matches for the

ExoMars Drill System are the DeeDri and Honeybee Robotics' SATM, but both of them still lack some capabilities (and in fact, the DeeDri is too large and SATM can not reach 2 m depth). The purpose of this literature study in this chapter is to familiarize the reader to this interesting topic of analysing the surfaces of celestial bodies, and to give a brief overview about the challenges of the missions.

The drilling and sampling instruments of chapter 3.4 are all concepts or prototypes. None of them have flown yet. It was not possible to acquire detailed technical information about them all, and some of them lack almost all technical details. The comparison is shown in Table 8.

Table 8: Comparison of driller and sampler concepts.

Instrument	Mission	Mass kg	Dimensions mm	Power W	Depth cm	Notes
Mars Core Drill	Concept study, 1980's	41.2	1765x142x140	236	100	50 cm/min regolith. 5 cm/min rock. Efficiency 2.28 kJ/cm^3.
DeeDri	Concept study, originally to NASA Mars Exploration Mission	8.3 [53]	540x175x175	~30 [112]	250 [53]	
SAHS (CanaDrill)	Originally for NASA MSL.	45 (EA)	NK	NK	1000	
HB Mini Corer	Originally to Mars Sample Return Athena Payload 2003 (not flown)	2.7	150x100x300	~100 (EA)	3	25 mm into strong basalt in < 6 minutes: < 36 kJ.
HB 1-m drill / SATM	Prototype	~8-9 kg	NK	NK	120	25 Wh/run(40 MPa rock), 1 cm/min, 13 mm drill string diam.
USDC	Prototype	0.4	Few tens of cm in total	3-25	Few cm to tens of cm	
SSA/DT	ESA TRP-project, proto 1995-1997	1.7	NK	5	Surface (MEE), 1-2 (corer)	
NASA's Mars Drill	Prototype, 2001-	~20	NK	60-100 [110]	Several metres	Consists of big modules.
CNSR	CNSR study 1990-1995	NK	NK	NK	60-140	Core diam. 10 cm.

HB = Honeybee Robotics, NK = Not known by the author. Some values might be hard to specify, e.g. the size of the Mars Drill (which consists of several modules), EA = Estimated by the author

As mentioned, many of these drill systems are prototypes or concepts, and thus there is not very accurate technical information publicly available. These instruments, as some of the previously introduced instruments, will be referred later in this thesis when comparison between different functions and solutions are made. Chapter 4 introduces yet one more prototype, the MRoSA2 drill, which forms the basis for the studies of this thesis.

4. THE MROSA2 ROVER AND DRILL

European Space Agency (ESA) initiated a GSTP activity “Micro Robots for Scientific Applications 2” (MRoSA2) in 1998. The project came to a conclusion in November 2001, when the final presentation was held at the ESA ESTEC. The goal of the activity was to design and develop a Robotic Sampling System (RSS) - a prototype of a tracked rover based drilling system designed to perform deep sampling, up to two metres, on a planetary surface. The main work was performed with the Martian environment as the planetary target, although the concept is generic to any celestial body that has the possibility for landing and which offers adequate anchoring for drilling purposes.

Figure 46: The MRoSA2 rover with Beagle-2 mock-up as a size-reference [24]. The length of the rover is 40 cm (Image: MA).

The MRoSA2 system was originally called RSS/N for "Robotic Sampling System based on Nanokhod" [15], later on ‘Miro’, ‘Micro RoSA2’ or ‘MRoSA2’. The MRoSA2 was a successor of the Nanokhod (project name ‘MRoSA’). Under European Space Agency’s TRP program, ESA funded the development of a concept of ‘Micro Robot for Scientific Applications (MRoSA)’, based on previous work performed at the Max-Plank Institute for Chemistry [11]. The result of this activity was a breadboard model of micro-rover, called the ‘Nanokhod’ (the name is in connection with the Russian “khods”, i.e. the ‘Marsokhod’ Mars rover prototype [20]). The aim was to offer a very high ratio of instrument-mass to rover-mass. The Nanokhod rover, though initially designed to perform in-situ scientific analysis, can also be equipped to acquire samples and retrieving them back to the lander for analysis [14].

The MRoSA2 system consists of the Mars lander (non-functional mock-up) and the rover. The rover carries the Drilling and Sampling Subsystem (DSS) module, which is able to penetrate and sample the Martian ground up to two metres, into unknown hardness up to number eight on the Mohs' scale. The rover is controlled by the lander, which would have a stereo camera system and image processing capabilities (simulated by the operator). Both the lander and the rover have their own computers to control their sub tasks. The lander was not implemented in this activity, and instead there was a PC computer simulating both the lander functionalities and the ground control. The PC was controlled by a human operator, who gave high-level commands to the “lander’s” (PC) software, which interpreted them to the rover. The main work in this activity was done in the rover and DSS. The drilling technology was new and never before tested in this purpose.

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.

4.1 Technical and operational requirements

As it has been learned from the NASA Viking and Pathfinder missions, sampling of surface soil and rocks can gain only limited scientific information. In fact, possible organic signatures tend to be erased by surface processes (weathering, oxidation and exposure to UV radiation from the Sun). Therefore, the Martian exobiology investigation must be performed on pristine samples that have never been exposed to the surface environment [5]. Two types of samples have this characteristic:

- Samples extracted from surface stones/rocks by coring at a depth of a few centimetres.
- Deep soil samples acquired vertically from a depth of more than one metre.

In order to fulfil the scientific goals, some general requirements were set to the system:

- Reach sampling locations in a 15 metres of radius around a lander spacecraft
- Acquire samples and deliver them to the lander
- Drill up to 2 metres into regolith
- Drill up to several centimetres into surface rocks/stones
- Drill into non-homogeneous regolith of unknown hardness
- Sample at a certain depth, material of that specific layer
- Allow investigation of soil layering
- Acquire pristine samples of unknown hardness and coherence
- Preserve morphology of the sample
- Size, mass and power restrictions.

4.2 System description

The system, divided in three separate categories, is described in this chapter. The three modules are:

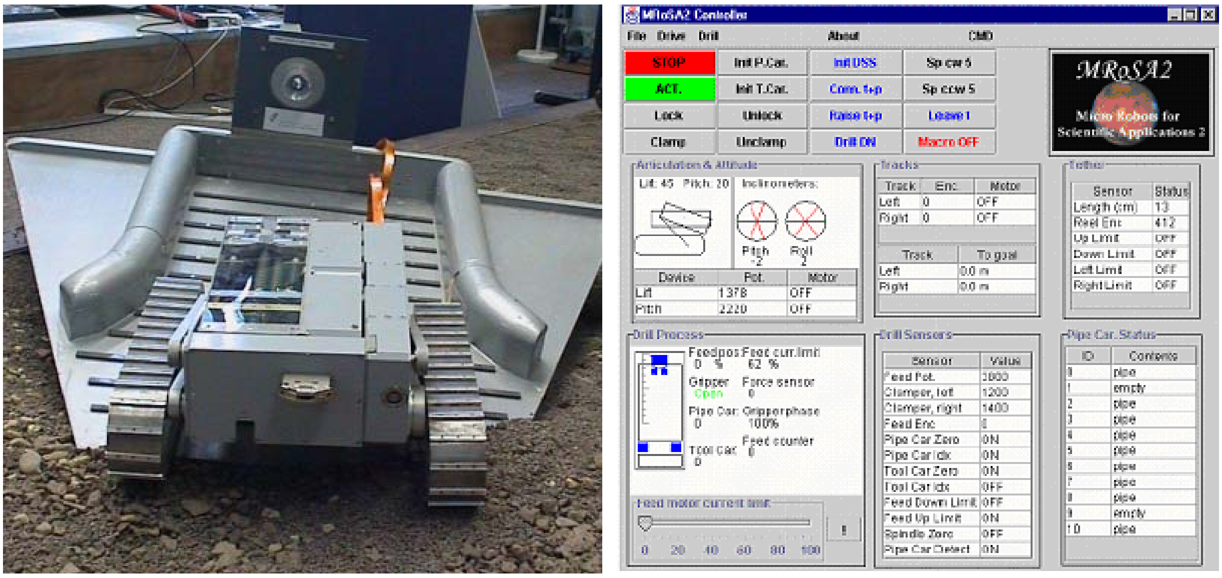
- Mars Surface Station (lander spacecraft mock-up)
- Rover Functional Mock-Up (RFMU)
- Drilling and Sampling Subsystem (DSS)

The operational scenario is as follows: a spacecraft lands on the Martian surface. Like the NASA's Pathfinder lander, the lander is immobile, but deploys a rover to study and sample the surface around the landing site. When the rover reaches an interesting location, it uses a drill to extract rock or soil samples from the desired depths, or from surface rocks and stones. The rover carries the samples (up to ten samples can be stored at a time) to the lander, which analyses their morphological, mineralogical, chemical and/or biological properties. The same rover can do several such sampling trips.

Anomalies that may occur in this scenario include problems with the rover (getting stuck, turning over, etc.), with the drilling (sticking in the hole, damaged drill bits, etc.), and the lander (tilt, rover exit and entry hindered by nearby rocks, etc.). Emergency actions are especially important for flight design, but their automatic demonstration would have required extensive software design. Therefore emergency operations were included in mechanical design, but they were demonstrated only in manual control.

4.2.1 Mars Surface Station

As mentioned in Chapter 4, the lander was not implemented in the MRoSA2 activity. Instead of the lander, we had a PC computer simulating the lander and the Earth ground control. The basic idea was that the lander sends only high-level commands to the rover, and the rover computer then executes the commands by using low-level commands to different actuators and receives feedback from the subsystems. It was also possible to use low-level commands from the lander or from the ground control, if needed for example in emergency situations.



a) *b)*

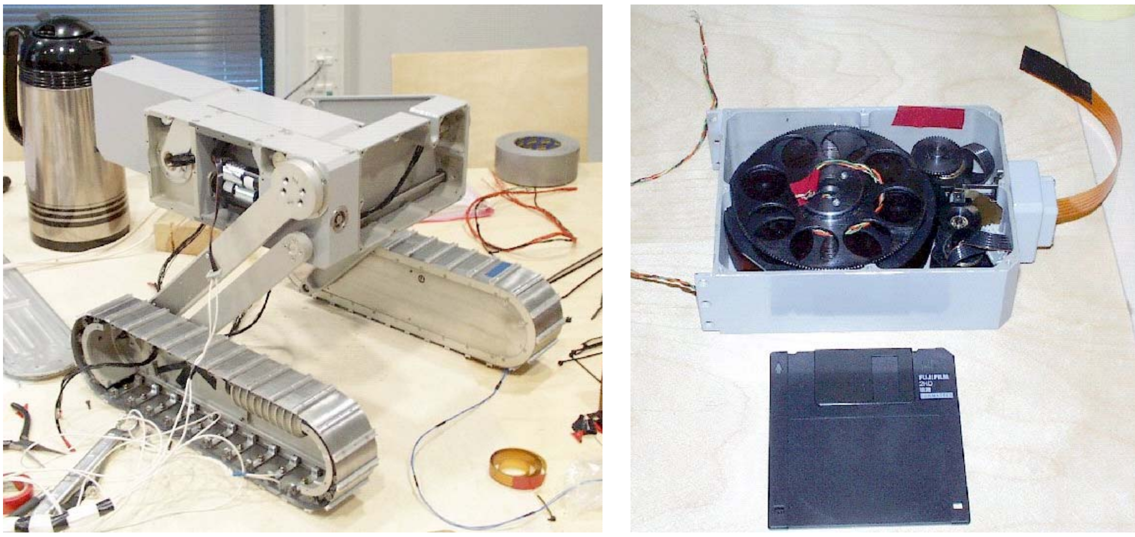
Figure 47: a) MRoSA2 rover's egress from the "lander". b) User interface of the PC, which simulates the lander spacecraft (Images: MA).

Figure 47a shows the lander petal that consists of directional guides (the walls that lead out from the lander) and traction aids. In the end of the petal is shown the Sample Delivery Port (SDP), which is the interface that receives the acquired samples to the lander. Figure 47 b) shows the Graphical User Interface (GUI), which is used to operate the whole system: the rover and the drill system [3].

4.2.2 Rover Functional Mock-Up

The requirements for the Rover Functional Mock-Up (RFMU) were that it should be a Nanokhod-like [9] robot that is able to carry the DSS and enable drilling in all angles. Furthermore the RFMU has to be able to make multiple sample acquisition trips on a radius of 15 m around the lander. The size of the DSS required that RFMU had to be scaled up from the original Nanokhod size. During the design phase it was also noticed that the constant bridge in the rear end of Nanokhod limited the clearance and formed a U-shaped "trap" for stones and other possible obstacles. This reduces dramatically the roving ability of rover on the stony surface of the Mars. The design of the RFMU was made together with Russian RCL-company, which is a spin-off of the VNIITRANSMASH institute – the original designer of the IDD family. RCL also manufactured the RFMU.

The rover has two tracks with the equipment and payload departments between the tracks (Figure 48). The whole middle part of the rover can be lifted, thus the clearance can be controlled between –20 cm to 20 cm. The symmetrical structure of the rover allows the use of negative clearance in the case of capsizing, i.e. there is no need for recovery. The payload part of the rover can be tilted full 360 degrees in order to allow the drilling in all angles. The 40m long rewindable tether allows rover to move without own energy storages. The tether serves also as communication link between lander and rover.



a) *b)*

Figure 48: a) RFMU chassis showing the worm gear of the right track (Image: RCL). b) Tether reel containing 41 m of Kapton cable (Image: HUT).

4.2.3 Drilling and Sampling Subsystem

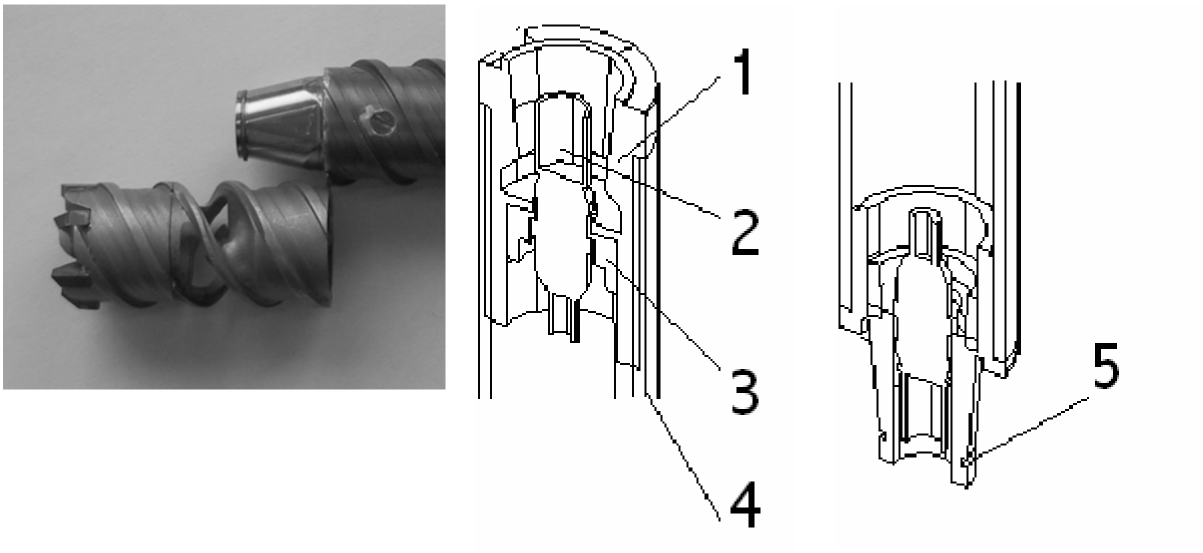
The Drilling and Sampling Subsystem (DSS), is restricted in very limited volume of 110 x 110 x 350 mm and in mass to 5 kg. In order to satisfy 2-metre penetration depth requirement and still be able to meet volume and size restrictions, the DSS features an extendable drill string. The string is assembled from up to 10 separate pipes in a similar manner that is used on terrestrial automatic rock drilling machinery. The DSS was the main part of the MRoSA2 project, as the RFMU served mainly as a platform for the DSS. The primary problems during the development of MRoSA2 system concerned specifically the DSS. The drill mechanics must operate in very little space, and many novel ideas were developed to find the solutions for making the DSS operational. The MRoSA2 Upgrade project later concentrated to the smooth operation of the DSS.

The drilling tool (Figure 49 a) is designed to drill a 17 mm diameter hole into rock hard material and to contain a 10 mm diameter and 20 mm long core inside it. In order to penetrate deep into soil the upper end of the core is ground into dust and ejected outside the tool through small holes in the side of tool.

The drill pipes are located in a carousel. The coupling between the pipes and between the string and spindle is realized with a conical connection that also provides a geometric constraint to transfer torque. The connection is locked with a split ring (C-ring). Spindle-tool connection is further secured with a motor driven wedge that prohibits contraction of the split ring and thus provides high holding capacity of connection. Originally, there were electrical connections for an ultrasonic drill tool. These connectors would have been located concentrically along the axis of the pipe cone using a coaxial plug. However, this ultrasonic drill tool was never developed or installed.

Connection between pipes happens by pushing the pipes against each other and simultaneously rotating upper pipe back and forth. Then the conical surfaces align the pipes and torque-transfer-slots (pipe connection walls) follow a ramp until it drops into place. Simultaneously the locking spring expands inside the cavity of the lower pipe. The force needed for pipe connection and disconnection is at least twice the maximum allowable axial force in pipe while drilling. The pipe ends are shown in Figure 49 b) and c).

Connection can start in any angular orientation of the pipes and allows three relative orientations between pipes. Inside diameter of the pipes is 13 mm, outside diameter is 15 mm, and three-ended helical flute (not shown) outside the pipe has 17 mm outer diameter.



a) *b)* *c)*

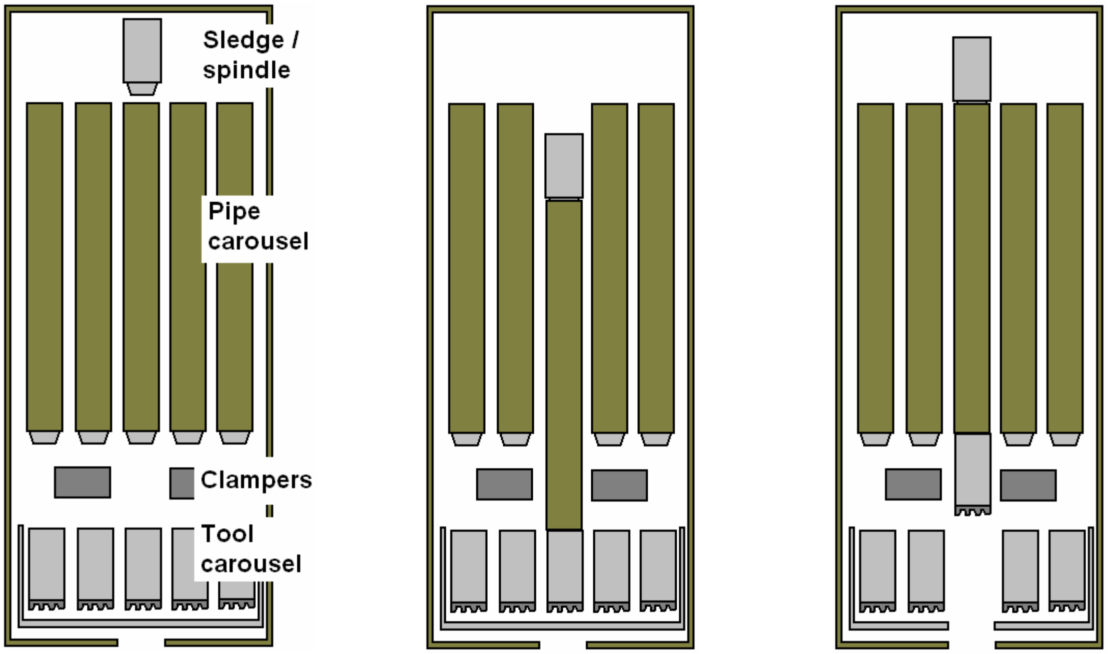
Figure 49: a) Drill bit and pipe connection, b) Drill pipe upper end: 1) Connection cone with features for locking C-ring, 2) Coaxial connector, 3) Connection insulator, 4) Casing (flute not shown), c) 5) Groove for locking spring (C-ring not shown). Images b) and c) refers to the old configuration with the electrical connections (Images: a) MA, b-c) VTT).

The DSS is shown in Figure 51 [87] and the operation principle is shown in Figure 50. The DSS's drill spindle consist of spindle coupling (quite similar to pipe couplings), spindle bearings, transmission gears, spindle motor, spindle solenoid and a slip-ring assembly. In order to combine the rotation of the spindle with the linear feed of the string the entire assembly is mounted on a sledge that moves up and down along a linear slide. In order to maximize effective tool length and minimize spindle extension above pipe carousel the motor is located aside the spindle and below the sledge and the motion is transmitted with train of gears. When feeding the string down inside diameter of carousel support allows the spindle motor to penetrate below lower end of the pipe carousel. The spindle position encoder has not been shown in figures above. A slip-ring assembly is used to transfer electricity from sledge to the rotating spindle for the spindle solenoid and ultrasonics.

A spindle solenoid (Figure 53) is used to operate a wedge that can prohibit contraction of the locking ring and thus control disconnection of the spindle coupling when separating pipes from each other and from the spindle. The solenoid is a flip-flop-type [87] using a permanent magnet core to maintain each of its two positions and thus does not require any springs, separate locking mechanisms or continuous power input [18].

Linear feed is realized with a thin ball screw, rotated with an electric motor, and a ball nut that is mounted on the spindle sledge. The sledge is guided by four ball splines that run along four guide rods.

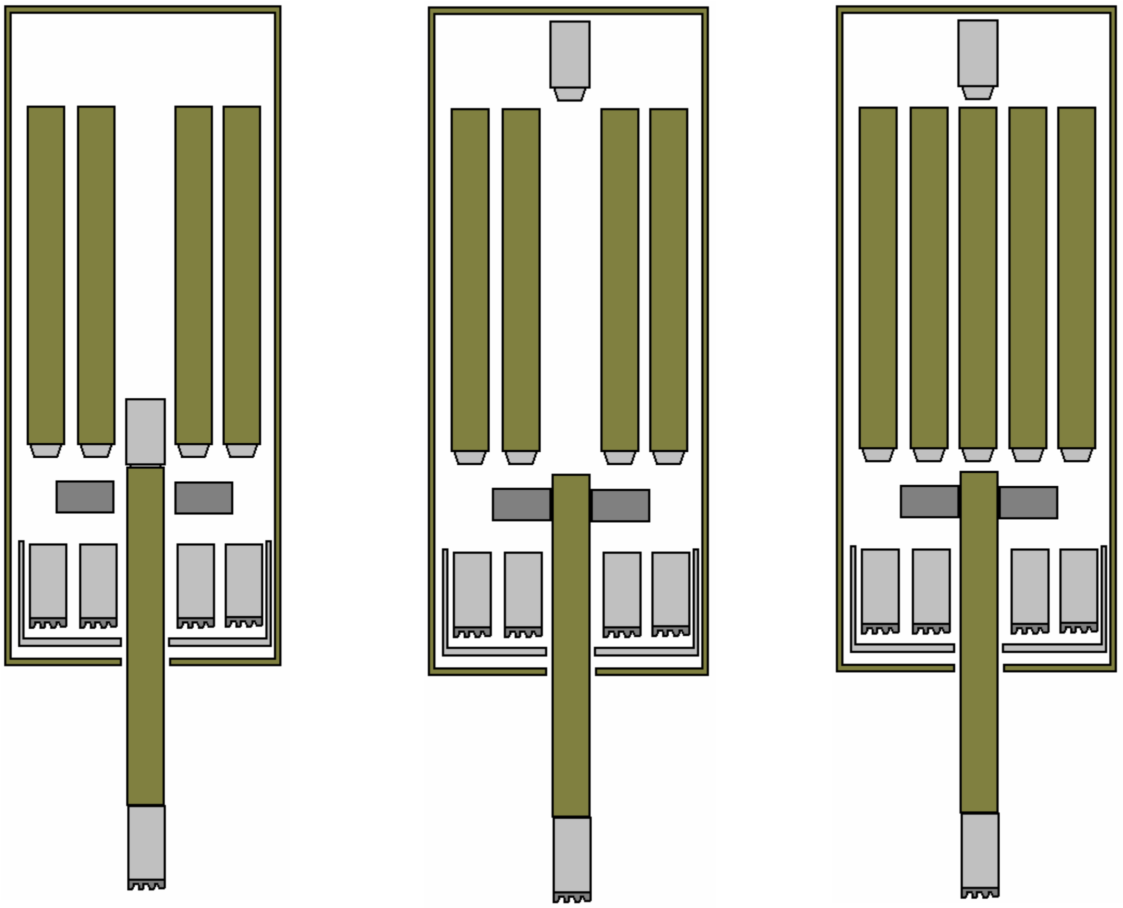
The pipes are located in a pipe carousel which consists of two disks supporting the shafts and connection rods to connect the two disks together. The rotation of the carousel is driven with DC motor located outside the carousel and a gear rim connected to the upper end of the carousel. The carousel is positioned to the correct angular positions with limit micro switches. Locations that hold the pipes are shaped so, that the pipes are positively kept in their places in radial direction by the carousel flanges, and axially restricted by stationary floor on both sides of carousel. In addition the upper flange has a small slot inwards that allows the neck of the sledge pass through it so that the spindle can push the pipe out of the carousel. The lower flange has a slot outwards to allow emergency rejection of the string in case it should get stuck into ground.



a) DSS in its starting position. The sledge is above the pipe carousel.

b) Sledge is driven down so that it connects itself to the pipe, which in turn connects to the tool.

c) The drill string is lifted up so that the tool carousel can be rotated to its empty position which allows drilling.



d) The drilling starts. The string is pushed down until the sledge is in its lowest position.

e) The clampers hold the drill string and sledge goes up above the pipe carousel.

f) A new pipe is rotated to the shaft and then the clampers will be opened, and drilling continues.

Figure 50: The DSS operation principle. Retraction of the drill string goes in opposite direction (Image: MA).

There are ten locations for drill tools or sample containers in a rotating tool carousel. In addition there is one hole to be drilled through. The rotation of the carousels is actuated with DC motor located inside carousel support. The position of the carousel is identified by micro switches.

A string holding device is used to hold the lower pipe in place when the spindle operates with the upper pipe and during pipe connection or disconnection. There are two clamps in the device that are operated with an electric motor and linkage. Open- and close-positions are indicated by micro switches. The clamps were coated with soft high-friction material (silicone rubber) to accommodate helical flute of the drill pipes.

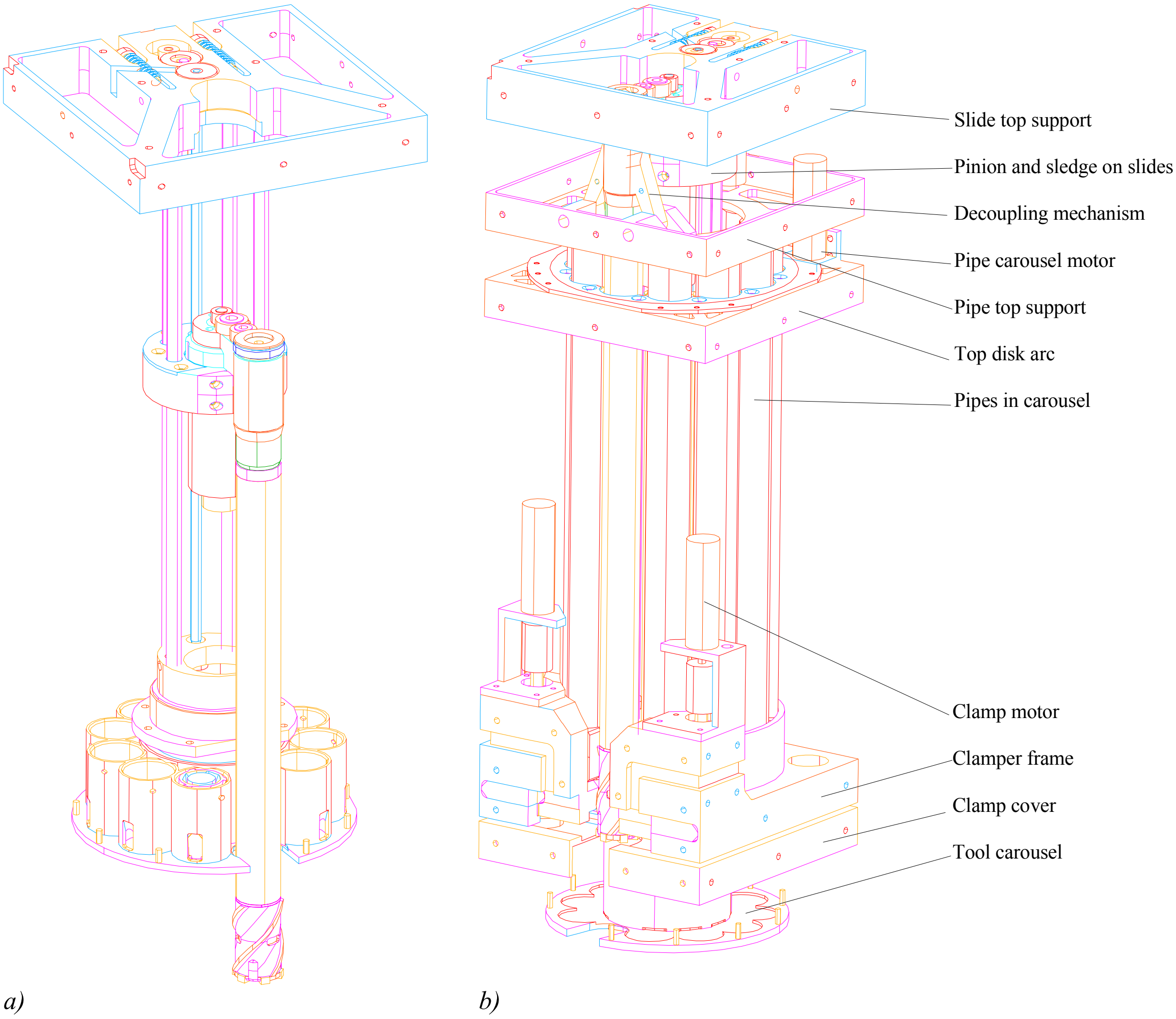


Figure 51: The Drilling and Sampling Subsystem (DSS) module [87], a) A view without the pipe carousel. b) DSS components (Image: VTT).

4.3 MRoSA2 Project results

The project proved that a small sized robotic sampling and drilling vehicle is feasible. A two-metre long drill can be built in relatively small dimension and still be functional. The innovative idea to use several drill heads, which also work as sample containers, provides possibility to drill different materials and collect multiple, separated samples during one trip. Long rewindable tether makes it possible to minimize the size of the rover and still provide enough power for the locomotion and drilling. It is much easier to produce and store the electric power in the lander than in the rover. However, the following matters need to be developed further or replaced before the concept is totally approved:

- The size and mass of the rover should be bigger in order to provide a rigid base for drilling, especially for deep holes.
- The existing power of the drill, 6 W, is too low for hard materials (Mohs > 4).
- The mechanical structure of the DSS is good in principle but some small details like solenoid in the pipe gripper, positioning accuracy of the carousels and the design of pipe clampers need tuning.

Despite these issues, the basic idea was functional, and the system was delivered to ESA ESTEC in November 2003. Later on, the project got continuation in the MRoSA2 Upgrade project, which will be discussed in later chapters.

4.3.1 Design weak points and lessons learned

The objective of the project was to study the principle of a small-scaled drilling rover feasible. There were no resources to make any iterative design work, thus the final system was constructed straight after design. Only a fast prototyping model was made in order to test the coarse functionality of the system. Even that the concept was functional, there were some design matters, which were listed as a primary points to reconsider in the future. The most critical matters are listed in below:

- Pipe and tool carousels: improved position accuracy needed
- Pipe clamping: better synchronization and surface structure needed
- Pipe Gripper System: solenoid system is unreliable
- Drill pipe connection: uncertainty in coupling and de-coupling
- Sensor feedback: some operations need to be confirmed by simple sensors
- Drill tools: two sampling tools needed in current configuration: one for loose soil and the other for hard rock.

As one can see, these bugs are more or less typical problems in mechatronic design. Other points that were listed to be re-designed or improved were:

- Drill power consumption
- Physical properties
- Drill system tests

<u>Pipe and tool carousel design</u>

The pipe carousel (Figure 52 a) has places for 11 pipes. The carousel is actuated with an electric motor and a gear rim. The angular position is detected with 10 +1 index pins and two micro switches. The tool carousel (Figure 52 b) contains ten tools/sample containers and it is also actuated with an electric motor and a gear rim. The tools are held in place with springs, and the angular position is detected as in the pipe carousel. However, the main problem with these carousels is that the angular position is not exact enough, causing some uncertainty in pipe/tool retracting and storing. The carousel stopping accuracy was quite poor. This was fixed in the MRoSA2 Upgrade project later, when new DSS software was used. Although this was a mechanical bug that could be fixed by intelligent SW patch, the design is still not robust enough for space flight use.

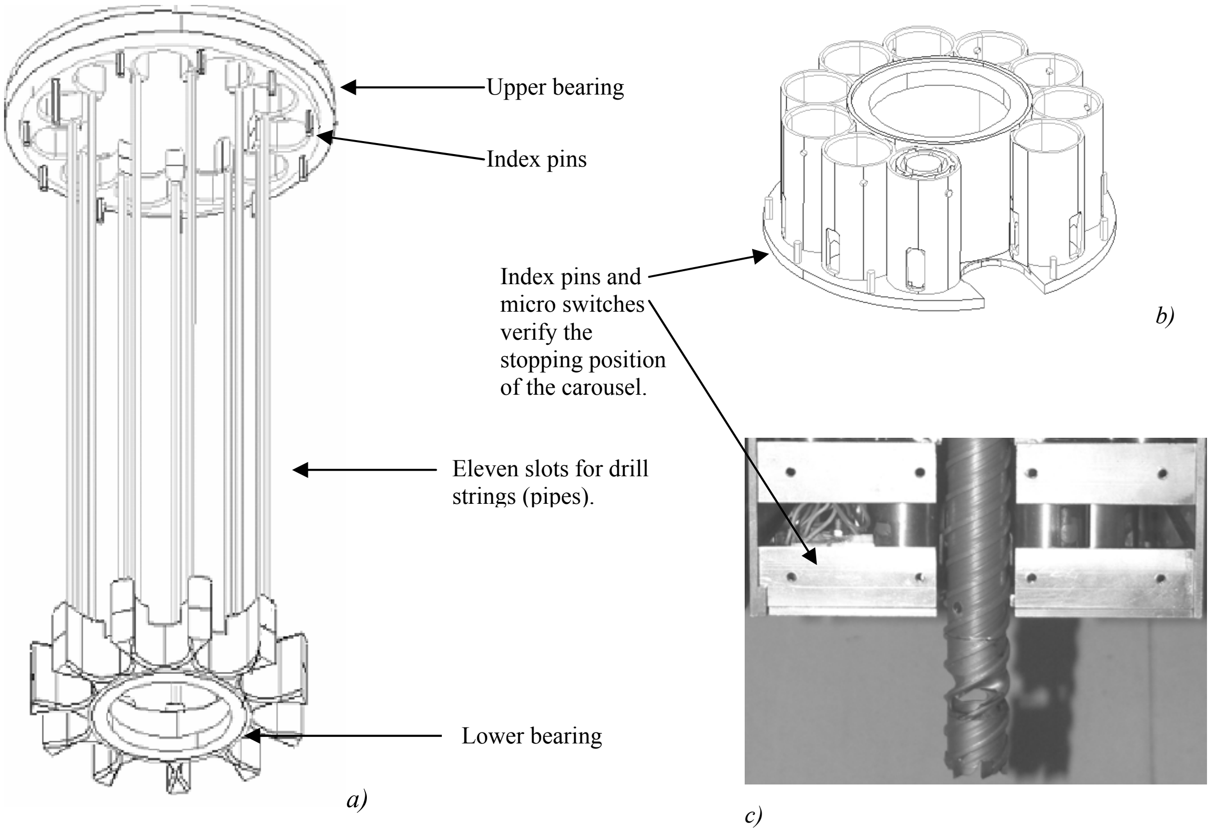


Figure 52: MRoSA2 Pipe and tool carousel (Image: VTT). Figure a) shows the pipe carousel. Figure b) shows the schematics of the tool carousel. Figure c) is a photo of the DSS, showing a pipe and a tool connected, and in front of the tool carousel. Tool slots are visible in the photograph (Image: MA).

Pipe Clamping Mechanism

The string holding device (visible in Figure 52), located between tool carousel and lower end of linear slide system, is used to hold the lower pipe in place during pipe connection or disconnection. Clamping of the pipe is done at both sides of the string with two paws, which are coated with soft high-friction material (silicone rubber) to accommodate helical flute of the drill pipes. The paws are attached to linear slide units and the linear movement and clamping force is actuated with two independent cam mechanisms located on the both sides of the string. Both sides have springs to actuate the opening of paws. The two motors are driven in synchronous way to guarantee that the paws will clamp the string with equal forces, which prevents the string from bending. Position of each slide is measured with a linear potentiometer. However, the synchronizing of the slides was not adequate, and they used to twist the pipe a little. The project team suggests that a single motor would do the clamping. The slides should be mechanically connected to ensure the synchronisation of clamper movement. Another weak point was the friction material, which wore out rapidly and caused sliding of the pipe in the jaws. The friction surface should follow the profile of the pipes, instead of being flat. This auger-shaped friction surface would offer firmer hold of the pipe.

Pipe Gripper System

Spindle solenoid is used to operate a wedge (Figure 53) that prohibites the movement of the mandrel hooks and thus control disconnection of the spindle coupling when separating pipes from each other and from the spindle. The solenoid is a flip-flop-type using a permanent magnet core (Figure 54) to maintain each of its two positions and thus does not require any springs, separate locking mechanisms or continuous power input. Power storage is realized with a capacitor that can produce a high short-term output power for solenoid, while collecting energy for the next operation with low input power.

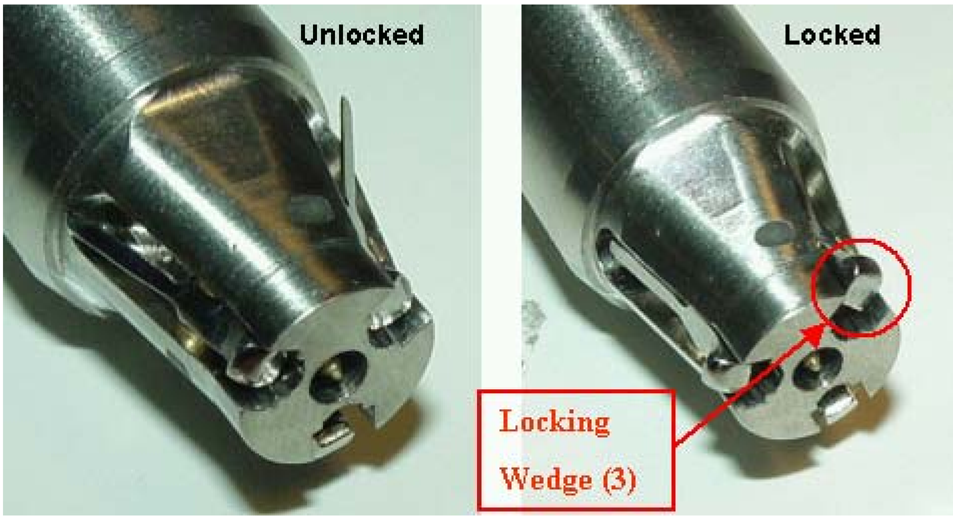


Figure 53: Solenoid driven mandrel hooks: Unlocked and locked position (Image: VTT).

Figure 54: Old solenoid configuration [18]. The match (as a size-reference) is 42 mm long (Image: VTT).

The solenoid caused a lot of problems while it jammed after collecting enough dust. The system was modified a few times, but the real problem was the permanent magnet locking, which was too strong to let the wedge move anymore, once it was locked. When the solenoid was brand-new and clean, it operated fairly well, but after some field demonstrations in sandy conditions, it jammed.

The MRoSA2 project team designed an improvement for the pipe gripper locking system. It consists of a screw drive, rotated by a DC motor. The hooks in the spindle remain the same, but the internal parts of the spindle are changed. This design is illustrated in Figure 55. Note that the figure does not include the spindle electrical connection rings, located in the exterior of the spindle.

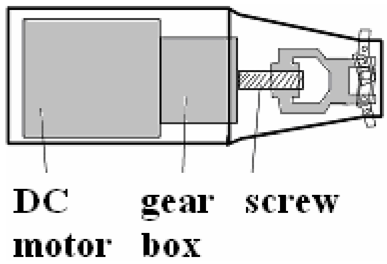


Figure 55: DC Motor powered pipe gripper locking system [1] (Image: MA).

During the MRoSA2 Upgrade project this design was implemented, and the new spindle concept is shown in Figure 56. The first mandrel prototype was refurbished and equipped with a new type of grabbing 'fingers' that can be locked with a vertically moving slide. Also new bearings are assembled. The mandrel has two flexible fingers that yield inwards when a pipe is assembled or disassembled. Yielding of the fingers can be prevented with the slide that moves up and down between the fingers, driven by a small electric motor (Faulhaber 0615 4.5S), located inside the mandrel, and a lead-screw (3 mm of diameter, 'M3') mounted directly to motor's output shaft. When the connection is locked the slide is driven down for 15 seconds until it reaches the hard stop. Upon lock release the slide is driven to the upper hard stop. Upon nominal operation motor current is approximately 45 mA, while at the hard stops it is electronically limited to 80 mA that guarantees that the lead screw does not stick too tight due to screw friction.

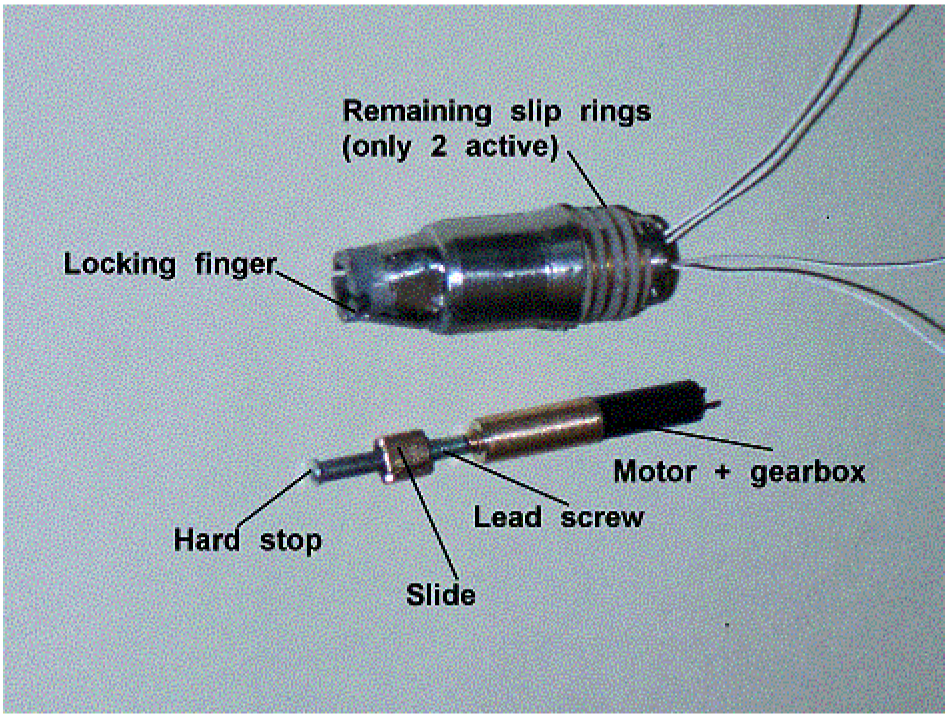


Figure 56: DC Motor powered pipe gripper locking system in MRoSA2U drill (Image: HUT).

Drill Pipe Connections

The drill pipes are located in a carousel. Inside diameter of the pipes is 13 mm, outside diameter is 15 mm, and three-ended helical flute outside the pipe has 17 mm outer diameter. Electrical connections for active tools were designed, but they were not used in this project. The places for connections are located concentric in the middle of the pipe cone for using a coaxial plug. The coupling between the pipes and between the string and spindle is realized with a conical connection that also provides a geometric constraint with triangular cross section to transfer torque. Coupling is locked with a split ring, or a C-ring, on the spindle part (male), the female coupling on the pipe upper ends has a mating groove for the ring. Shape of the groove is made non-symmetric with different conical angles such that coupling by pushing happens easily, but de-coupling by pulling requires a force close to 100 N, which is close to linear drive capacity. It was soon learned that the C-rings needed to have a special design to operate with desired forces. Several different designs were incorporated and tested. Groove for the C-ring has angled surfaces so that the slightly contracted ring causes some pre-load for the coupling. The project team found that there is some uncertainty in the force, which is needed for de-coupling the pipes. Also, if the pipes were not in the same angular position, coupling needed more power. However, the force had to be limited due to the strength of the linear feed system. One possibility to solve these uncertainties would be screw coupling of pipes.

Sensor Feedback from the Drill Subsystem Functions

Drilling requires several mechanical functions inside the DSS module. These operations need to be foolproof for successful drilling. However, when the dust enters the DSS, which is hard to avoid, the mechanical reliability suffers. During the drill tests this happened a few times, caused by dust or other abnormalities. To ensure reliable drilling operation, the mechanical functions should be verified by several sensors, giving accurate data to the drill software. There are some sensors already in the system, i.e. limit sensors for linear feed and for clampers. The most valuable information that was missing during the testing phase was an exact knowledge of successful pipe coupling/de-coupling. This information would require sensors and electrical connections inside the drill pipes.

Drill Tools and Sampling Mechanism

The tool (Figure 57) is designed to drill a 17 mm diameter hole into rock material and to contain ~9 mm diameter and ~20 mm long sample core inside it. A crown that carries out the cutting is constructed of several cutting bits made of hard alloy. In order to penetrate deep into soil the upper end of the core is ground into dust with a secondary cutter blade and ejected outside the tool through small holes in the side of tool. Drilling does not utilize any hammering action and relies only on cutting and grinding. Therefore its ability to penetrate into rock is limited to softer materials like limestone. Acquired sample is stored and transferred inside the tool. A hard core was originally supposed to be broken with the aid of a core lifter (a ring shaped wedge) that grasp on the core when the tool is elevated. However, the prototypes did not work and later the core removal was handled by changing the rotational direction. The tool bits are made of hard alloy and have a sharp cutting edge, instead of dull point that would be suitable for a hammering drill. After a sample is captured inside the tool the string is retracted from the borehole. The coring tool where the sample is stored is transferred to the tool carousel in the end of a pipe. The tool containing the sample is locked into the tool carousel with the procedure described above.

Grabbing, breaking and holding of the rock core with given wedge-design was not reliable. The wedge was too stiff to properly grab on core. Accidentally a core broke by itself, and then the wedge was able to grab it and hold it stiffly. In this case the core inside the tool prevented any deeper penetration. A new design of a wedge was then developed. Also the preliminary objective was to develop a drill tool that is capable to drill and sample both hard rock and loose soil. The results were not very good for that, and instead the project team developed two different drill tools, one for hard rock and the other one for sand sampling. Hammering or ultra-sound vibration would also improve the drilling ability.

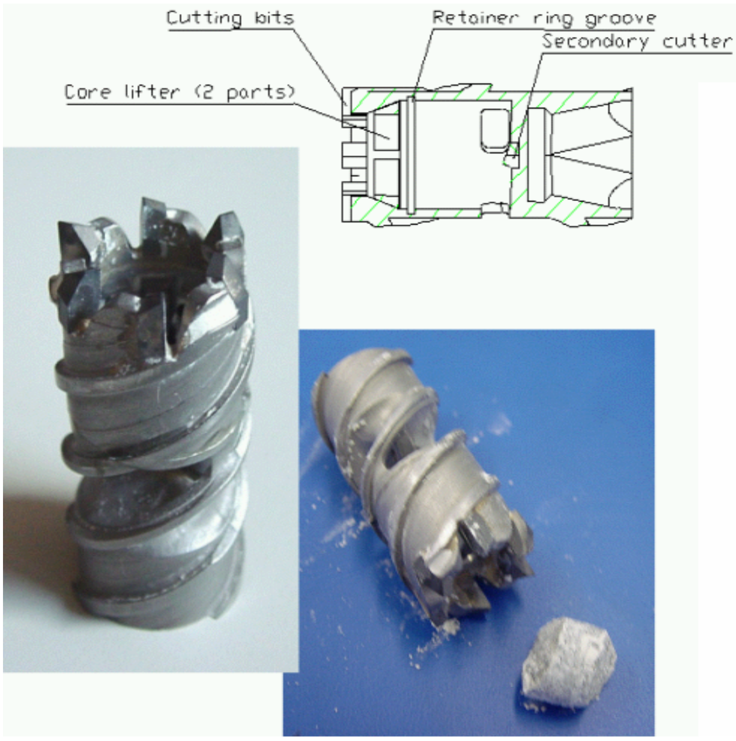


Figure 57: The drill tool and a core sample. The drill is 17 mm of diameter. Flow-through design allows both coring and penetration in depth. The cutting teeth are made of 'DZ05' hard-alloy (saw-teeth) (Image: VTT).

Drill power consumption

According to the drill tests the 6 W drill power and 30 N thrust are enough for the sand and soft limestone. For harder materials more power and possibly some percussion (hammering) are needed. With hard materials like granite the drill without percussion both got blunt after some time and the material surface was burnished to more hard. To ensure the function with hard materials and in difficult environments the given power and thrust of the drill should be remarkably increased. Team estimated during the MRoSA2 project that doubled thrust and 40 – 60 W power would be enough. Later these values were refined by the author for the MASA drill concept (discussed in Chapter 7).

Physical properties

Physical properties, such as size and mass for the whole rover, and for the subsystems, were quite strictly outlined. The concept works in such a small scale and in laboratory conditions, but for dusty real rock drilling there should be more robust design, increasing mass and size. The mass of the rover is about 11 kg, not including the 5 kg DSS module. Total mass of the roving drill platform is 16 kg. As the mass is also used as a counterweight for the drill, and as the gravity in Mars is only 38% of Earth's gravity, the system has counterforce for the drilling of only about 60 N. This force might not be enough for deep drilling in high-friction borehole, as the rover might not be a stable "anchor" anymore.

4.4 MRoSA2 Upgrade project

The MRoSA2 Upgrade project was accomplished during November 2002 to May 2003. It was a direct purchase order from ESA ESTEC to SSF, and the objective was to finalize some undone work during the MRoSA2 project, and also improve the general performance of the rover-drill system. SSF used HUT Automation as its subcontractor. VTT was not any more involved in this Upgrade project. HUT used RCL as its subcontractor for the rover development. The general work packages of the Upgrade project as explained in below:

Following tasks were identified in the project plan [88]:

- *Solenoid* has to be replaced with a more powerful one or with a motor/linear gear combination. Space will most probably be a problem.
- *Load cell* has to be replaced. It might be difficult to find a similar one with reasonable price.
- *Thrust motor/gear* has to be replaced with more powerful one.
- *Clamper surfaces* have to be reformed (in order to prevent pipes sliding).
- *The pipe carousel surfaces* have to be coated with friction material (in order to prevent pipes sliding)
- *Stopping accuracy of carousels* has to be tuned.
- Rover lifting and pitching actuator worm gears should also be tuned or changed.
- SW task 1: Development and Test Environment: Re-building the HW/SW test bench
- SW task 2: Mechanical changes in Rover and DSS requires following modification in the control SW:
    - Spindle lock/unlock functions and error handling procedures.
    - Small modifications on the drilling SW due to the friction pad modifications.
    - Implementation of variable speed algorithm to control the pipe carousel.
    - SW upgrades due to Rover's tether reel repair to ensure smooth reeling
    - Feedback (TM to GUI / internal rover SW)
- SW Task 3: GUI PC: General changes in sensor data telemetry to the GUI computer. Small software upgrades are required to ensure better and more robust operation in a possible "unknown mechanical anomaly" situation. All the mechanical tasks described above require respective updates in the Graphical User Interface.

In the end of April 2003, the system was tested and demonstrated to the team Finnish members and all sub-systems all working fine. Final demonstration was held in ESTEC in May 2003. It was now possible to drill down with multiple drill pipes by attaching and detaching the pipes during operation. However, due to the design matters of the drilling sub-system (DSS), there are still number of criticalities, which are beyond fixing in this upgrade project. These criticalities cause uncertainty in operation and need for experience to operate the system flawlessly. The upgrade project team (SSF, HUT) documented all these criticalities (see Chapter 4.5) so these design aspects may be used in future projects.

4.5 Conclusion of the MRoSA2 projects

The acquisition of deep soil samples is a very demanding task, requiring careful study and an experimental approach based on a staged series of prototypes. MRoSA2, for lack of resources, could only begin such series.

During the definition phase of the MRoSA2 project, the team made a system requirements document (SRD) [16]. The SRD included all the requirements that were mentioned in the original MRoSA2 "Statement of Work" document (SoW) [14]. The SoW was compiled by ESA ESTEC, and the SRD was compiled during the beginning of the MRoSA2 project by the project team.

However, even in its stage, the mechanical implementation of the DSS was quite demanding, for the very limited available room and the problem of drilling dust. The project goals were very challenging, and some of them had to be descoped to concentrate on more important issues. Despite of some descoped goals, the development was very beneficial in acquiring experience useful for possible future drilling projects.

The results of the project, measured by the ESA SoW and SRD requirements against the results that were achieved, are shown in Table 9. The requirement numbers in third and fourth columns are shown for reference.

Table 9: Requirement Correspondence Matrix.

Description	**Result**	**ESA req.** [14]	**Correspondent Requirement in the MRoSA2 SRD** [16]
SYSTEM REQUIREMENTS			
Functional and Performance Requirements			
Perform sample acquisition from its launch location on the lander.	OK	r2.1.2.1.1	DSDSR-BD-1 DSDSR-BD-2 DSDSR-BD-3
Perform at least 3 sample collection trips.	OK	r2.1.2.1.2	DSR-SMPL-8 DSR-SMPL-9
Acquire samples of surface stones or rocks	OK, although the sample collector needs to be improved.	r2.1.2.1.3	DSR-SMPL-2 DSR-SMPL-3 RR-STR-8
Acquire soil/rock samples in depth	OK. As above.	r2.1.2.1.4	DSR-SMPL-2 DSR-SMPL-3
Return to the lander and deliver samples to the Docking and Sample Delivery Port	OK	r2.1.2.1.5	DSR-DRL-11 DSR-DRL-14 DSDSR-SD-1 - 5 RR-STR-6 RR-STR-8 DSDSR-DO-1 - 3
Operational Requirements			
Perform drilling and sampling operations in automatic mode, requiring only high-level ground commanding	Descoped	r2.1.2.2.1	SWR-DSA-1 SWR-DSA-3 SWR-DSA-4
SYSTEM CONSTRAINS			
Environment Constrains			
Any hardware part of the RSS/N shall be designed to operate in environmental conditions as outlined in AD1 [13]. However, considering that the purpose of this activity is to demonstrate the concept of a RSS/N and not to build flight hardware.	OK	r2.1.3.1.1	DSR-ENV-5 RR-STR-6
Any hardware part of the RSS/N shall be built to operate in terrestrial outdoor environmental conditions	OK	r2.1.3.1.2	DSR-ENV-4 RR-STR-5 RR-STR-7
Resource Constraints			
The Drilling and Sampling Subsystem shall not exceed the volume of 110x110x350 mm	OK	c2.1.3.2.1	DSR-ENV-1
DSS shall not exceed the mass of 5 kg	OK	c2.1.3.2.2	DSR-ENV-1
The Docking and Sample Delivery Port shall not exceed the mass of 3 kg	OK	c2.1.3.2.3	DSDSR-WC-1
Interface Constraints			
RFMU and DSS shall draw power from single laboratory power source	OK	c2.1.3.3.1	RR-STR-12

RFMU shall interface to a personal computer using a RS232 line with a D type 9-pin connector	OK	c2.1.3.3.2	RR-STR-13
Docking and Sample Delivery Port shall allow the routing of the tether.	OK	c2.1.3.3.3	DSDSR-OT-1
Implementation Constraints			
RFMU shall be implemented using as much as possible COTS components	OK (basically this concerns only the electronics)	c2.1.3.4.1	RR-STR-3
Specific Requirements to RFMU			
RFMU shall carry around the DSS	OK	r2.2.1.1	RR-STR-9
RFMU shall be able to dock with DSDP	OK (with operator's assistance)	r2.2.1.2	RR-FUN-4 DSDSR-DO-1 - 3
RFMU shall present the same scaled-up physical appearance of the Nanokhod Breadboard	Descoped	r2.2.1.3	RR-STR-1
RFMU shall implement locomotion (two tracks) and articulation subsystems (payload hanging on two sequential pitch axes) reproducing the functions of the Nanokhod Breadboard ones	OK	r2.2.1.4	RR-STR-2
RFMU shall be equipped with a computer, interface electronics and software to allow control of the locomotion, articulation and DSS subsystem	OK	r2.2.1.5	RR-ORE-1 RR-ORE-2 RR-ORE-3 RR-ORE-4 RR-ORE-5 RR-ORE-6 - 7
RFMU shall be equipped with a RS232 serial line, which allows connection to a PC, in order to send commands to the On-rover control system and receive rover status data	OK	r2.2.1.6	RR-ORE-12 RR-STR-10
RFMU shall be equipped with a 40 m tether cable in which the serial line and power lines are combined	OK	r2.2.1.7	RR-STR-10 RR-STR-11 RR-STR-12 RR-STR-13
Specific Requirements to DSS			
Drill at commanded elevation angles from 0° to 90°	OK	r2.2.2.1	DSR-ENV-3 SWR-DSA-6
Allow multiple drilling	OK	r2.2.2.2	DSR-SMPL-8
Drill in low gravity	OK by design (no reliance on gravity in mechanisms)	r2.2.2.3	N/A
Drill at depths ranging from 0 to 2 metres with 5 mm accuracy	5mm accuracy descoped	r2.2.2.4	DSR-SMPL-1 DSR-SMPL-5 SWR-DSA-5
Drill into non-homogeneous material of density and hardness ranging from loose sand to hard rock (max H=8 Mohs' scale)	OK	r2.2.2.5	DSR-SMPL-4
Drill with independent rotation and thrust actions	OK	r2.2.2.6	DSR-DLR-1 SWR-DSA-7

Allow control of drill depth (0-2m), rotation speed (0-30RPM), thrust force (0-30N)	OK	r2.2.2.7	DSR-DLR-1 DSR-SMPL-5 SWR-DSA-5 SWR-DSA-8 - 9
Acquire cylindrical samples (radius 5 mm and height 2 cm) of non-homogeneous material of density and hardness ranging from lose sand to hard rock	OK (reliability of sampling is only satisfactory)	r2.2.2.8	DSR-SMPL-22 DSR-DRL-13
Ensure that the sampled material belongs to the specific depth of sampling (i.e., do not carry down material from upper layers)	OK (as above)	r2.2.2.9	DSR-SMPL-11 DSR-SMPL-13 DSR-SMPL-7
Preserve the morphology of the sample (i.e. do not scramble, compress or stretch it)	OK (as above)	r2.2.2.10	DSR-SMPL-14 DSR-SMPL-15 DSR-SMPL-16
Preserve the purity of the sample (i.e. do not mix it with other material)	OK (as above)	r2.2.2.11	DSR-SMPL-11 DSR-SMPL-12 DSR-SMPL-13
Allow acquisition and storage of at least 10 samples per trip	OK	r2.2.2.12	DSR-SMPL-9 may not be feasible, preliminary changed to seven.
Allow delivery of samples to the Docking and Sample Delivery Port	OK	r2.2.2.13	DSR-DRL-11 DSR-DRL-14
Specific Requirements for DSDP			
Hold RFMU in stowed position during launch and landing	OK (in concept level, but not implemented)	r2.2.3.1	DSDSR-BD-1
Allow sampling of soil from un-deployed position	OK (in concept level, but not implemented)	r2.2.3.2	DSDSR-BD-3
Allow deployment of RFMU on soil	OK	r2.2.3.3	DSDSR-DE-1 DSDSR-DE-2
Receive samples from RFMU	OK (with operator's assistance)	r2.2.3.4	DSDSR-SD-1 - 5
Supply samples to Sample Processing and Distribution Subsystem	Descoped	r2.2.3.5	N/A
Provide alignment guide to allow docking of RFMU (when returning to Lander)	OK	r2.2.3.6	DSDSR-DO-2
Specific Requirements on Lander mock-up			
House DSDP	OK	r2.2.4.1	LMR-1
Allow demonstration of DSDP functions	OK	r2.2.4.2	LMR-2
Mimic appearance of Mars96 small station lander (flattened sphere with petals)	OK (petal only)	r2.2.4.3	LMR-3

As mentioned, the MRoSA2 project achieved partially its objective by demonstrating the concept of micro rover and driller. But it was not until the MRoSA2 Upgrade project that the system achieved the level of reliable operation (reliable for laboratory demonstrations). Even that the latter project was concluded successfully, there are some remaining criticalities in the system. One motivation for this thesis is to evaluate those points and try to find solutions to achieve adequate readiness level for building a flight instrument. The remaining criticalities are explained in Chapter 5.2.4 (MRoSA2 Upgrade tests).

5. TEST WORK ON DRILLERS AND SAMPLERS

There have been four different test periods of MRoSA2 drill hardware regarding this thesis, either the drill module (with and without the rover) or the drill pipes and bit only. These testing periods are:

- Tests conducted during the MRoSA2 project in 1999-2001:
    - Drilling tests, performed by VTT Automation in Finland.
    - Systems testing for the rover and drill module, performed by the author, SSF, HUT, and VTT.

- Tests during the MRoSA2 Upgrade project in 2002-2003:
    - Systems testing, performed by the author and HUT.
    - Drill functionality testing, performed by the author and HUT.

- The MIRANDA project, 2003:
    - Soil drilling tests, performed by the author and HUT student team.
    - Rock drilling tests, performed by the author and HUT student team.

- The MIRANDA-2 tests, 2004:
    - Temperature tests during rock drilling, performed by the author.
    - Rock drilling tests, performed by the author.
    - Drill pipe friction and pull-resistance tests, performed by the author.

These tests, their plans, contents and results are discussed in the following chapters. In addition to those tests, some other drilling related tests, performed by different institutes and companies, are covered. The results of these tests are used in the design process of the new drill concept. This concept, the MASA drill, is explained in detailed manner in Chapter 7.

5.1 The drilling tests of MRoSA2 project

During the MRoSA2 project, in which the VTT developed the drill system (DSS), VTT performed some drilling tests to find out the drill's ability to penetrate different materials. The drill tool (drill bit) design was tested in a test bench in VTT's premises in Finland, and VTT built also a test bench for the system tests.

5.1.1 Drill bit tests

Tests were done with a gear motor installed into vertical linear slide (Figure 59a). The weight of the motor gave a 30 N thrust force and the motor speed was set to 30 RPM in most of the cases. The tests showed 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 10). The tools that were tested were as following [4]:

- ∅6 and ∅16 mm impregnated diamond core drills for cutting of glass (commercial bits)
- ∅16 conventional hard-alloy-tipped drill for hand-held hammering drills (commercial Hilti bits)
- ∅16 mm hard-alloy tool for metal cutting (∅4 mm core, commercial bits)
- ∅16 mm custom made hard alloy core drill (Terätrio company)
- A concept of two surgical knife blades rotating at ∅16 mm radius (~∅14 mm core, Figure 58)

Table 10: Some preliminary MRoSA2 drilling tests results of the VTT tests.

#	Drill bit	Material	Speed RPM	Force N	Hole depth mm	Speed mm/h	Duration h
1	Diamond	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	Marble	30	24	16.6	1…2.2	8
5	Hard	Marble	30	25	17.8	2.6	6.5
6	Diamond	Marble	30	24	11.1	0.5…2.1	6
7	Diamond	Marble	60	24	13.2	0.7…2.4	6
8	Diamond	Marble	60	24	15.1	1…2.2	8
9	Diamond	Limestone	30	24	6.7	0.3…3.9	4.5
10	Diamond	Limestone	30	24	10.6	1.7…3.4	5
11	Knife	Limestone	30	25	3.4	6	0.5
12	Sonic hard	Limestone	30	12	4.3	1.5	Different sonic (1) vibration
13	Sonic hard	Limestone	30	12	6.1	1.5	
14	Sonic hard	Limestone	30	12	2.3	1.5	
15	'Terätrio'	Limestone	30	27	9.8	18	0.5
16	'Terätrio'	Granite	50	High (2)	0.9	3	10
17	'Terätrio'	Granite	120	High (2)	6.2	36	10
18	'Terätrio'	Granite	120	27	2.3	2.2	1.3
19	Sonic knife	Granite	30	12	1.5	0.2	2
20	Knife	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

(1) The term 'Sonic'in the table means vibration in a frequency range of some kilohertz (kHz). The test cases 12-14 differ only by the vibration mode, which was unfortunately not documented in more details. (2) The 'High' force means a variable force in a range of ~20…45 N.

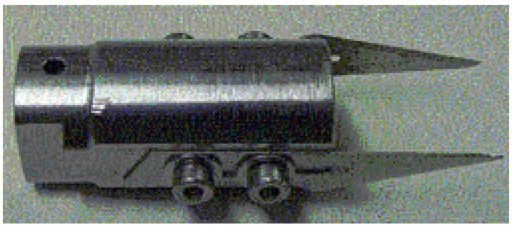


Figure 58: Drill bit with surgical knife blades, custom made in VTT (Image: VTT).

There were two different methods in the tests. In the first one (Table 10) the sample was stationary and the drill that was used was an ordinary hand-drill, which was attached to a vertical sledge that descended against the rock sample. In the second method (Table 11), the test bench comprised of 'reversed' design, i.e. the drill itself did not rotate, but the sample was attached to a sample holder, which rotated. In the latter design, the sample was placed atop of force and momentum sensors (model: 'Kistler'). The drilling force was controlled with weights, which were attached to the drill bit. The drill bit moved only in vertical direction. This latter method allowed the use of the momentum sensor.

3

a) b)

Figure 59: VTT drill test bench and sample rocks.

Figure a) demonstrates a deep drilling test. In this test, the rotational speed is 30 RPM, thrust is 30 N, power is 3 W, and the test was 24 hr long. The result was a hole of 8 cm depth and of 17 mm in diameter in dense marble [37].

Figure b) shows results from the shallow drilling tests. The drill did not rotate, but moved only vertically. The rock was mounted atop of a force/momentum sensor ('Kistler'), which rotated against the drill. There is clearly visible different kind of holes drilled in the rocks. Note especially the sample (inner core in the hole), which in some cases has not yet been retracted from the hole. The rocks are marble, limestone and granite (from left to right).

The second test case involved monitoring of additional parameters. Table 11 shows the results of these tests, which include reruns of the first tests (see Table 10). The term "none" in the last column of Table 11 indicates that there was no measured wear in the drill head, or that the wear was less than 0.03 mm during the testing period (5…10 hours). It is notable that none of these bits were selected for the MRoSA2 DSS, since VTT manufactured later a custom-made hard-alloy bit for the DSS. This was partially because of the system requirements, and choices made inside the VTT at that times.

Table 11: Controlled and measured parameters in VTT's drilling tests.

Controlled parameters					**Measured parameters**			
#	**Drill bit**	**Material**	**Speed / RPM**	**Force / N Pressure / kPa**	**Torque / Nm**	**Axial speed / mm/h**	**MRR / mm^3/h**	**Wear**
1	diamond Ø16	marble	30	24 / 311	0.1	0.3 .. 2.5	23 .. 190	none
2	hard alloy	marble	30	25 / -	0.1	2.6	280	none
3	diamond Ø16	granite	30..120	24 / 311	0.1	0	0	none
4	hard alloy	granite	30	25 / -	0.1	0	0	none
5	diamond Ø16	marble	30, 60	24 / 311	0.1	1 .. 2.2	77 .. 170	none
6	diamond Ø16	sand brick	30	24 / 311	0.1	0	0	none
7	diamond Ø6	marble	30	24 / 1190	0.1	0.49 .. 2.1	9.9 .. 42	none
8	diamond Ø6	marble	60	24 / 1190	0.1	0.66 .. 2.4	13 .. 48	none
9	diamond Ø6	limestone	30	24 / 1190	0.1	0.3 .. 3.9	6 .. 79	none
10	diamond Ø16	limestone	30	24 / 311	0.1	1.7 .. 3.4	130 .. 260	none
11	surgical blade	limestone	30	25 / -	0.2	6		none
12	surgical blade	limestone	30	10 / -	-	2.4		none

5.1.2 Drill system tests

VTT Automation also prepared a test setup (see Figure 60), which consisted of 2-metre long transparent acryl tube. The purpose was to place the rover on top of the tube, and let it drill through the sand that was supposed to be placed into the tube. This would have revealed the possible rotation friction of the all-the-way-long drill rod. However, this test was never done, despite the fact that the drill test bench was manufactured, and later delivered to ESA ESTEC during the final presentation of the MRoSA2 project in November 2001. The reason for skipping the test was mainly the already-late schedule. VTT had lack of human resources and the project needed to be finished even without all the tests. This was actually one reason for the author of this thesis to start designing of the MIRANDA tests bench. There was no data yet on drilling to deep sand column with the MRoSA2 drill tool.

The results of this test would have been collected through the rover's own telemetry system in addition to an external test monitors and measurements. The sample sand or other material was to consisting of dry sand with varying grain size and compactness, added with occasional boulders of marble, lime stone and sand stone. Aim of this test was to determine drilling speed, power and forces, and to demonstrate capability to obtain samples from desired depth and from desired materials.

Figure 60: Test bench for deep drilling tests.

Above: The MRoSA2 rover on top of the test bench. The rover stands in a drilling position.

Left: The 2 metre long plastic tube with the MRoSA2 DSS on top of it.

In addition to general mechanical unreliability in single operations, there were even more reliability problems to perform successful sequence of operations. As SSF and HUT personnel provided a teleoperation interface (GUI) to the drill mechanism and they heard and saw the operation of the drill mechanism, a trained operator succeeded in generating series of motions that fulfilled tasks of a potential mission. Penetration speed to sand exceeded all expectations. However, the reached reliability level was unacceptable for space operations. This was one reason for the MRoSA2 Upgrade project. The basic idea of the drill seemed to be operational, but the biggest flaws were in reliability issues. Confirming sensors were found to be needed, because the operator did not always know the status of the drill mechanism. According to discussions at VTT two different tools are needed to three different soil types: a tool for sand and dust, and another for cliffs, gravel, and stones in the surface or hidden in the sand [87].

Waste material removal

The amount of waste material from the borehole was studied also (Table 12), since there must be adequate ground clearance between the DSS and surface. If the DSS is lying on the ground, the waste material will climb inside the DSS, causing severe blocking of the mechanics. If the drilling depth is 2000 mm the amount of material removed from the hole is approximately following for the different drill shaft outer diameters:

Table 12: Estimated amount of material to be removed from the borehole [89].

Borehole diameter, mm	Amount of material, dm^3
10	0.16
15	0.35
20	0.65
25	1.00
30	1.47

The dust could be wiped away with a wiper mounted to a string guiding wheel, or the wiper might have its own motor. In addition, the dust could be blown away with a gas jet, or helical horizontal augers could be used to transfer dust further away from the rover. The design of waste material removal apparatus was left open, but a very simple brush was manufactured which performed in satisfactory level, but it wouldn't be reliable enough for flight mission use.

5.1.3 Summary of MRoSA2 project drill and system tests

The VTT drilling tests were done first into a limestone. The tests showed that penetration deep into limestone was 14 mm/hour (at 3 W electrical power, 30 N thrust and 30 RPM) coring (10 mm diameter core), and 3 mm/hour during drilling deep (making a bore hole 17 mm in diameter, holding a 20 mm (length) core inside the tool). Up to 8 cm deep was drilled in 24 hours. Dust exits the borehole properly and flow-through design of the tool is functional. The 20 mm core remained inside the tool during drilling as planned.

The amount of waste material is also tolerable, providing that there is adequate ground clearance for the DSS, and there is some means to brush away the dust from the drill strings before they are lifted back inside to the DSS.

The drill system tests by VTT and SSF showed mainly, that the drill concept is functional, but the reliability of the mechanics was not adequate but only for demonstration purposes. These reliability tests continued in the MRoSA2 Upgrade project, explained in the next chapter.

5.2 The MRoSA2 Upgrade tests

The MRoSA2 rover with the drill went through several of tests during its manufacturing period in Finland in 1999-2001. However, the tests mainly concentrated on the mechanical issues and reliability of the mechanics in both the sub-system functions (so called atomic operations) and in long sequences (macro operations). The tests for the drill system's ability to drill sand or stones were performed in laboratory conditions in a test bench (by VTT Automation) during the earlier MRoSA2 project, but actual tests with the final hardware (drill in the rover) concentrated only to the functionality of the mechanics (during the MRoSA2 Upgrade project).

5.2.1 Drill sub-system tests

These tests concentrated on the drill module (DSS) and the actuators on it. It is notable that the tests were not actually part of the current project (MRoSA2 Upgrade project funded by ESA), but the tests were performed to gather test results material for this thesis and to learn more about the system for possible future projects. These tests were performed by the author of this thesis (acting as a project manager at the time of the tests) during the period from January 2003 to May 2003. However, despite being optional regarding the project, these tests were also documented and delivered to ESA [19].

Table 13: Tool carousel: Stopping accuracy and position-knowledge test.

Parameter	Value
Test runs	100 times for varying target slots (slot 0 to 10)
Found correct slot	100 %
Time needed for one full revolution	10 sec. (~9.5…10.5 sec.)
Current needed for nominal operation	0.03 A (24 V voltage; 0.72 W electric power)

Table 13 shows the results of the tool carousel tests. The tool carousel contains one electronic actuator, a DC servomotor, which rotates the carousel to both directions. The position knowledge comes from two microswitches: one indicating every slot on the carousel and the other indicating a full revolution. The test was performed 100 times for different slots (slots 0…10 evenly distributed; about 9 times per each 11 slots), and it revealed no problem in the mechanical functions in the upgraded DSS tool carousel. However, it is notable that the microswitches are not the best way to get the position information, since during earlier phases of the project they were sometimes broken due to the mechanical fatigue. They simply exceeded their lifetime (nominal lifetime is unknown), partially because they were somewhat misplaced and were hitted by the carousel pins sometimes, or were stuck by a piece of debris/sand after long drilling sessions. Possible alternatives for microswitches are e.g. magnetic Hall sensors or optical sensors, and they are discussed later in this thesis.

Table 14: Pipe carousel: Stopping accuracy and position-knowledge test.

Parameter	Value
Test runs	100 times for varying target slots (slot 0 to 10)
Found correct slot	97 % (errors were not mission critical)
Time needed for one full revolution	14 sec. (~13…15 sec.)
Current needed for nominal operation	0.03 A (24 V voltage; 0.72 W electric power)

Table 14 shows the results of the pipe carousel tests. The pipe carousel, similarly to the tool carousel, contains one electronic actuator, a DC servomotor, which rotates the carousel to both directions. The position knowledge comes from two micro switches: one indicating every slot on the carousel and the other indicating a full revolution. There is also a third micro switch, which counts the pipes in the carousel. The test was performed 100 times for different slots (slots 0…10 evenly distributed; about 9 times per each 11 slots), and it revealed that problems rarely occurred with the mechanical functions in the upgraded DSS pipe carousel. Once more it is notable that the micro switches are not the best way to get the position information, since they tend to be unreliable in long run. The reason for failing three times out of 100 was the micro switch accuracy combined with the drill software. The pipe detection micro switch accuracy failed due to poor calibration two times and once the real-time software (SW) was in ‘wrong part of the loop’, which disabled it to read the micro switch for the signal time. The SW runs in a continuous loop in a frequency of 15 Hz, and during the ~67 ms loop time it cannot detect the signals for a couple of milliseconds (hardware (HW) initialising period).

The drill pipe clampers are relatively simple mechanical clamping devices, but during the first MRoSA2 project they were diagnosed to have some fundamental problems. Since they did not have any firm lock-in-position capability, they lost some grip when the drill string vibrated and tensioned during the attaching and detaching of drill strings. The most robust solution would be attained, if the mechanics would achieve a dead-stop position when the calmper were closed. So when the clampers would be in tension, they would lean against the dead-stop of the mechanics (Figure 94). This is discussed more in Chapter 7.3.2.

The clampers, which are used to clamp the drill pipe during attachment and detachment of pipe segments, also underwent some modifications during the MRoSA2 Upgrade project. Main modifications concerned the friction material of the paws. Since it was observed, that the clampers were unable to ensure full grip in every situations while in rest (in locked position), we developed a new operation mode for the clamping function. The clampers were driven *dynamically*, i.e. the motors were always on during critical operations (attachment and detachment), even that they could not move any further. This mode ensured enough grip that the pipe didn't move during critical operational cycle. The drawback was that the motors consumed more power and they were in a risk of overheating. However, this was best that could be made in the frame of this update project. The test results are shown in Table 15.

Table 15: The test results of the pipe clampers' tests.

Parameter	**Value**
Time needed for open-to-close or close-to-open –operation	Less than 1 sec.
Current consumption (nominal mode)	0.07 A (24 V voltage; 1.68 W electric power)
Current consumption (dynamic mode)	0.21 A (24 V voltage; 5.04 W electric power)

The linear feed function, which moves the drill sledge up and down, was improved mainly concerning the position-knowledge. The overall length of the vertical movement is 220 mm (the pipe length is 200 mm) and the position of the sledge is measured by an encoder, potentiometer and end-sensors. The resolution of the encoder is 0.15 mm, which is accurate enough. The problem is that the position shifts in long duration operations, which is a typical encoder problem. The end-sensors (microswitches) are used to calibrate the position when the sledge is in either end. If the drill module is initialised in a position where the end-sensors are not triggered, i.e. the sledge is somewhere in the middle, the encoder cannot be used to calibrate the position until the sledge positions is initialised. This is done by the potentiometer, which measures the absolute position of the sledge (encoder is relative sensor in this sense). However, the potentiometer is not very accurate, giving readings of ±1cm. Therefore it is imperative to calibrate the encoders, if possible in the current situation, in either ends. The test results are shown in Table 16.

Table 16: The test results of the linear feed.

Parameter	**Value**
Time needed to perform full end-to-end movement in full speed.	80 sec.
Current needed for nominal operation	0.09 A.
Power needed for nominal operation	2.16 W.
Maximum thrust (by motor and gearbox)	~400 N
Maximum allowed thrust (to prevent structural damage)	~100 N (adjustable: measured by a load-cell)
Precision (by encoder):	Theoretically: 0.15 mm. In practice: 0.5 – 1.0 mm.

The pipe gripper is the device that locks the drill pipe to the drill motor's axis (mandrel). The whole locking concept was changed during the MRoSA2 Upgrade project, and the new concept includes a DC motor and 'hooks', which locks the drill pipe to the mandrel. The screw tightening takes some time to close or open, and there are no sensors to verify the result of the operation. Therefore the DSS software runs the gripper ~25% overtime to ensure closing or opening. The lack of sensors is due to the confined space in the gripper. The test results of the pipe gripper are shown in Table 17.

Table 17: The test results of the pipe gripper.

Parameter	Value
Time needed to perform opening (unlock)	19 sec.
Time needed to perform closing (lock)	19 sec.
Operation time.	22 sec. (~125% of needed)
Current and power in nominal operation:	0.05 A (24 V: 1.20 W)
Current and power in stall.	0.09 A (24 V: 2.16 W)
Performance result	98% (2 operations out of 100 failed. Propably mission-critical errors.)

Critical points were operating while the pipe is pulled heavily from the spindle, and pushing the pipe against the spindle. The latter does not affect in gripper's operation, but may affect to the electrical connections between the mandrel and the sledge (slide ring connections).

5.2.2 Combined operations tests

The previous chapter presented the results of the single operations tests. In addition to those operations, also the combined operations (macro commands, i.e. series of single operations) were tested.

Since many of the DSS sensors are relative sensors instead of absolute, the control software is unaware of the situation in the DSS when it is started. An initialising operation must be done first before any drilling can take place. The DSS initialising consists of the functions presented in Table 18.

Table 18: Steps of the DSS initialisation.

Step #	Operation	Verification
1	Open clampers	Absolute sensors: linear potentiometers
2	Unlock pipe gripper	No sensors; time limit only
3	Linear feed up	Potentiometer gives rough position when started. Up limit verified by micro switch. Encoder can be used after micro switch gives calibration value, and before reaching the up limit encoder gives only length and direction (no position).
4	Rotate pipe carousel 1-2 full revolutions, depending on the starting position.	Three micro switches: one is used to count full revolutions, one is for slot marker and one counts the pipes and their positions in the carousel.
5	Rotate tool carousel 1-2 full revolutions, depending on the starting position.	Two micro switches: one is used to count full revolutions and the second one is for slot marker.

Total time to perform full initialisation varied from 33 seconds to 135 seconds, depending on the starting position of the linear feed (mandrel vertical position). Maximum current drawn is 0.09 A during the initialisation.

Besides the initialisation, there are six other macro commands in use. Those commands and their sub-commands are:

1) Connect spindle to pipe and pipe to tool
    a. Keep pipe gripper open
    b. Rotate spindle slowly back and forth (changing its direction in every 4 sec.)
    c. Push down linear feed slowly until certain encoder mark, and then stop all.
    d. Close pipe gripper (lock pipe to the spindle).
2) Add another pipe to the string:
    a. Linear feed is its top position; clampers closed keeping lower pipe in hold.
    b. Rotate new pipe to the drill axis place.
    c. Rotate spindle slowly back and forth (changing its direction in every 4 sec.)
    d. Push down linear feed slowly until certain encoder mark, and then stop all.
3) Raise tool from the tool carousel slot
    a. Rotate spindle (and pipe+tool) slowly counter-clockwise.
    b. Lift linear feed up slowly until certain encoder mark.
    c. Stop rotation and lift up.
4) Detach two pipes
    a. Clampers closed keeping lower pipe in hold.
    b. Pipe gripper locked keeping upper pipe in hold.
    c. Lift up 5 mm.
5) Detach mandrel from pipe
    a. Clampers closed keeping lower pipe in hold.
    b. Pipe gripper open.
    c. Lift mandrel up to its top position.
6) Leave tool
    a. Keep pipe gripper closed.
    b. Rotate spindle slowly clockwise.
    c. Push down linear feed slowly until certain encoder mark, and then stop all.
    d. Lift linear speed up.

1. Connect spindle to pipe and pipe to tool

The first connection (spindle to pipe and pipe to tool) is a dual operation. Both connections, ‘pipe top to spindle’, and ‘pipe bottom to tool’, will be made at the same time. Successful connection is verified by encoder value, which measures the distance of the spindle from its upper limit. This seems to be quite accurate method, if encoder has been calibrated in up limit just before attaching the connections. However, problems remain in finding the right positions for connections and sometimes also in verification of the connection. Average time needed to perform both connections is ~25 sec. (nominal variation 18-30 sec. depending on the rotation angle between the pipe connections). Criticalities occur when linear feed’s current limit is too high (pushing force > 35%, when optimal is ~25-30%). Connection is more reliably established to a tool, which is in a slot where is a pin securing the tool’s rotation movement. Overall success rate of these connections was tested to be ~93% (tested 100 times, which of 7 failed: 5 failed in pipe-to-spindle, 2 failed in pipe-to-tool connection).

2. Add another pipe to the string

This command seemed to be very reliable, with an average reliability of 99% (out of 200 tested operations which of 2 failed). The operation is similar to the first macro command, but because the lower pipe is held steady by the clampers, the connection is established with more reliability.

3. Raise tool from its slot

Best results where achieved when a tool is raised from a tool slot where a pin is not located. However, the macro operation “Raise tool and pipe” is pretty reliable (~90%) when operating with a tool slot with a pin also.

4. Detach two pipes

Detaching works well (only one problem encountered; 99% success rate), if the feed current limit is set to 40% (of the nominal current) or more. 30% is enough for some times, but due to the variations of the C-ring stiffness, it is advisable to use some more power.

5. Detach mandrel from pipe

Detaching mandrel from pipe works well. Possible problem situation is when the pipe has some tension downwards, transferring this tension force to the gripper hooks. When the pipe and spindle are not in tension (pulling force outwards from the spindle), there were no problems detected.

6. Leave tool

Leaving tool was somewhat problematic at first. The drill must rotate clockwise slowly at the same time that it is pushed down. There were no accurate reliability analysis from this operation, but after the right drill parameters were found, the operation went mostly flawlessly.

5.2.3 Reliability analysis

As seen in previous MRoSA2 test results, the reliability of each single operation is commonly more than 90%, even 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 19.

Table 19: Drilling down to two metres; power, time and reliability issues.

Depth cm	Total attachments + detachments	Cumulative time min	Cumulative energy J	Cumulative reliability
20	2 (1) + 0 (3)	4	~400	80 %
40	4 (2) + 1 (4)	10	~1300	76 %
60	6 (2) + 2 (4)	16	~2200	72 %
80	8 (2) + 3 (4)	22	~3100	69 %
100	10 (2) + 4 (4)	28	~4100	65 %
120	12 (2) + 5 (4)	34	~5000	62 %
140	14 (2) + 6 (4)	40	~5900	59 %
160	16 (2) + 7 (4)	46	~6800	56 %
180	18 (2) + 8 (4)	52	~7700	53 %
200	20 (2) + 9 (4)	58	~8600	50 %

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.

In the Table 19 above, the values of the "cumulative reliability" column derive from the reliability tests of the MRoSA2 Upgrade project (Chapter 5.2.1). The measured reliability of different DSS functions is statistical score, so the cumulative reliability of multiple functions is not possibly a fact, but a demonstrative value. As an example, drilling to 20 cm requires the following phases with empirical/statistical reliabilities (the MRoSA2 Upgrade DSS tests):

- Tool carousel locates a tool (100%) [Table 13].
- Pipe carousel locates a pipe (97%) [Table 14].
- Spindle is driven so that it pushes the pipe against the tool. Both the connection of pipe-and-tool and pipe-and-gripper detaches (93%) [Chapter 5.2.2].
- Gripper is being locked (98%) [Chapter 5.2.1].
- Tool is raised from slot and tool carousel rotates so that the drill can proceed (90%) [Chapter 5.2.2].
- Drilling starts (100%).

The combined reliability is then:

$$1.00 \times 0.97 \times 0.93 \times 0.98 \times 0.90 \times 1.00 = 0.80$$

As seen above, in the case of MRoSA2, four tests out of five (80%) were successful when the aim was to start drilling. In practise, this was pretty much the case in all demonstrations. When the aim is to drill down to 40 cm (two drill pipes), the overall reliability decreases slightly more, since in addition to above there has to be made one detachment (pipe from gripper) and two attachments (pipe to pipe, pipe to gripper). The reliabilities are 98%, 98% and 99%, respectively. The reliability of attaching the second pipe is:

$$0.98 \times 0.98 \times 0.99 = 0.95$$

And the total reliability so far is now:

$$0.80 \times 0.95 = 0.76$$

As seen, every pipe that is increased to the system decreases the reliability of successful operation. With ten pipes (when the drill string is 200 cm long) the overall reliability is then:

$$0.80 \times 0.95^9 = 0.50$$

The overall reliability to extend all ten pipes of the MRoSA2 Upgraded DSS is 50%. This is yet not counting the drilling force influence and the lifting of the drill string back to the surface. The result is not very impressive, but one must remember that the purpose was mainly to test the concept principle of revolver-type miniature drilling mechanism. The concept is working, and the reliability can be improved greatly by concentrating to the mechanics' sensors and position knowledge.

5.2.4 Remaining criticalities

Even that the MRoSA2 DSS was successfully upgraded to the demonstration level, there are still multiple points to modify, that the drilling operation could be done flawlessly in Martian conditions:

The remaining criticalities after the MRoSA2 Upgrade project are [19]:

- Slip ring brushes are too stiff and contact to slip ring has low reliability. This can be fixed only with complete disassembly of the drill unit and sledge.

- Mandrel does not reach far enough at the lower limit to allow any slippage of the pipe between the clamps. Any slippage during drill string retrieval endangers mandrel's capability to grab the pipe and return it to the carousel. This can be helped slightly (1-3 mm) with complete disassembly of the drill-unit, carousel, sledge unit and clamper unit, and machining some material off from the carousel, sledge and clamper units. Any further development requires complete redesign and manufacture of the system. Operational back up for the case when the drill string has slipped too far down can be to use the rover's capability to lower to bridge and so bring the drill and mandrel closer to the end of the drill string.

- The locking springs inside the tool carousel appear to be quite weak.

- Accuracy and lifetime of the limit-switches is questionable.

- Push force of the linear feed is not very well adjustable at the lower end. Even the minimum operational motor current gives a remarkable push force. When connecting the couplings together, if the couplings happen to be 30 degrees misaligned (the worst case), friction generated by the axial thrust overrides the torque available from mandrel back-and-forth motion. Because of this the couplings cannot find the correct orientation and coupling procedure fails. Axial force is much more than needed for a successful coupling, and reduction of the force would increase reliability of the coupling process. Better control of axial force could be achieved with a bigger motor and smaller gear ratio. Alternatively mandrel torque could be increased, but this would require changing the open loop voltage control of mandrel motor to a closed loop speed control.

- Overall margin in mechanical operations is too low.

- Sensor feedback from the following sources is too low (more accurate information is needed to ensure reliability):
    - Tool carousel slots: tool present and in the bottom?
    - Pipe couplings
    - Tool coupling

5.3 The MIRANDA study and tests

In January 2003, ESA announced the 'AURORA Student Competition' [26]. The purpose of the student contest was to allow graduate and undergraduate students from European Universities to propose, on a competitive basis, innovative ideas, design concepts and new enabling technologies that are relevant to Aurora programme goals and scenarios. The student contest was organized by ESA with the support of primary Academic Institutions in Europe and the involvement of space experts. It consisted of selected student teams, one for each European University in any given category, developing innovative ideas and approaches on aspects of the Aurora programme that was presented and judged by a panel of senior experts in September 2003.

The author of this thesis acted as a team leader of HUT Automation Laboratory's team, the 'MIRANDA' team [27]. The purpose of the MIRANDA study was to design, build and test a setup for drilling, sampling, and in-situ analysing of a simulated Martian subsurface regolith. As the time and resources of the project were restricted, the team made some assumptions, and constituted the plans on some already existing designs for drilling subsystems. The starting point of the study was ESA's MRoSA2 Mars rover prototype with a deep driller.

5.3.1 Theory of rock drilling process

Basically, a rock excavation process can be divided into two stages, which can be done either simultaneously or separately. The first stage is breaking the rock by some means, and the second stage is the removal of debris from the borehole. If the cuttings are left in the borehole, they begun to crush and pulverize into even smaller particles, leading to inefficient drilling. The drilling process should produce as large cuttings as possible to excavate the borehole with minimal energy. However, this is a compromise with the available torque for drilling, since the required torque is somewhat proportional to the particle size [97].

Rock excavation devices remove rock by one of four basic mechanisms [99], as shown in Figure 61: thermal spalling, fusion and vaporization, mechanical stresses, and chemical reactions. Some advanced drilling tools utilize exotic systems such as lasers or electron beams to melt or vaporize rock. Also explosives or electrohydraulic discharges can be used to impact and shatter rock [98].

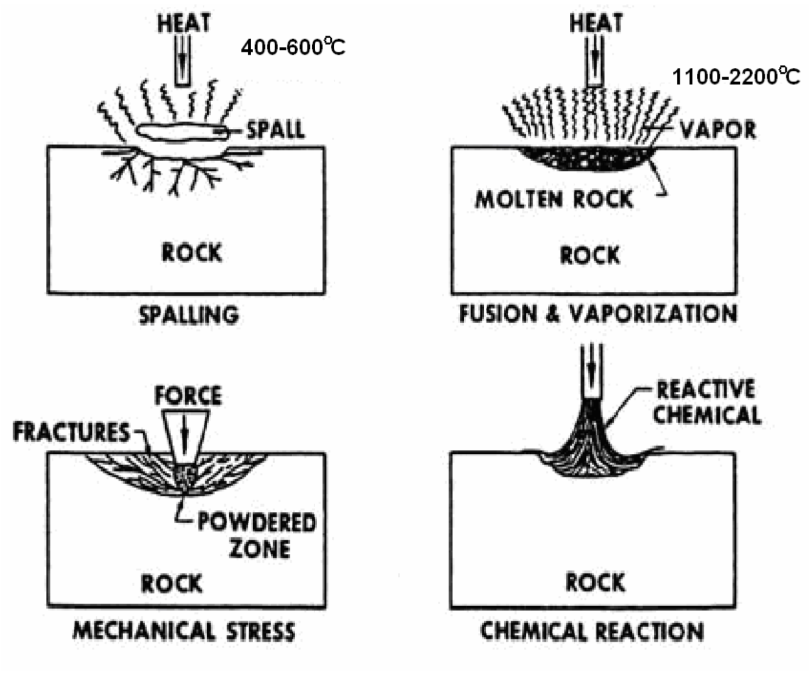


Figure 61: Basic rock excavation mechanisms [99].

Drilling systems, which melt or vaporize the regolith, such as laser and electron beams, can not be used for Mars soil sampling, because they produce a change in the properties of the target material. This is not allowed, since the main reason for drilling is to acquire a pristine rock/soil sample for analysis. This same reason prevents the use of thermally fracturing excavation methods and chemical use, because those tools might produce sample melting or chemical alteration.

The only possible method for rock excavation is then mechanical scooping or drilling. Scooping may be done only in porous ground, and rocks need to be drilled for acquiring samples. The most effective drilling methods are rotary, percussive (hammerinkg), or rotary-percussive drilling. This thesis concerns only the rotary drilling method, even that some concepts are explained which uses e.g. ultrasonic percussive drilling (see Chapter 3.4.5, the USDC device). Rotary drills use diamond, tungsten carbide (WC), boron nitride (BN) or other hard material cutting teeth, and a mechanical system for removing the cuttings and rock core from the hole, such as the auger. It is also notable that even though diamond is the hardest of known materials, it has one drawback; diamond is carbon, and when the diamond teeth pulverizes even in small amounts to the target while drilling, it leaves traces of carbon. This might confuse some of the instruments, which are looking for carbon-based signs (of life). However, this is a question of the measurement principle of the analysis instruments.

One clear benefit of using conventional rotary drilling method is that cutting removal can be accomplished using an auger (in the sides of the drill string, see e.g. Figure 49a). Rotary drilling has also some drawbacks. Rotary drilling requires both significant weight to push the bit against the rock surface and torque to turn the bit, unlike for example the other methods presented in Figure 61.

There are some important terms and variables, which are used in drilling calculations and in the drilling tests that are explained further in this thesis. These terms and variables are explained in below:

- **Drilling** and **cutting motion** is a relative motion between the drill tool and the target surface. Usually the tool rotates, but it can be also the other way. For example, in the VTT drilling tests, explained in Chapter 5.1.1, the tool was stationary, and the target rotated.
- **Drilling speed, v** (m/s), is here equivalent to the rotational speed (and proportional to the **angular velocity ω**). This is the speed that the drill bit's teeth scrape the target surface).
- **Feed, f** (m), is the lateral distance travelled by the tool during one revolution. The term feed can be used also to define the total feed of the drill tool in a given time unit. However, the total feed is usually referred as the **drilling depth, d, (**m) or **depth of cut** (m).
- **Feed speed,** is the lateral speed of the drill tool (m/s). Also "speed of penetration" is used.

- **Area of cut, A_C,** is the surface area that is being excavated. In cylindrical, non-hollow drill tool this is: $A_C = \pi r^2$, and for hollow drill tools, such as the MRoSA2 drill tool (until the core blade reaches the rock), $A_C = \pi r_{outer}^2 - \pi r_{inner}^2$.
- **Volume, V,** (m^3, also cm^3 and mm^3 are used) of drilled material, is equal to $A_C \cdot d$.

The variables and basic equations are explained in below:

Material Removal Ratio (MRR)

The MRR is defined as the volume of excavated material from the borehole. The unit of the MRR is m^3 (also cm^3 and mm^3 are used). Equation (1) for calculating the MRR is shown below:

$$MRR = A \cdot f \cdot N = \frac{\left(\pi \cdot D^2\right)}{4} \cdot f \cdot N \qquad (1)$$

where:

A	= area of cut
f	= feed (distance/revolution)
N	= number of revolutions
D	= drill bit diameter

Specific Drilling Energy (SDE)

The energy consumed in removing a unit volume of material is called the specific drilling (or cutting) energy, SDE. Energy (or work) is force (F_c) x distance (L) over which the force acts. The volume of material removed (per revolution) is V = h ωL, so the specific cutting energy can be written as [126]:

$$SDE = \frac{F_C L}{h \omega L}, \qquad [J/m^3] = [N/m^2] \qquad (2)$$

where:

F_c	= cutting/drilling force
L	= distance (circumference distance, or teeth travel)
h	= height (depth)
ω	= angular velocity

It is common to use also [J/cm³] units or even [Wh/cm³] units, depending on the reference.

Specific Drilling Power (SDP)

The term 'Specific Drilling Power' (SDP) is used especially in Tecnospazio's (TS) drilling tests (Chapter 5.5.2), and it is similar term to the 'Specific Cutting Power' (SCP), used commonly in machining industry. SDP is a specific variable for determining the cutting efficiency with respect to different drilling parameters. SDP (W mm^{-1} minutes) indicates directly how much power (W) is needed to achieve a corresponding speed of penetration (mm/min.). SDP depends on properties of target material, tool geometry, rotation speed, thrust, and drilling method (rotary, percussive or rotary-percussive). In the TS tests all other parameters were kept constant, but effects of drill rotation speed and feed rate were 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 [4].

$$SDP = \frac{P_{Drill}}{\left(\frac{d}{t}\right)} = \frac{P_{Drill} \cdot t}{d}, \tag{3}$$

where:

P_{Drill} = Drill input power
d = borehole depth in given time (mm)
t = drilling time (minutes)

Drilling Strength (DS) and Specific Energy (SE)

All of the cutter load results presented here have been normalized by the cross sectional area of the cut, A_C. This results in units of specific energy or stress which can be taken as a measure of the strength of the rock and its resistance to cutting. The normalized indentation load is referred to as drilling strength (DS):

$$DS = F_A / R_C \tag{4}$$

and the normalized tangential load is referred to as specific energy (undimensional):

$$SE = F_T / R_C \tag{5}$$

Drilling strength provides a measure of the weight-on-bit required to achieve a given cutter penetration while specific energy is a measure of the bit torque. Note that the units of specific energy J/m^3 are dimensionally equivalent to strength unit Pa [127].

5.3.2 Test setup

The test setup was built at the facilities of the HUT Automation Technology Laboratory for the purpose of participation for the ESA's Aurora Student Competition. Team MIRANDA designed and assembled test setup described in this section. An illustration of the principle of the test setup is shown in Figure 62 and a photograph is shown in Figure 63. It consists of a 130 cm 'regolith column' filled with sand, gravel, dust and stones. Material can be loaded and unloaded through the transparent and removable front plexiglass covers. The sample column can be moved independently from other measurement setup, including drill mountings.

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.

The sample to be drilled into is prepared inside a transparent vertical box 1.2 m high (see Figure 62 and Figure 63). 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.

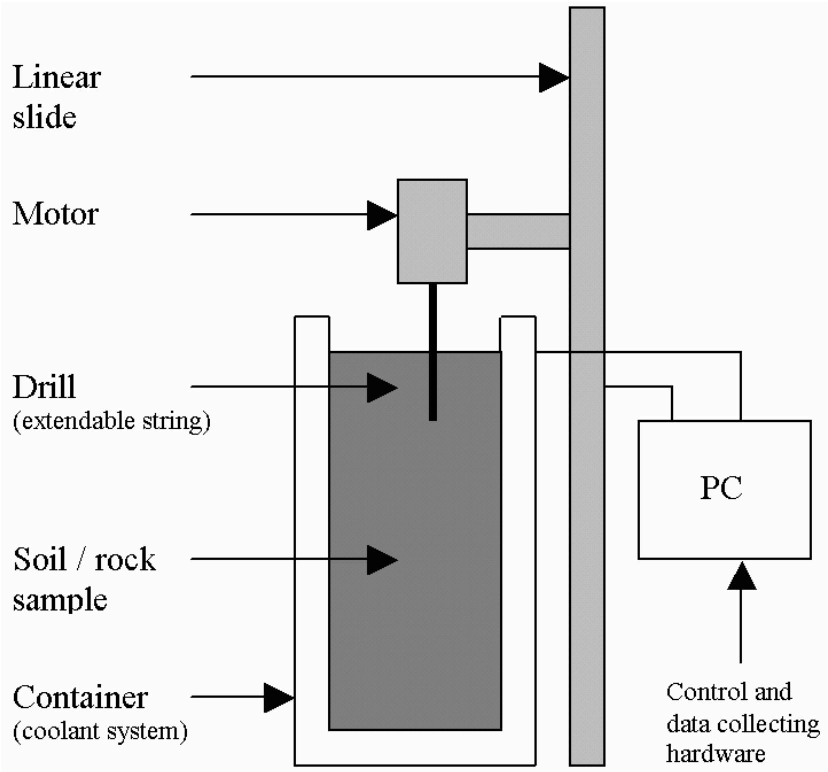


Figure 62: The principle of the MIRANDA drilling test bench.

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.

With the test setup designed and built, the MIRANDA team conducted a series of drilling tests. Several drilling parameters were monitored during the tests. These parameters include:

- required torque
- power consumption
- feed force
- drilling speed
- drill rotational velocity

These test results are essential knowledge in defining and designing future planetary deep drilling projects, because currently there are no wide test results nor common test policy for miniature sized planetary drills. The test setup produced also provides possibilities for further study on drilling and sampling equipment (e.g. the MIRANDA-2 study, explained further in this thesis).

Additionally, the work of the MIRANDA team can be used for designing better drill heads for the MRoSA2 DSS and other future planetary landers with drilling capabilities. Team MIRANDA is providing the basic research needed to design in-situ analysing tools, which can be drilled down through the borehole, and which can in the future perform in situ analysis like optical microscopy, spectroscopy, temperature, magnetic measurements etc.

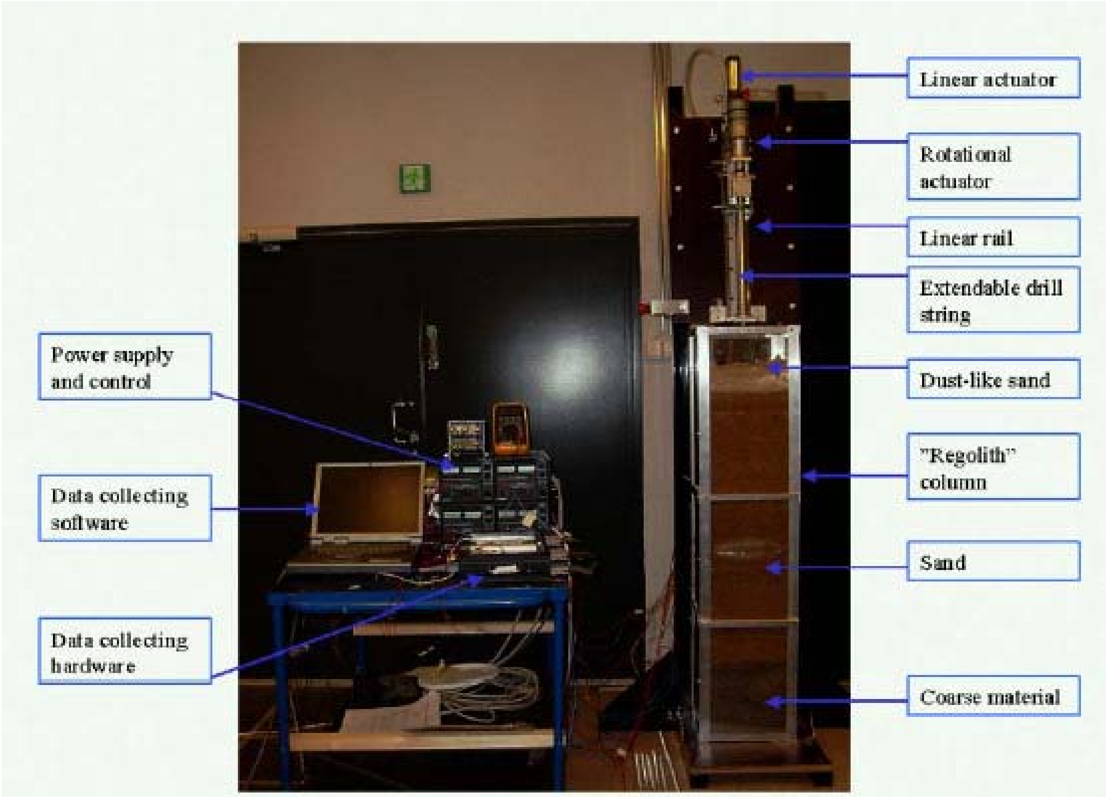


Figure 63: MIRANDA test setup (Image: MA).

The drill is attached to a linear actuator above the regolith column, with which the axial location of the drill can be controlled and measured to an accuracy of 0.278 mm. The drill is mounted on a sled, which slides along vertical linear guides driven by a ball-screw and an electric motor. The sled carrying the drill is isolated from the moving part of the linear actuator with the aid of a spring assembly. Drilling force is generated by stretching the springs. This method allows smooth control of drilling force, reduces force peaks on the drill tool and isolates the linear drive from drill induced shocks and vibration. Further the linear drive can be switched off during most of the drilling time which reduces overall power consumption. The calculated angle resolution in measuring the angle of the drill head is 2.27 deg. Minimum and maximum drilling force can be inserted via a graphical user interface (GUI).

One advantage of driving separately the drill vertical location (or drilling force) and drill rotation is to have all available power on the drilling. This is achieved by pushing the sledge down with the linear actuator up to a point when the load on the springs has increased above the limit set by the user on the user interface.

The drill tool is similar to the one presented in the MRoSA2 project. It has a hollow coring tool layout drilling a 17 mm hole leaving an 8 mm core inside. The tool is 20 mm long (inside length of the sample chamber), and the upper end holds a core cutter bit, that starts to grind the upper end of the core as soon as the tool has advanced into sufficient depth inside a rock. The ESA requirements for the ExoMars/Pasteur drill tool asked for a core 20 mm long and 10 mm in diameter [82,83] at the time of MIRANDA tests (later the length requirement was changed to 40 mm Chapter 7).

Thus the MIRANDA corer tool is in size quite close to the ExoMars requirements, and test results can be considered applicable for further ExoMars/Pasteur development. A closer look at the drill sledge is taken in Figure 64 where the setup is shown on both the flexed and unflexed states of the force control springs. The drill rod is attached to the drill mandrel with a drill attachment collar. A coupling is mounted between the gear and the drill rod to avoid transforming any lateral stresses from the drill string to the motor.

The drill rotational motor used was Dunkermotoren GR 63x55 (24V), the rotational gear was Dunkermotoren i=20.25:1, and the encoder US-Digital E2-500-315-G. Linear guide used was SMC Ball screw with a linear ball guide LTF8YFDNH-500-X10. It had the length of 500 mm and a pitch of 10 mm/revolution. Ball screw motor was Antriebestechnik M24x40I, the gear P42/46:1, and the encoder IGO 200/2.

Suppose a situation where the drill string is driven down by the linear actuator against a hard surface. This causes a tension to build up on the force control springs (right side of the Figure 64). Springs thus generate the force exerted by the drill on the surface (added with the weight of the sled) and this is how the drilling force can be controlled. A potentiometer is used to measure the stretching of the springs. The spring parameters were measured and the potentiometer calibrated so that the force exerted by the drill could be calculated. Spring constant of the two 'force controlling springs' amounts to a total of 1.62 N/mm. The mass of the drill sledge is 4.7 kg (resulting in 46.1 N down force), and the spring pre-tension is 2 kg (19.6 N), which means that this setup cannot measure forces below 65.7 N (equalling to 6.7 kg mass) in any accuracy as there is no load on the springs at such a low levels.

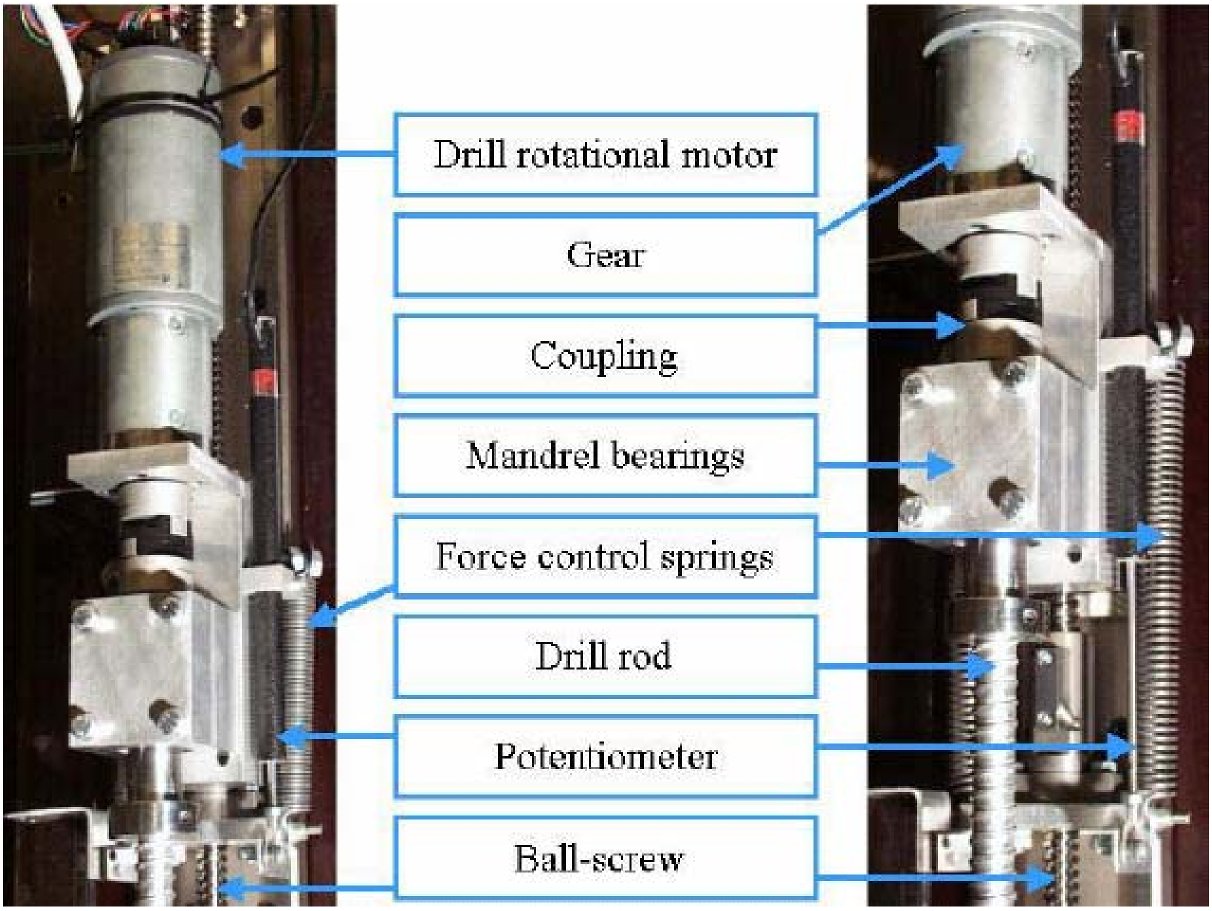


Figure 64: Force control springs in action. On the left side of the image, the springs are relaxed and no additional force is transferred to the drill head. On the right side of the image the sledge is driven downward by ball-screw, which has caused the force, control springs to extend. Potentiometer measures the extension of the springs, which can be interpreted into the force exerted.

MicroDAQ data acquisition hardware is used to acquire the voltage and counter values from the measurement devices. Measurement data is transferred via USB to a portable personal computer (PC). Data collection software prints the data on a text file. Data from the test cases were later analysed in Matlab. The drill controlling and monitoring software was specifically coded for this project on C++.

The graphical user interface (GUI) of the data collecting software is shown on the Figure 65. On the user interface, logging of the results can be started and stopped. Current timestamp (seconds from the beginning of the test run) is shown, as well as the drill rotation voltage and the drill rotation current, the potentiometer count scaled to show the spring elongation, and a the current drill force computed from that spring load. ‘Rele ON’ and ‘Rele OFF’ buttons switch a relay (‘rele’ in Finnish), which switches the drill downward driving authority between automated and manual modes. In the automated logging mode, the drilling force is kept automatically between the limits user has set on the ‘Lower Force Limit’ and ‘Higher Force Limit’ fields. Thus it is possible to leave the system unattended for long drilling periods and yet feel comfortable that the force will stay between the desired limits. A mechanism like this could also work on the Mars, as the system could be left to drill with the desired parameters even when no communications connections to the Earth were available at the moment.

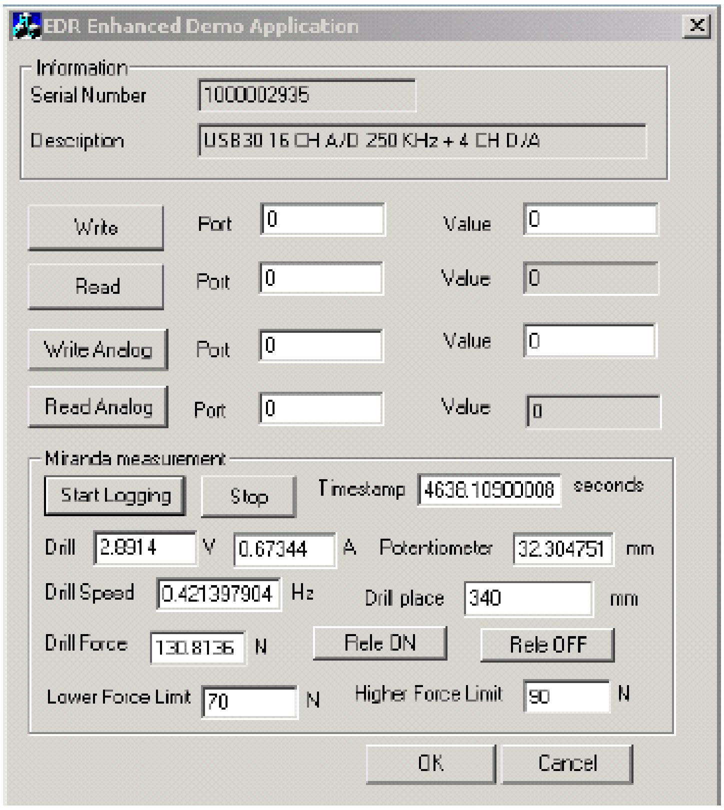


Figure 65: Data collection software GUI.

A typical drilling session starts in filling up the regolith column with the chosen simulant material. After this power units are turned on, and the drill is driven manually to its topmost position, where the linear rail counter is reset. Adjusting the drill rotational voltage sets a suitable drill rotational velocity. The required drilling force is set on the user interface. After ‘Start Logging’ button is pushed, the drill starts advancing into the simulant material and data is being collected. Data is read ten times a second. In a usual test drive only every tenth data row is written into file. These quantities include the time, force controller spring elongation, drilling force, drill voltage, drill current, potentiometer output voltage, potentiometer excitation voltage, sledge location and drill rotational frequency. Pressing the ‘Stop Logging’ button stops the drilling session.

5.3.3 Imitating the Martian regolith and surface conditions

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. NASA's Mars Odyssey orbiter has proved the possibility of water ice near the surface [141], which might lead to a harder drilling. Even if there would be no rocks in the drilling spot, the soil might be tied tightly by ice.

For best estimate for 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 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. Tested rock materials were: mafurite (Uganda, Kyambogo Crater) as an example of igneous stone, and carbonatite calcite (from Finland, contains mainly calcite) as an example for easier rock drilling. Water ice was supposed to be used to bind the loose soil and to simulate actual hard, cold ice, which the drill would hopefully face. However, the ice drilling was cancelled due to the time constraints.

The team used the ExoMars rover's Pasteur payload's System Requirement Document (SRD) [82,83] as a baseline for the tests. The Pasteur SRD states average power consumption of the drill to be 10W. In designing and testing the drill, this was kept as baseline and most of the tests were run on these low power levels. In addition, some tests were performed at higher power levels, as the Pasteur drill system is expected to consume up to 40W in peaks and over 70W in emergency situations (mainly if the drill gets stuck) [83].

Martian gravity

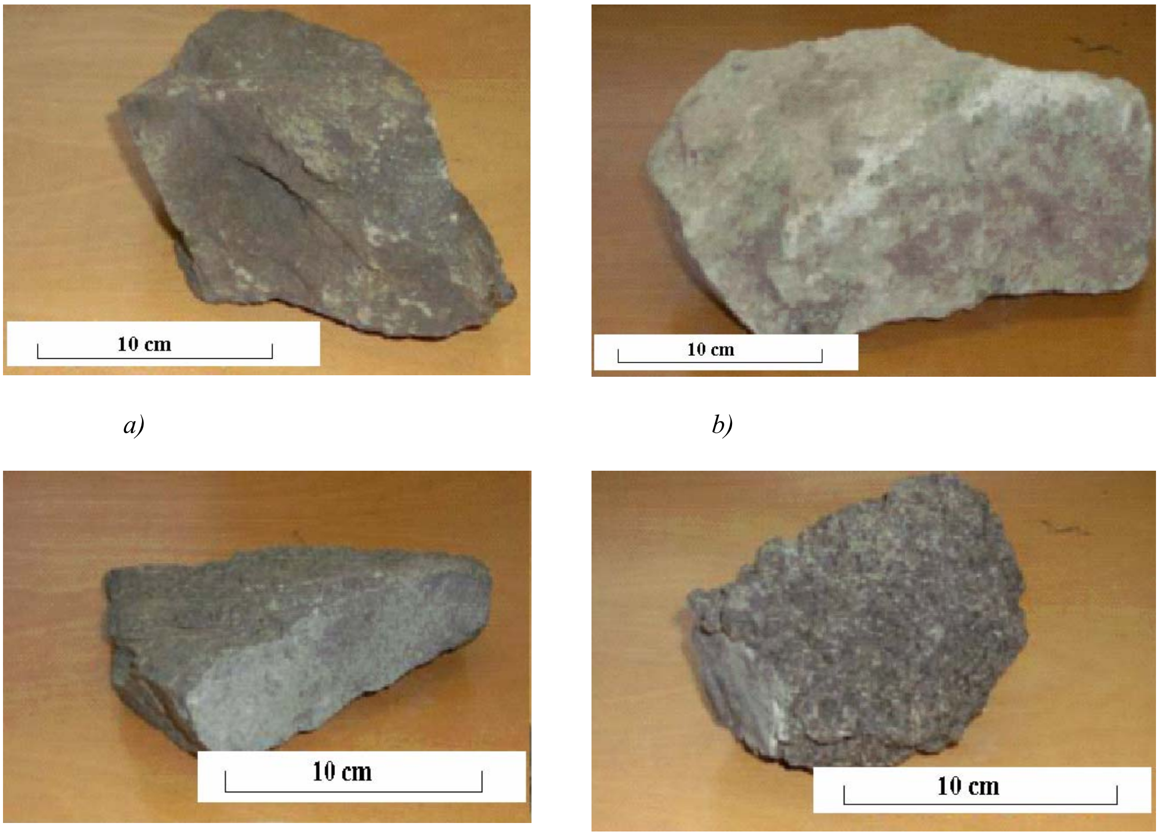
Martian environment poses severe challenges to any surface instruments. For a drilling device, most constricting is the surface gravity, which on Mars is only 0.379 times that on Earth. This leads into a decreased drilling force with a small lander if no anchoring devices are used to provide extra force in addition to that of lander mass gravity.

Drilling first smaller holes where 'anchors' could be fastened would provide an opportunity to pull the lander towards ground and thus increase the available drilling force. Fragile and sandy Martian soil might not provide reliable anchoring spots. Also, one could use the robotic arms on a lander to gather stones and gravel on the top of the drill, where a lightweight cone could be spanned for this purpose. Also other solutions are bound to exist, and a further study should be conducted to gain optimum drill force also on light landers.

ESA's ExoMars mission anticipates a rover system of 200 kg mass [83]. On Mars weight of the rover would then be 75.8 kgf, or 743.6 N. It is clear that for stability reasons applied drilling force must be clearly below this. During the MIRANDA drilling tests, the drilling force was maintained between 100-200 N, which is less than 27% of the rover weight. Thus the drilling parameters for MIRANDA tests were compliant with ESA ExoMars requirements.

Rock drilling material

In order to test the drill in as authentic Martian environment as possible, stones corresponding the ones on Mars (of course this is still just an estimate) were acquired. Four different stones, mafurite, carbonatite, diopside and diabase (see Figure 66 and Table 20) were chosen to serve as test subjects. Judging from the recovered Martian meteorites and existing planetary mission data, the types similar to all of them could exist on Mars.



a) *b)*

c) *d)*

Figure 66: a) Mafurite (Uganda), b) carbonatite (Siilinjärvi, Finland), c) diopside (Finland), and d) diabase (Finland).

The mafurite stone used here was collected during the Finnish East African Expedition (FEAE) on 14th of July 1952 (sample no: 40) [85], from Kyambogo Crater, Bunyaruguru field, Ankola, Uganda. Mafurite, especially this sample, is quite similar to basalt in its origin. Mafurite is an ultrabasic (chemical analysis: SiO_2 content < 45 m-%, while basalt has SiO_2 content of 45 to 52 mass-%) rock consisting of phenocrysts of olivine and minor pyroxene in a groundmass of diopside and kalsilite with small amounts of perovskite, olivine and biotite. Basic difference between basalt is, that basalt contains plagioclase, but instead of that, mafurite contains kalsilite. The drilling properties of mafurite were thought to be quite similar to that of basalt (however it is thought that the mafurite sample contained glass, which made it difficult to drill. This is explained later in MIRANDA results).

The carbonatite (calcite) sample, collected from Siilinjärvi (Finland), contains also harder apatite, but is mainly composed of fragile calcite [84]. Stones near the Martian surface, that have been weathered and eroded by the extreme environment, could be similar to carbonatite in the hardness as well as in the other drilling characteristics.

Diopside, Ca (Mg, Fe) Si_2O_6, can be found in various places between South Africa and Outokumpu (Finland). The hardness of diopside is about 6 Mohs.

Diabase is similar to basalt in its mineral content but differs from it in structure. It might very well exist in the lava fields of Mars as a slow cooled core of a lava bed. Having hardness of 5.8 Mohs, Diabase is only a bit softer than diopside. Furthermore, even a small weathering of the surface greatly reduces the hardness of diabase [85].

Table 20: Test rock properties. Note that granite was not used in MIRANDA tests, but in MIRANDA-2 tests.

Rock	Hardness MPa / Moh	Density kg/m³	Notes
Mafurite	>250 / >6	2545	Igneous rock from Uganda, Kyambogo crater.
Calcite	~50 / 3	2710	
Diopside	~120 / 6	3260	
Diabase	~220 / 5.8	3080	Finnish rock, “Varpaisjärvi diabase”
Granite	~180 / 6.3	2580	Finnish red granite, “Karelia Red”, used only in MIRANDA-2 tests.

5.3.4 Test results

Testing was performed by the MIRANDA team in June and July 2003 regarding the ESA Aurora competition. The author continued tests in August to November 2003 for the purpose of this thesis. An overview of the tests done during the MIRANDA project and later drillings is described in this chapter.

Preliminary results and testing of the configuration

The first real full-scale rock-drilling test was done on June 2003. Target stone was calcite, as it was the easiest to drill among the four different stones. The drilling test was done just to test the system and no exact measurement of drilling parameters was performed (the motor input voltage was roughly 15 V, current roughly 0.9 A and thrust roughly 100N). The drilling lasted 30 minutes, and the drilled hole was 25 mm deep. The core sample was also drilled from its top, and it was cut in one piece spontaneously as was intended.

In the second test, the target rock was again calcite. The drill rotary motor voltage was kept in 14.8 V (voltage scale is 0…24 V to the motor). When started, the motor draw 0.78 A current, and the average current was 0.8 A (during the first 8 minutes of drilling). The average current rose to 0.9 A during the next 7 minutes of drilling. Thrust force was kept in 100 N, with a variation of ±10 N. At one point the thrust was increased to 150 N for a couple of seconds (for test purposes; the maximum thrust that is possible with current configuration is 230 N), which increased also the current drawn by the rotary motor to 1.2 A. The drilling was done with the MRoSA2 drill tool.

The drill penetrated 15-18 mm to the calcite stone. The surface of the calcite was inclined, so the drill penetrated 18 mm to the stone in the “uphill” side, and 15 mm in the “downhill” side, as shown in Figure 67. The depth of the sample chamber of the drill tool is 20 mm, so this test did not reveal the drilling properties of the sample chamber tooth. Although the core was not completely drilled, it still became crushed because of the weak structure of the calcite stone. Instead of a single piece of rigid core, the drilling produced several pieces of the core sample.

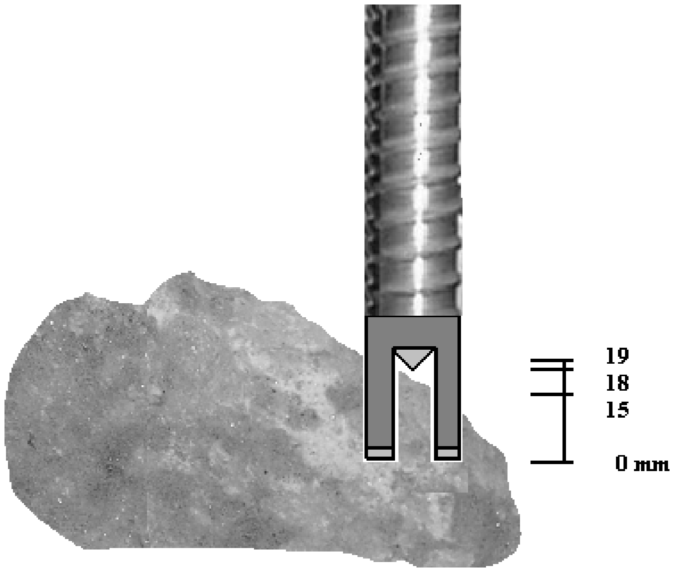


Figure 67: An illustration of the first drilling to calcite stone (Image: MA).

During the first and second tests the sample chamber inside the drilling tool did not manage to capture the sample, but only some drilling dust. The sample (or sample pieces, as was the case in the second test) was left in the bottom of the borehole.

Drilling power was 11.8-13.3 W during the second drilling test, resulting total energy consumption of 3.2 Wh (11.52 kJ) in 15 minutes period. It is notable, that the drill drilled only the "ring" shaped hole, but not the core bit yet, because the drilling was stopped before the core cutter blade touched the rock.

These tests proved that the MIRANDA concept is working and the PC program could gather the drilling data.

Drilling into rocks

The setup was tested with plain rocks lying on the top of the regolith column. All of the stones were drilled to a depth of about 1 cm, rotating the drill with 15 V, which corresponds to the drill rotational frequency of approximately 1-2 Hz (60-120 rpm) depending on the resistance of the soil/rock. Current was running in between 0.5 and 1.5 A, resulting on the average power consumption of about 15 W, which is very plausible to achieve on the future Mars landing missions.

At one occasion, when touching down with the rock, there was especially unequal surface under the drill bit. The drill string started to wobble violently and there was a risk of damaging the equipment. Thus the safety release switch was immediately triggered. The measurement software recorded this unsuccessful start and the result is shown in the Figure 68, where also the voltage and current reading of our test setup is demonstrated. It can be seen that as the drill was guided in the wrong way, the power consumption began to shoot up but immediately came down when the emergency stop was triggered after 18 seconds from the start of the experiment.

Figure 68: Emergency stop performed in a real situation when the drill started to wobble violently. The drill rotational voltage (blue), current (red), and power (black) are shown.

A drill sent to Mars on a mission should have an automated feature that cuts the voltage supply and freezes the drill whenever the power consumption increases dramatically. Thus the situation could be reasoned and the monitoring data studied in Earth before deciding wether continuing on the drilling would be safe or not. On plain rocks, the effect of drill rotational speed to the power consumption was studied. Results for calcite and mafurite are shown in Figure 69. The drilling force was kept in between of 140 and 160 N. As expected, the power consumption linearly rises with the rotational frequency. It can also be seen, that the measurement error rises with the rotational frequency. This was tracked down to the potentiometer being faulty. Old potentiometer gave wrong output when on the move or vibration. During the drilling of a harder substance, there is always some vibration. However, as the calibration of the potentiometer was done in a static state, this fault was not noticed until the beginning of the measurements. This potentiometer error reflects also to the drilling distance as well as the drilling force calculations. Also the strong DC current of the drill motor disrupted the potentiometer, which is why a digital measurement rod would be more accurate in its place.

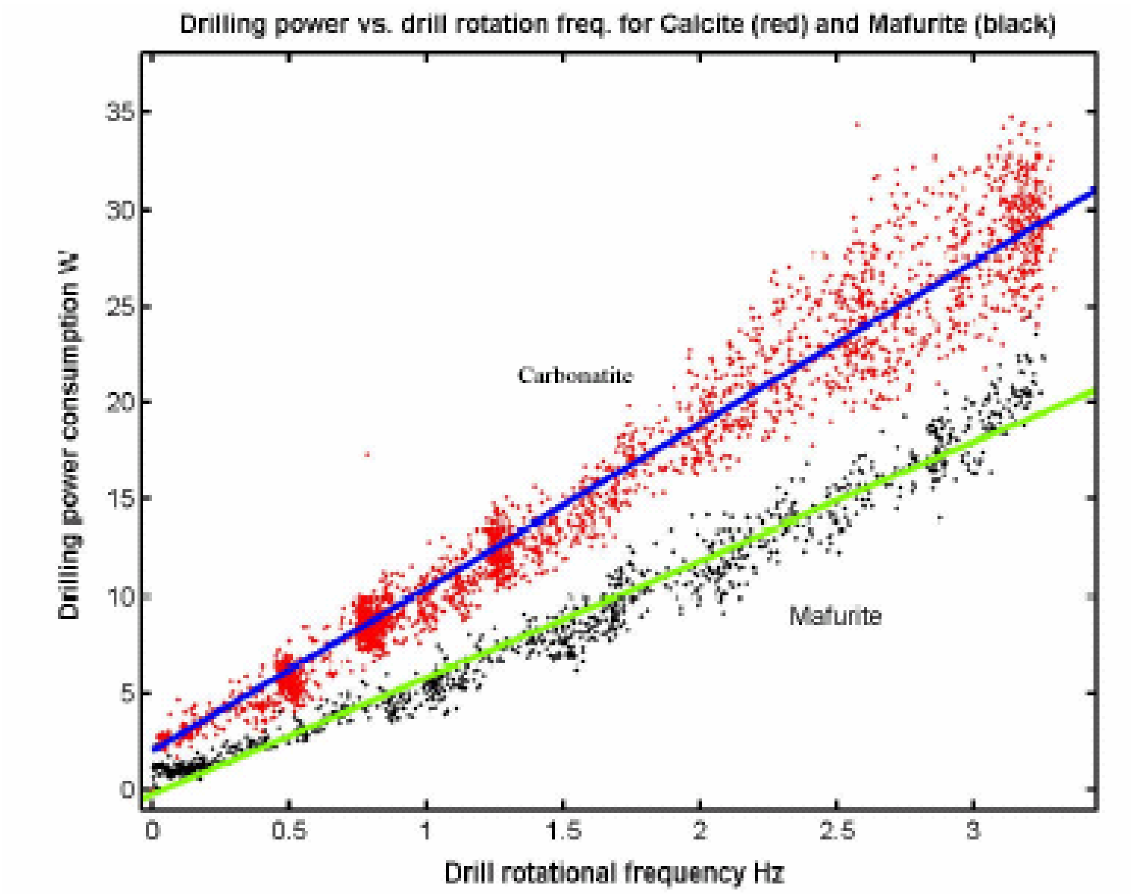


Figure 69: drilling power as a function of drill angular frequency (speed in revolutions per second, Hz). Red dots indicate measured drilling power values as a function of drill angular frequency for the carbonatite (red dots), and the black dots for the mafurite. A linear fit (Matlab 'polyfit', resulting in average of 10% error margin here) is also shown in blue for carbonatite and in green for mafurite. Drilling force was kept between 140 and 160 N.

Mafurite is very hard stone and the drill very easily gets distracted off its course when facing the hard and slightly uneven surface of the mafurite. Once getting a hold of the stone, the drilling continues smoothly. To make initial starting easier one could start the drilling with a sharp pointed 'starting head', and continue with another coring head. However, the test setup demonstrated almost 100% reliability in starting the drilling, even into hard stones and even with the coring tool, without any sharp centering point. This indicates that drilling capability of a coring tool must not be underestimated.

On drilling the carbonatite, grip was relatively fast achieved and a sample was retrieved successfully. Carbonatite is by far the softest of our stones; this is clearly shown in the easy entry and fast drilling speed. Carbonatite does not form a very solid core, at least not in this diameter. Often the core was broken by itself and it remained at the bottom of hole in the form of few fragments. However a couple of solid cores were also collected successfully. A larger core diameter (~15 mm in diameter) would allow more reliable core formation.

Diabase was somewhat problematic. Due to the uneven surface of the rock, beginning of the drilling was very hard. Porosity of the stone also caused the drilling depth to advance in steps (Figure 70). Nevertheless a solid core sample was collected.

Diopside, being the smallest of our test stones, started to vibrate first violently, but after the drill got a hold of it, this test surface drill produced a perfect sample left on the core cavity of the drill head.

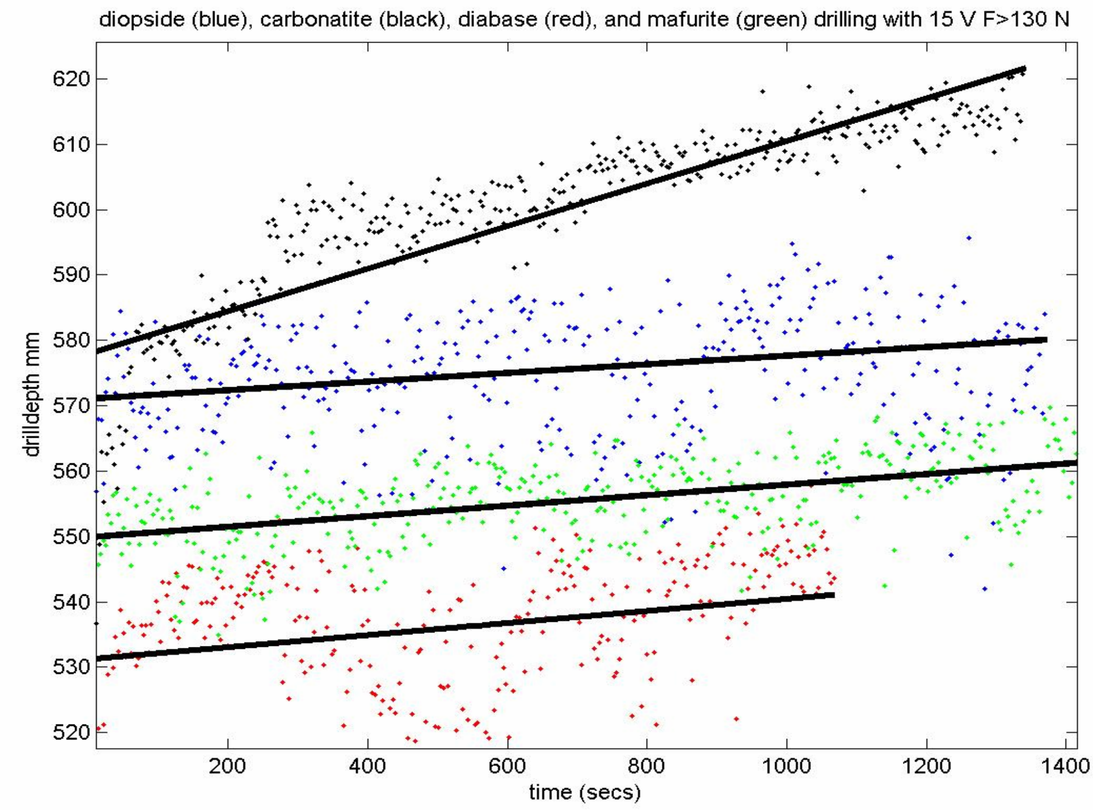


Figure 70: Drilling results for diopside, carbonatite, diabase and mafurite. The depth indicates the position of the drill spindle. Due to the noisy data an approximation of 15 % error margin is used in this linear fit (Matlab 'polyfit'). Diopside and mafurite gave the most linear results here.

Drilling into rocks through a sand layer

On Mars, dust has covered the entire surface (exluding the polar caps). Rocks near the surface are sterilized by a strong UV radiation, so it is needed to dig deeper to find any signs of life. When drilling samples from the soil, it is essential to study the effects of a sand layer covering the test subject.

Problems might be introduced by gravel, which might be blocking and disturbing the drilling. Also, sample-lifting capabilities might suffer, especially as the drill head used in these experiments is not designed to separate or lift a sample. In this section, a 10 - 20 cm layer of sand covered the stones. Three biggest of the MIRANDA test stones were tested in this setup and the results were as follows:

The first test was done by drilling the mafurite, buried under 5 cm of coarse, inhomogeneous sand and 10 cm of smooth 'beach' sand. Drilling voltage was chosen to be 3 V and the drill force 100 – 120 N, corresponding to a 30 kg drill mass on Mars, which would be achievable even with the very smallest of Mars landers. At first, after easily sliding through the sand, drill head had some problems of getting a good start on the mafurite and wobbling occurred. After a short while drill stabilized and was left to drill for over three hours. Drill movement caused the sand in the near vicinity to separate so that closest to the drill near the surface largest grains gathered. This power level of minimal 3 W was found to be inadequate for drilling mafurite, at least in this time scale. Drill had scraped a small dent on the surface of the rock and drill head moved down 2.5 cm during this drill session. This indicates that the rock itself has been pushed deeper into the sand during the drilling. This might very well happen also when drilling into small rocks on the Mars. After the drilling session we tried manually to push the rock down but were not able to introduce any changes in its position. As a second step, we increased the drill force up to 120 - 140 N and raised the drill voltage up to 5 V. With this setup, the drill had even more trouble on getting a good start, but settled after a while. Power still was not enough for this time scale, and nothing much was done. Only a 1 mm dent was achieved on the surface of the rock during the one hour with 7 W of drilling power.

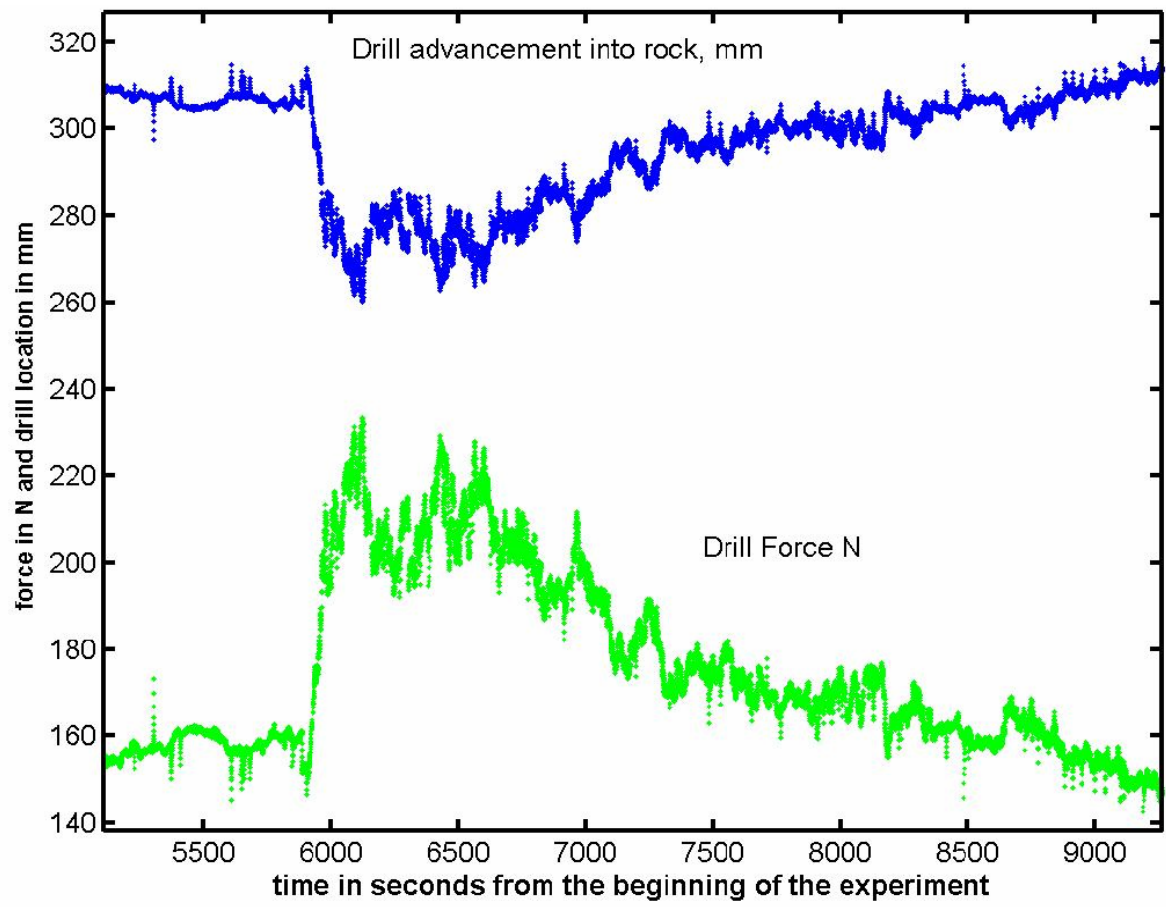


Figure 71: Mafurite stone lifts up for unknown reason and the drilling force shoots up to 200N. The location indicates the position of the drill spindle.

For the third run on the mafurite, we drove the drill slowly through the sand until contact was established. In the beginning we let the drill make a start at about 80 N and after stabilization slowly increased the power up to 140-160 N (average was maintained around 150 N). Drill wobbled more in the beginning than for the other rocks, and because of that a crater of sand formed around it. A bigger gravel was separated in the crater. No core sample was retrieved and only a hole of less than 8 mm was produced in the drilling session, which proceeded with 15-20 W power for 150 minutes. There was one peculiarity during the last of the mafurite drills: after 6000 seconds (or one hour and forty minutes), the force suddenly rose from below 160 N up to over 200 N. A closer data analysing revealed that at the same time the drill head was actually pushed up from below by more than 2 cm. This is shown on the Figure 71 above. One explanation for this could be that due to vibrations induced by the drill, a cavity would have formed below the stone. The stone would then have dropped its other end into this cavity and in the process pushed the drill head up. Slowly during the next hour the stone is pushed back to its original angular position. The stone warmed up considerably during the drilling. ExoMars Pasteur requirements demand for pristine and also thermally undisturbed samples. The test performed indicates that there are still issues to be considered about the allowed heat generation, drilling power to be used, drilling depth and drilling time available. Possibly some means to cool down the drill head are needed.

The carbonatite was easier to drill than mafurite. Drill was driven to the calcite slowly and when contact was achieved the beginning was allowed to form with 80 N. After situation quickly stabilized, force was raised to 140-160 N. A sample was returned to the surface with the drill head: two solid pieces of carbonatite of about 4 mm in diameter and a considerable amount of dust. A 21 mm deep cavity was visible on the stone after only 15 minutes of drilling. Figure 72a shows the drill head rising from the sand, holding a sample of carbonatite. Notice the tidy hole produced. Energy consumption of 15 minute drilling session was less than 3.8 Wh.

a) *b)*

Figure 72: Drilling Calcite through a sand layer. The drill is 17 mm in diameter. Side view is shown in figure a), and top view in figure b). The auger threads are covered with calcite dust from the buried rock (Image: MIRANDA Team).

Diabase was much easier to drill when buried in the sand. With 140-160 N, and 15V on the drill rotation produced a very positive result on diabase. A perfect 15 mm long core sample was retrieved. Drill head penetrated 25 mm into the stone during this 50 minute drilling session. A picture of the drill head being retrieved from the depths of sand, carrying a sample of mafurite, is shown in Figure 72b. The diabase dust was raised to form a barrier around the drill hole. The diabase sample was returned to surface with only 14.5 Wh.

Figure 73: Drilling Diabase through a sand layer. The drill is 17 mm in diameter.

Summary of drilling the buried stones

In drilling the stones buried in sand the differences between the materials were clearly highlighted. As seen on Figure 74, we were able to drill into carbonatite more in a quarter of an hour than on the diabase during almost an hour. Mafurite was by far the hardest rock, and only a few millimetres were achieved during several hours of drilling.

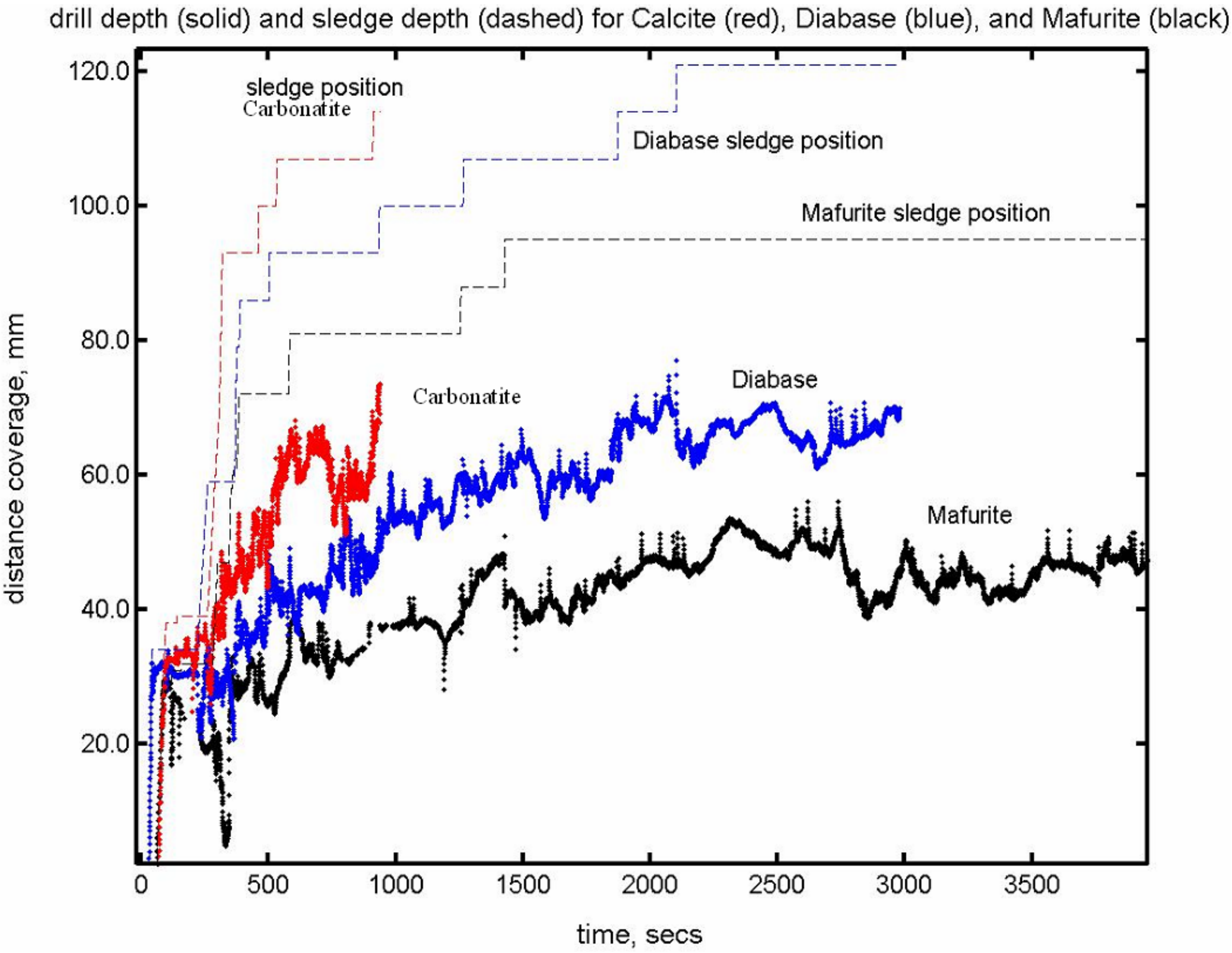


Figure 74: The advancement of drill head (solid) and the sledge position (dashed) for the three biggest sample stones. (Noise generated by a faulty linear potentiometer is visible in the drill depth graphs.).

In these tests, the drilling power stayed within about 10-20 W, which was achieved by steady drill head rotational voltage of 15 V, and a drilling load constricted within 140-170 N. The results of these drilling sessions are summarized in Table 21. The time consumption of the drilling is first shown, along with the resulting hole depth on the stone, which was measured once the stone was dug up after the drilling. Third column shows how much the stone sank to the sand during the drilling. This was measured from our drill records from which the hole depth was subtracted away. It might seem that the sink is surprisingly high, but dry sand can indeed quite easily be packed to a third of its initial non-forced volume. This phenomena will also be effective in real surfaces, but not in such a great amounts. The fifth column of Table 21 shows the total energy in Wh dissipated during the drilling. This is integrated by Simpson's method 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 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 Figure 75.

Table 21: Comparison of drilling results to different stones with a power of 10...20 W.

Rock	Time h	Hole depth cm	Stone sink cm	Energy Wh	Energy per cm Wh	Speed of penetration cm/h
Diabase	0.83	2.5	1.5	14.5	5.8	3.0
Carbonatite	0.26	2.1	2.0	3.8	1.8	8.1
Mafurite	2.7	0.1	2.9	43.2	432	0.04

a) *b)*

Figure 75: Carbonatite (a) and diabase (b) drilling holes and the corresponding retrieved core pieces. The borehole is 17 mm in diameter.

Drill never penetrated into the mafurite enough to cut a core piece away from it. However, a promising start was acquired. On the lower left corner of the Figure 76 is shown a start of a wobbling drill session. This clearly demonstrates how hard it is for the drill to begin on the hard rock. On the upper right the final drilling hole on mafurite is shown. The hole has a severe scrape on the lover edge, caused also by a wobbling start of drilling. As seen in Table 21, mafurite is clearly above the others in required drilling energy. This was surprising, and the author continued testing mafurite drilling later after the MIRANDA project with similar results. Theoretically, mafurite should not be that hard to drill, since all the main minerals of mafurite are less than 7 in Moh scale, usually even less than 6. Mafurite and basalt should be quite similar in minerals, and the differences are concerning the abundance of plagioclase-feldspar replaced with kalsilite. Even though basalt is hard to drill, the results were quite strange. A possible solution to this odd behaviour is that the mafurite could contain glass (due to the forming process). This could not be verified, but glass would explain the high energy needed to drill mafurite. Even though that the mafurite was extremely strong to drill, it was one of the highlights of these tests. It was clearly seen that a target rock as hard as mafurite would be far too hard to sample from depths. It is possible to extract a core sample, but taking into account the energy that is usually available in planetary drilling, there is not possible to drill mafurite (or similarly hard rock) to a depth more than few centimetres. For plain soil drilling, the MIRANDA hardware is somewhat rough. An estimate of 10 W-min of energy per each 10 cm was used, as it is in line with the MRoSA2U value.

Figure 76: Mafurite drill holes. Note the unsuccessful drill-start of the left hole.

Conclusions of the MIRANDA tests

The test setup was found to be working and filling its purpose. It is believed that the test setup can provide information useful in designing future planetary drilling missions.

At the moment the drill tool does not hold any active means to collect a soil sample or a core sample, it is designed only for coring tests. However, quite often it was seen that the tool collected a core and transferred it up to the surface even without any additional core holding methods. Such core cutting and holding systems to be inserted inside the tool are some important steps when developing this tool further. Core cutting did not effect on the drilling speed, which was somewhat surprising. On the other hand, this effect is very hard to measure, since the rock core tended to break easily.

Drill very easily gets distracted off its course when facing hard and uneven ground. This is because the drill head we used has the sample cavity in the middle and cutting bits only on the edges. When a bit at the edge gets stuck, it will introduce a wobble to the system. On the beginning it thus might be useful to use another drill head to make a starting dent for the sample holder head. This would be possible in the MRoSA2 design, where the drill heads are changeable.

Further technical development of test setup

During the MIRANDA tests, it was realized that in the future, temperature measurement equipment should be installed on both the drill head, soil in vicinity of the drill, and on the subject of the drilling. This was seen as an important improvement, as if the drilled stone heats up too heavily, fragile signs of life might be destroyed in the drilling process.

Also, ground could be frozen to better simulate the Martian conditions. Cooling some sand-rock-ice mix down to Martian temperatures, acting like local permafrost, and drilling down to the maximum required depth could simulate Mars soil drilling. This would also reveal whether the system has enough counterforce (keeping in mind that the rover should be lighten down to the gravity equivalent of Mars), and is the drill capable to drill such a deep hole in real environment.

It would be beneficial to add a viscous damper in parallel with the tension springs between the sled and linear actuator. The damper would prevent any fast and uncontrolled movements of the sled in occasions when drilling resistance rapidly decreases; as for example when drilling into a cavity inside a rock.

Pretension of the springs added with the weight of the sled during the MIRANDA tests made it impossible to measure any thrust force below 6.7 kgf (the mass of the sledge). An improvement and counter-mass solutions were studied but not developed during the MIRANDA tests.

The temperature measurements issue, as well as the counter-mass mechanism was developed later in the MIRANDA-2 study, explained in Chapter 5.4.

Starting the drilling

During the tests, an efficient and working method for starting the drilling was developed. The team achieved a working beginning on most of the drillings when the drill was introduced to the surface of rock slowly with 80-100N of force. On the contrary, when coming into contact with more than 100N, the drill (not being able to find a suitable starting point) wobbled violently at first for several seconds before an effective drilling started. Drilling force was only increased once a good start was achieved. Drills operated on Mars should have automation to immediately decrease the drilling power once a hard material is encountered. This would increase the amount of successful drillings and minimize the stress introduced to drill heads.

New ideas for the sample retrieval

Although the drill head used in these drillings was a prototype and possibly not the best for reliable sample retrievals, the team still had plenty of success in delivering core pieces to the surface. This feature could be enhanced in many ways though and some ideas sprung up although none were tested due to lack of resources, namely time and financing. The feature, shown clearly with the diabase, of the drill to lift finely grained stone material to the surface, could be used productively. An Archimedes screw like this could be build inside the drill to lift the uncontaminated grained sample all the way up to the drill base. This would require a non-rotating section to run in the middle of the drill. It could also be used as the sharp point to facilitate starting of the drill efforts. This would, however, require massive amount of product development but might provide an option for some future planetary exploration drilling systems.

5.4 The MIRANDA-2 tests: The temperature aspect

The drilling action induces thermal increase due to the friction between the sample and the drill. Basically, the thermal increase is a function of drilling power and type of the material. These can be divided further into a set of parameters:

Drilling parameters, which affect to the thermal increase:

- Drill force (pressure against the material to be drilled)
- Drill rotation velocity (revolutions per time unit)
- Drill bit type (friction and thermal conductivity)

Material parameters, which affect to the thermal increase:

- Target material (structure, friction, composition, thermal conductivity)
- Surrounding material of the target (thermal conductivity)

The reason, why this temperature aspect is important, is the affect that high temperature may affect to the sample and to the drill. The sample composition may alter due to the temperature increase, and the higher temperature may affect the drilling.

However, the temperature may affect not only to the sample, but also to the drill itself. If the drill bit heats too much, it may damage itself, or possible miniature instruments inside the drill bit or pipe. Ice melting and freezing is also another factor, which is critical to the drilling: if the drill melts ice (if there is ice) to liquid water deep in the borehole, and then let the water freeze again, it might get stuck. A freezing ice can act as ‘glue’ between the drill string (and bit) and the borehole walls, sticking the drill permanently to the hole.

Regarding the ExoMars mission, there are some requirements (Appendix IV) that concern directly the temperature issue, e.g. ‘RM-1-4235’, which states that the drill system shall preserve the possible water fraction in the sample in its original condition, e.g. ice or permafrost. This requirement means that the drill system must preserve the physico-chemical properties of the sample. In essence this translates to ensuring that the sample is kept at temperatures that do not induce undesirable changes, (e.g. possible water ice melting and chemical changes in for example carbonates or hydrated salts).

The reason of MIRANDA-2 tests was especially the thermal issues of drilling. The explanation of the test setup and the results are covered in the following chapters.

5.4.1 Theory of drilling thermodynamics

The MIRANDA-2 tests were completely empirical testing, but it is useful to know the theory behind the heat formation process in rock drilling. The heat energy, E_H, developed in mechanical drilling to a given depth with a drilling tool is a complicated function, depending on the applied load, drill speed, geometry, and mechanical properties of the materials (drill and rock). Because no adequate drilling energy/temperature data for volcanic rocks in Mars were found, a parametric model is offered as a coarse guide for the factors that influence to the heat energy (E_H).

A tool bit of diameter d, is pushed with a force F and made to spin at an angular speed ω, in a material of compressive strength Y. A simplistic model that assumes a linear relationship between the shear, σ, and compressive strength Y, leading to [117]:

$$E_H \propto E_A + E_B, \tag{6}$$

where E_A and E_B are defined as:

$$E_A = k_1 \omega F d^2 \sigma, \tag{7}$$

$$E_B = k_2 \omega^2 \tag{8}$$

Term E_A represents the energy that is required to excavate a cylindrical volume $\propto$ ($\omega F d^2$) from the bore hole. Term k_1 represents the efficiency (in a scale of 0…1) of the heating, that the mechanical work heats the cuttings. Thus k_1 is defined as W_T/W_M, where W_T is the work that heats the cutting, and W_M is the mechanical work.

The second term ($k_2\omega^2$) is suggestive of the heat generated via sliding friction at the tool's tip that is in contact with the target rock surface. Heat delivered by the tool will raise the temperature T of the shavings removed by a cutting tool and the abraded surface by an amount that depends on the thermal conductivity λ and heat capacity c of the material. The rate at which debris is generated varies with 1/σ and so, ignoring numerical factors, the cut material will experience a temperature rise, ΔT, that is proportional to $H\sigma/c$. The mean temperature of a chip will be influenced by its thermal conductivity in a complex manner.

In summary, increasing a material's shear strength, σ, generally results in reduced cutting rates and, for the same drill speed ω, gives rise to raised bit temperatures. However, rock drilling processes like the MIRANDA tests do not significantly increase the temperature of the drill bit or the rock. Therefore the changes in the shear strength of the rock are negligible in these tests. This issue would be more important in cryogenic water ice drilling in e.g. cometary conditions, because water has significant differences in the compressive strength in the temperature level of 100…273 K (100K being possible value in cometary environment).

As there is no numerical modeling of the temperature rise performed in this thesis, it is important to know how the drilling parameters relate to the ΔT of the cutting area. In the following MIRANDA-2 drilling tests main emphasis has been given to the empirical study of the drilling parameters' relation to the drilling temperature.

5.4.2 Test setup

The drilling test bench is the same that was used during the MIRANDA tests in 2003. There are two major changes that have been made:

- The drill sledge has a counter weight to neutralize its mass (downforce).
- The drill bit has temperature sensors inside (Figure 77).

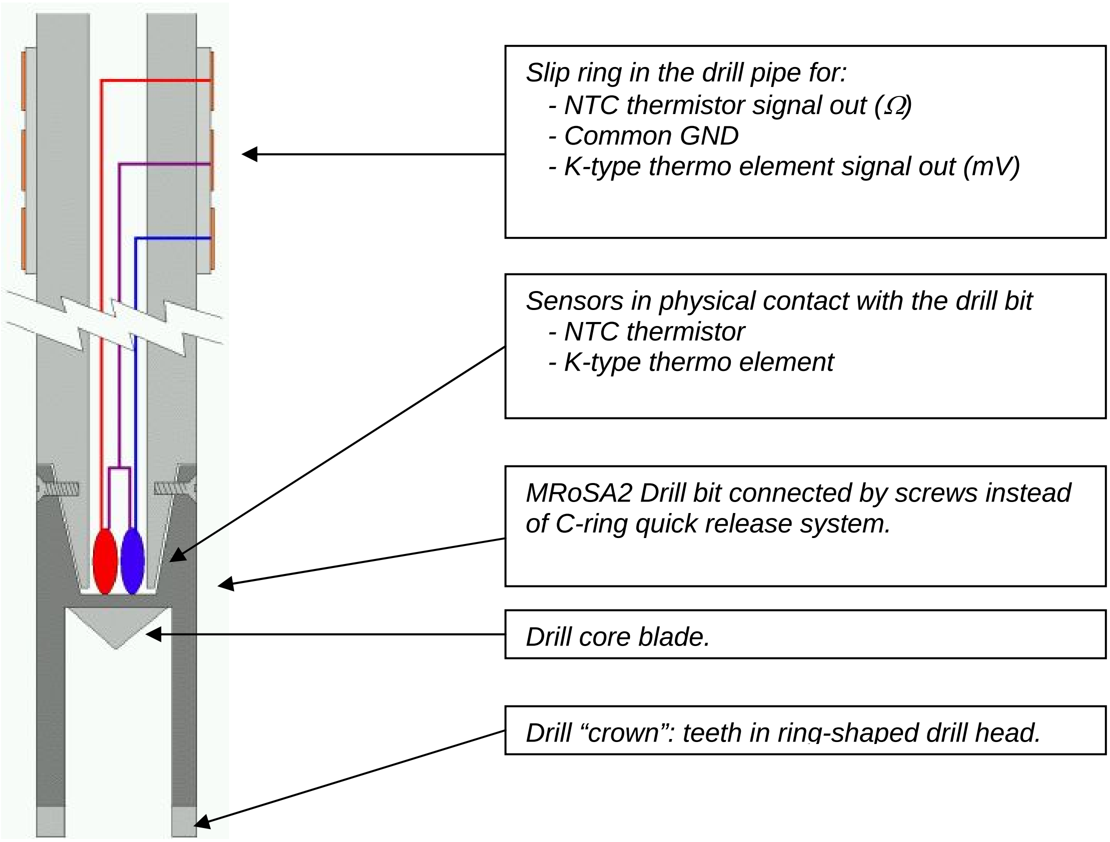


Figure 77: MIRANDA-2 Drill tool schematics.

5.4.3 Preliminary temperature measurements

The preliminary tests were conducted in September 2004. The first target was the diopside rock. The NTC thermistor inside the drill tool was used to measure the drill bit's temperature. Room temperature was 19.6 °C, and both the drill and the rock were measured to be in the same temperature. There were three test cases, which all were conducted using 100 N thrust, except once the thrust was increased to 200 N in the end of the test. The test results are shown in Table 22.

Table 22: Preliminary test results of the temperature measurements during drilling.

t/s	T/C	T/Ω	T/NTC	F/N	U/V	I/A	P/W	D/mm	rpm	MRR/ml	Note
0	19.7	12500	19.99	100	0	0	0.0	0	0	0	
100	21.5	12180	20.56	100	10.1	0.65	6.6		75		
200	21.7	11850	21.17	100	10.1	0.61	6.2		77		
300	21.9	11700	21.46								
400	22.1	11580	21.69	100	10.1	0.63	6.4		76		
500	22.0	11450	21.94								
600	22.0	11370	22.10	100	10.1	0.63	6.4		77		
700	22.1	11300	22.24								
800	22.1	11250	22.34	100	10.1	0.63	6.4		77		
900	22.1	11210	22.42	100	10.1	0.63	6.4		77		
1000	22.2	11100	22.64								
1100	22.2	11060	22.72								
1200	22.2	11050	22.74	100	10.1	0.63	6.4	1.04	77	0.3	
0	19.8	12200	20.53	100	20.0	0.87	17.3	0	151	0	

100	20.6	11060	22.72	100	20.0	0.80	16.0		153		
200	24.5	10570	23.74	100	20.0	0.77	15.4		153		
300	26.6	10470	23.96	100	20.0	0.76	15.1		152		
400	29.0	10440	24.02	100	20.0	0.72	14.4		153		
500	29.1	10290	24.35	100	20.0	0.74	14.7		153		
600	33.3	10250	24.44	100	20.0	0.74	14.7	1.67	153	NM	*1**
0	19.6	12060	20.78	100	25.1	0.77	19.2	0	248	0	
100	24.5	10270	24.39	100	25.1				248		
170		9880	25.25	100	25.1				248		
220	25.3	10000	25.00	100	25.1	0.80	20.1		248		
250	26.0	9790	25.48	100	25.1	0.79	19.8		248		
300		9890	25.25	100	25.1	0.75	18.8		248		
400		9900	25.23	150	25.1	0.88	22.1		245		*2**
500	30.5	9780	25.51	200	25.1	0.90	22.6	0.35	240	NM	*3**

Table explanation: t/s = time (sec.); T/C = tool bit outside temperature (°C) in tool's uppermost section; T/Ω = NTC thermistor resistance; T/NTC = temperature of the NTC (°C); F/N = thrust in Newtons; U/V = rotary motor voltage (V); I/A = rotary motor current (A); P/W = rotary motor power (W); D/mm = achieved depth (mm); rpm = revolutions per minute; MRR/ml = mass removal ratio in milliliters; Note = special notes regarding that measurement. Table notes: 1 = Measured drill bit crown temperature: T = 39.5 °C; 2* = Increase thrust from 100 N to 150 N; 3* = Increase thrust from 150 N to 200 N. "NM" = Not measured.*

These results explain rather clearly that the temperature increases when the thrust and power are increased. However, the results also show one fundamental thing: the temperature rise is not very much. In fact, it is far lower than was expected before the tests. The reason is quite clear: the thermal mass of the drill bit and string is too big to allow the NTC thermistor to be placed inside the drill tool, several centimetres from the drill crown. This fact is also obvious in this particular drilling case (diopside target rock), because the drill never penetrated deep enough to allow the core blade begin cutting. Therefore the only cutting was made by the crown teeth, and the thermal increase in NTC is only a slight trace of that, what could be in the crown. The thermal increase is seen in Figure 78, and as said, it has very minimal effect.

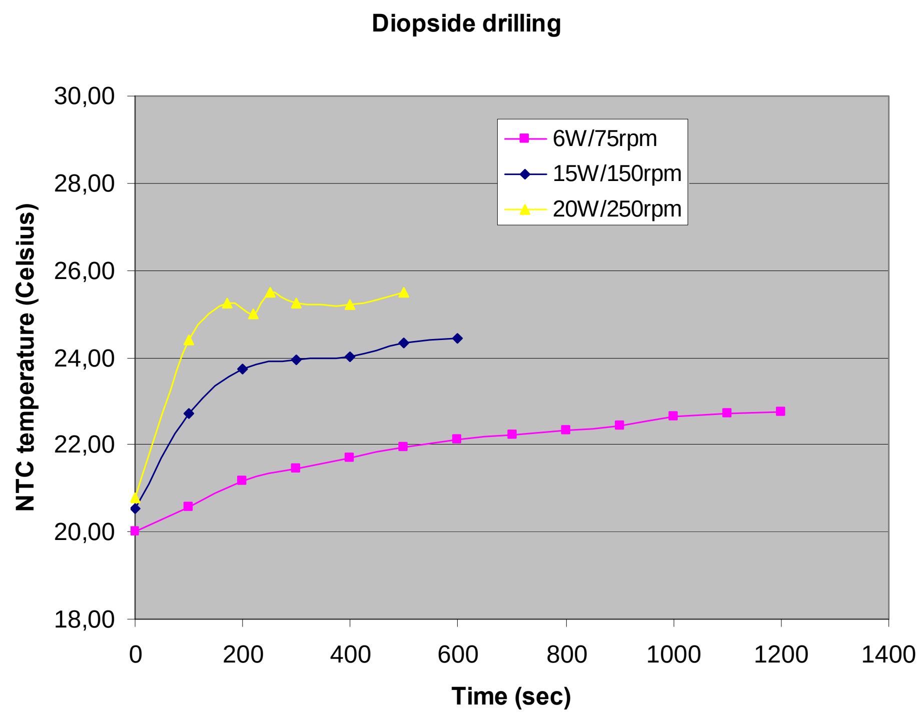


Figure 78: Thermal increase in the uppermost part of the MRoSA2 drill bit.

These kinds of results were somewhat expected, and the confirmation was got by using infra-red (IR) hand-held thermometer. After second drilling session, the drill was quickly raised from the borehole, and the teeth temperature was measured. The reading was 39.5 °C, which was 6.2 °C more than the outside temperature of the drill bit, and 15 °C more than the NTC measured. The IR thermometer was not very accurately pointed, but it gave good reference measurements. During the drilling, the IR thermometer was reading the temperature of the uppermost part of the borehole (side friction of the drill bit), and the drill bit's outer surface, as shown in Figure 79.

Figure 79: Temperature measurement setup (Image: MA).

The preliminary MIRANDA-2 tests showed that the NTC is badly placed. On the other hand, the three diopside-drilling test cases resulted to the same kind of results that was achieved from the MIRANDA tests in 2003. The drilling efficiency appeared to be very much the same.

5.4.4 Temperature results of the updated drill configuration

The following drilling tests were done in October and November 2004. The tests were divided in the following three parts:

1. Temperature tests using different rocks and drilling parameters.
2. Drilling efficiency and core sampling tests (continuation of MIRANDA 2003 tests).
3. Drill string friction and torque tests.

As detected in preliminary testing, the location of the NTC thermistor was not good. The second test setup was done by using the same equipment, but an additional NTC was placed inside the drill tool, near the drill teeth (as shown in Figure 80). The NTC was mechanically connected to the drill teeth, and was just a little higher (~1.2 mm) than the bottom of the teeth, so it did not crush immediately when the drilling started.

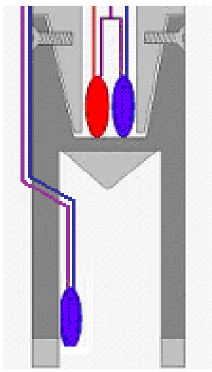


Figure 80: An additional NTC near the drill bit's teeth.

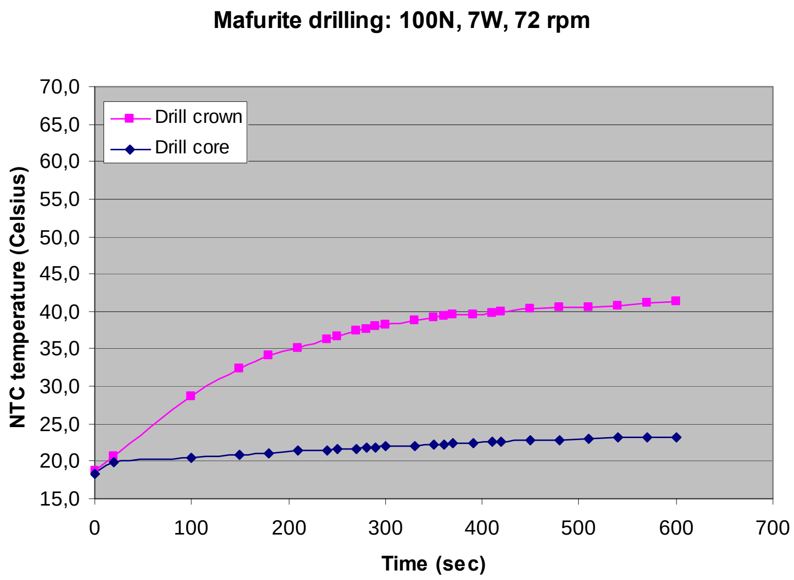
General notes

The results of the first drillings were good. The NTC was in direct contact with the teeth material and so near to the drill bit's top, that it detected the same temperature that the drill bit's top. Unfortunately this configuration resulted to damage of the NTC very often, so it had to be replaced several times during the tests. The tests were done using several different stones. In addition to the MIRANDA stones, Finnish red granite was also used to simulate very hard rock drilling (see Table 20).

It was quickly detected that the temperature tended to rise very quickly after the drilling was started, but then it begun to settle to a certain temperature. This temperature is called the equilibrium temperature (T_{eq}). The equilibrium temperature is reached when incoming heat energy is equal to the heat that is conducted and emitted away. Incoming heat energy is mainly a result from the drilling friction, and outgoing heat is resulted mainly from the heat that is being conducted by the drill pipe and drilled material.

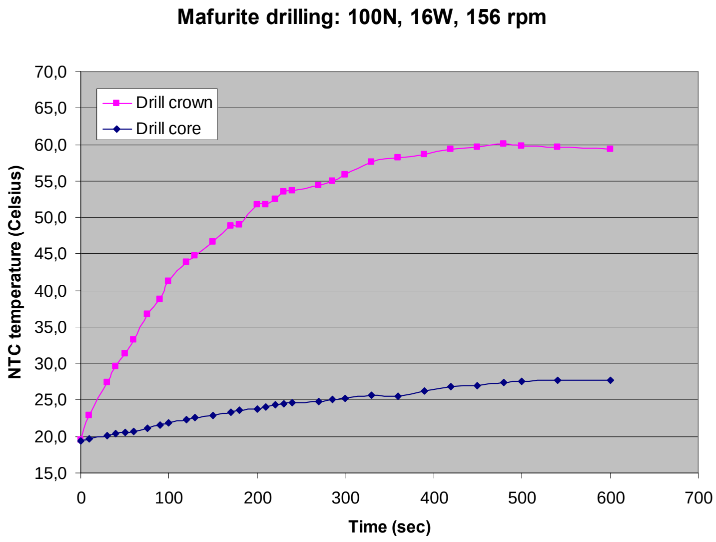
Drilling session one

These tests were done using the mafurite rock as a target. Drilling time was 10 minutes, and the temperature was measured both from the tip of the drill tool, and from inside of the drill tool. However, the drill never penetrated deep enough that the core blade would have begun cutting. Thrust varied from 100 to 200 N and drilling power varied from 7 to 23 W. Four different drilling tests were performed. The results are shown in Figure 81 a-d.



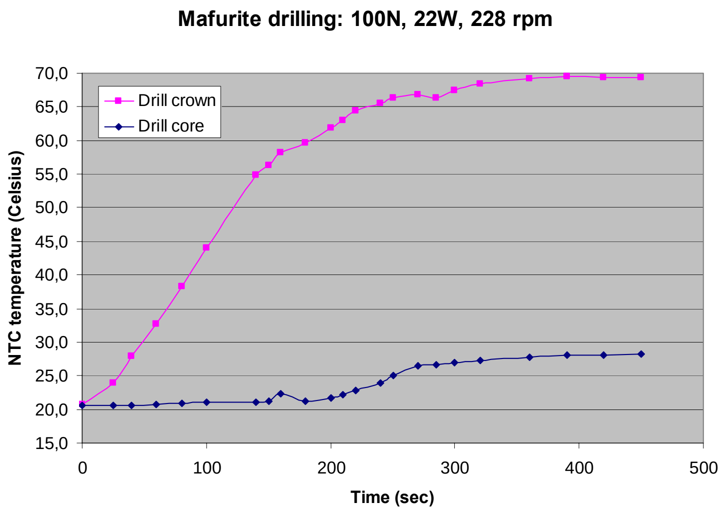
a) Low-thrust and low-power drilling. The drill power (6W) was the same that was maximum drilling power of the MRoSA2 DSS.

The equilibrium temperature was measured to be about 41℃, resulting in ΔT = +22K.



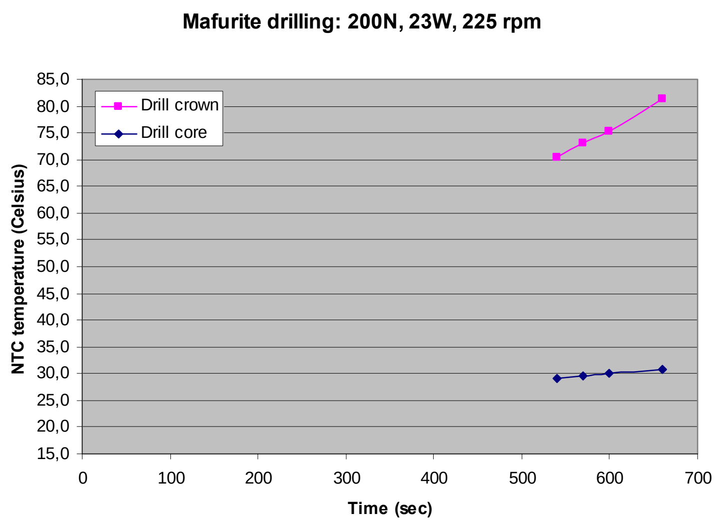
b) Low-thrust and mid-power drilling. The drill power (16W) was about the same that is defined for ExoMars Pasteur drill.

The equilibrium temperature was measured to be about 60°C, resulting in ΔT = +41K.



c) Low-thrust and high-power drilling. The drill power (22W) was slightly more than what is defined for ExoMars Pasteur drill.

The equilibrium temperature was measured to be about 70°C, resulting in ΔT = +49K.



d) High-thrust and high-power drilling. The drill power remains the same than in c), but the thrust is increased to 200 N. This test was a continuation of test c), and the graph shows how the temperature rises.

The equilibrium temperature was measured to be about 82°C, resulting in ΔT = +60K.

Figure 81: Drilling temperature results of mafurite rock drilling.

No core samples were collected during these mafurite drilling tests. The two main reasons were:

- NTC was positioned so that it prevented core drilling (coring would have broken it).
- Drilling time was not enough for attaining full-sized core samples.

The starting temperature during these tests was room temperature (18.6°C – 20.7°C). The main purpose was to measure the temperature increase, ΔT. The results are shown in Appendix VIII. The drill core temperature results in Figure 81 a-d are due to the conducted heat from the tip of the drill tool.

Table 23: Mafurite drilling test results.

Test #	T_{start} °C	T_{eq} °C	T_{max} °C	ΔT °C	Force N	Power W	rpm	Note
1	18.6	~41	41.3	21.7	100	6.9	72	
2	19.5	~60	60.1	40.6	100	16.2	156	
3	20.7	~70	69.5	48.8	100	22.5	228	
4	69.4	~82	81.4	59.7	200	23.3	225	Continuation of test #3. ΔT is measured from T_{start} of test #3.

Drilling session two

The next tests used calcite rock as a target. Testing time was 20 minutes, and six different drilling parameters were used. The time, 20 minutes, was determined to be sufficiently long, since all test cases showed clear stability in the temperature curve even after about 10 minutes. This was verified twice, when the test was extended to 60 minutes (with calcite, using the same parameters as in 'Calcite #4' and 'Calcite #5', respectively. Parameters are shown in Table 24), and no further increase was detected after 10 minutes. The testing time was doubled from the previous session (mafurite drilling tests), to verify that the equilibrium temperature had been reached within the 10 minutes time limit used in the previous tests. Thrust varied from 50 N to 400 N, and drilling power varied from 5 W to 22 W. As was the case with the mafurite drilling (Chapter 5.4.4), the temperature rise in the drill tool settled at some point, when the equilibrium temperature (T_{eq}) was achieved. The results are shown in Figure 82. Calcite was relatively easy to drill as it was the softest of the tested rocks. It is notable that the temperature sensor in the drill tool broke several times, as was expected, when the drill proceeded deep enough to the calcite. There was a 'quick-attach' system in the NTC sensor, so it was rapidly replaced (~30-40 sec.) after it was detected being broken. This change procedure is shown in the results in the following points:

- 3rd drilling (200N, 7.5W): 500 sec.
- 5th drilling (100N, 16W): 300 sec. and 700 sec.
- 6th drilling (400N, 22W): 500 sec., 800 sec. and 950 sec.

At some points the NTC sensor was lifted up about 2-3 mm, resulting that it measured the temperature in a point that was about 3-4.5 mm above the rock's surface. This should not have too much effect, since the drill tool is solid steel at the top, and it conducts heat effectively within the first 5 mm length. However, the effects of breaking the NTC and the time needed to change it are clearly visible in the Figure 82. Despite the expected pause in testing, the T_{eq} is easily detected from the results.

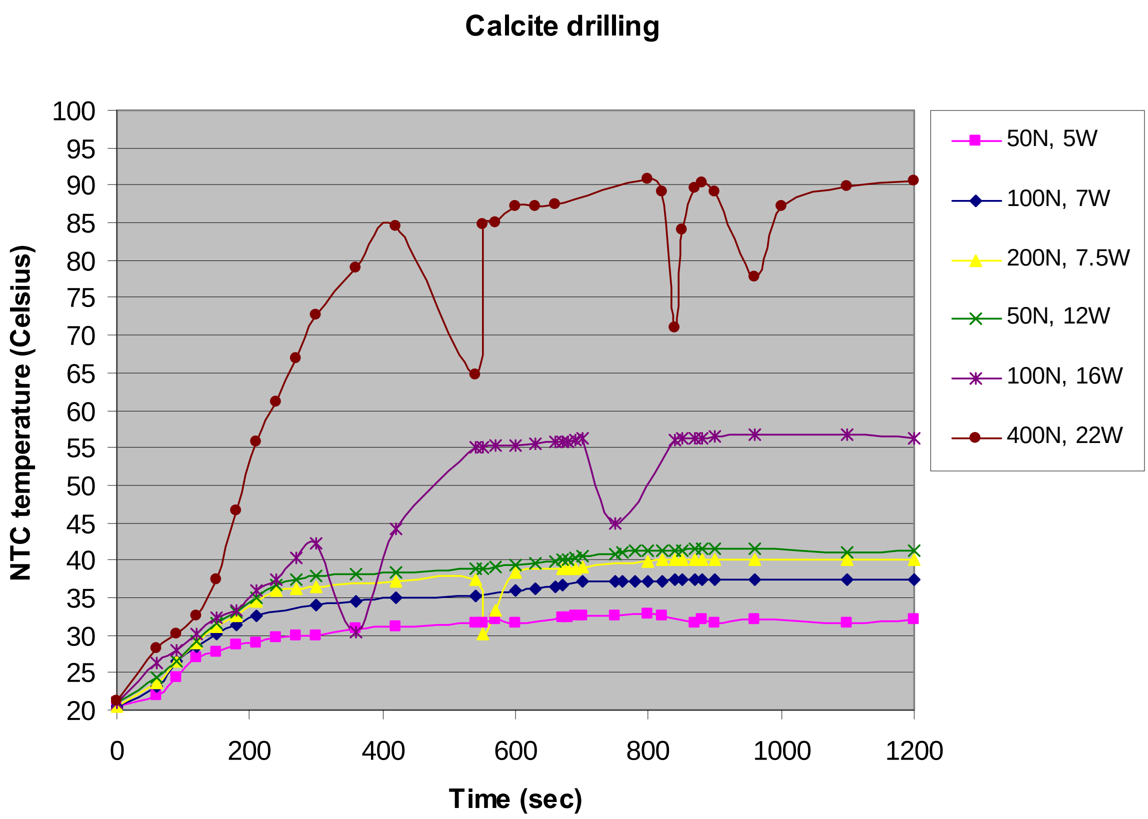


Figure 82: Calcite drilling results with six different drilling parameters.

During these calcite drilling tests, core samples were not collected (as was the case also with the mafurite drilling tests). Three main reasons were:

- NTC was positioned so that it prevented core drilling (or otherwise it would have been broken).
- Calcite is very porous material, and acquiring a solid, good core sample is pretty difficult. Usually the core tends to break before it is acquired, and then it is easily crushed in pieces.
- Drilling time was not enough for attaining full-sized core samples.

The starting temperature during these tests was room temperature (20.5°C – 21.3°C). The main purpose was to measure the temperature increase ΔT in the tip of the drill tool. The results are shown in Table 24. The tests cases are later referred as “Calcite #1” to “Calcite #6”, respectively.

Table 24: Calcite drilling test results.

Test #	T_{start} °C	T_{eq} °C	T_{max} °C	ΔT °C	Force N	Power W	rpm	Note
1	20.5	~33	32.8	12.3	50	5.3	81	
2	20.5	~38	37.5	17.0	100	7.0	72	
3	20.5	~40	40.1	19.6	200	7.5	67	NTC broke once.
4	20.9	~41	41.5	20.6	50	11.6	168	
5	21.0	~47	56.7	35.7	100	16.0	156	NTC broke twice.
6	21.3	~90	90.9	69.6	400	21.8	201	NTC broke three times.

Drilling session three

The third drilling test used Finnish red granite as a target rock. Rock properties are shown in Table 20 in Chapter 5.3.3. The granite was chosen as a target for two reasons: It was interesting to measure the drill advance, as granite is very hard rock. In addition, as granite is very hard rock, it was a good target for measuring the temperature during drilling, as the drill did not penetrate very much, and thus the NTC sensor did not break during the measurements. There was no significant difference in the temperature rise comparing to mafurite, diopside or calcite.

The drilling test lasted 90 minutes, and six different drilling parameters were used during the tests. Once again, the T_{eq} was clearly detected after every change in drilling thrust/power. The results are shown in Figure 83 (results are in table format in Appendix VIII). This was the first test that the T_{eq} was tested also backwards; when the drill power was decreased, it was noted the T_{eq} decreased also, as was expected, but not proven before. This effect is seen in Figure 83, at the end of the temperature curve, which illustrates all of the six tests in the same graph. The tests cases are later referred as "Granite #1" to "Granite #6", respectively.

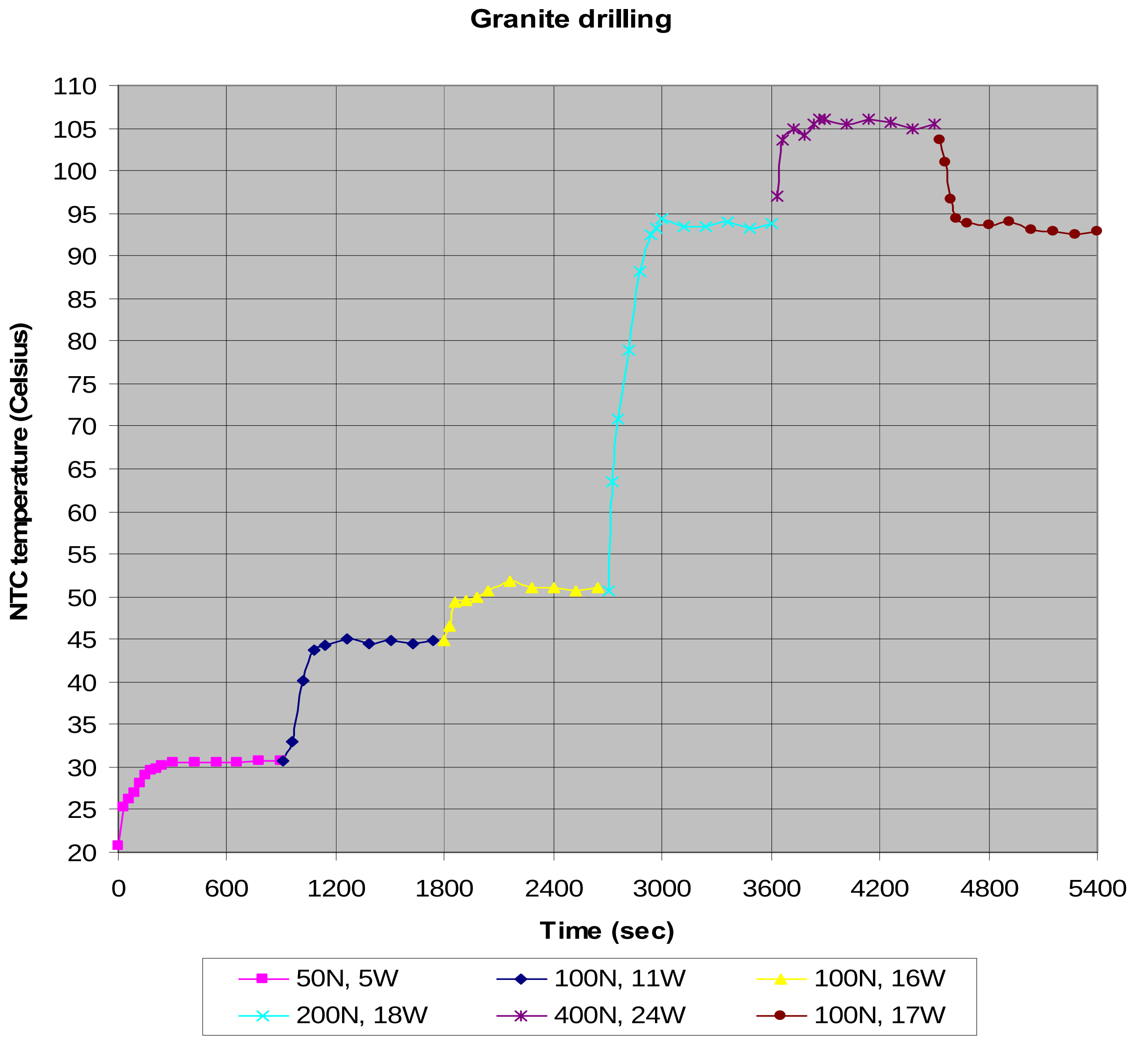


Figure 83: Granite drilling results. Six different drilling parameters were used.

In addition to the temperature test, the drilling efficiency to granite was also measured in another drilling session. Three drilling sessions were performed, and an average penetration of 5.45 mm was measured. One drilling session took 60 minutes with 150 N thrust and 10 W power. This leads to 18.5 Wh/cm drilling energy consumption value (for crown-blade drilling). It was expected, that granite is harder to drill than diopside (5.8 Wh/cm), but easier than the volcanic mafurite (containing possibly glass).

Table 25: Granite drilling tests for measuring the drill penetration.

Test session	Time min	Hole depth mm	Force N	Power W	Energy Wh/cm
Granite drilling #1	60	5.20	150	10	19.2
Granite drilling #2	60	6.10	150	10	16.4
Granite drilling #3	60	5.05	150	10	19.8

5.4.5 Summary of the MIRANDA-2 temperature tests

In the final configuration, the drill tool had three temperature sensors, which of two were used in the final tests. The K-type thermocouple sensor electronics was not accurate enough for these tests, and thus only the NTC sensors were used. The upper NTC, placed inside the drill tool, sensed only small increase in temperature when the crown blade was the only cutting blade. Surprisingly, the few tests that included core blade cutting did not result to significant increase in inner NTC sensor readings. The main reason to this is that the radial velocity of the inner blade is small, and the main thrust force is applied to the crown blade. In addition, the heat conducted from the crown blade to the inner NTC masks the measurements from the inner NTC.

Most of the drilling tests, regarding the drilling penetration measurements (MIRANDA tests) and the temperature measurements (MIRANDA-2 tests), were done using only the crown blade, so the drilling depth was less than the depth of the core sample chamber (20 mm). This aspect was emphasized especially after it was observed that the main temperature increase happens in the crown blade area. In addition, it is not the main object to penetrate deep into rock, but to penetrate through the regolith (sand, gravel etc. porous material) to find a rock for acquiring a near-surface core sample from it.

The temperature rise (ΔT) is proportional to the velocity of the cutting blade (proportional to the second power of the velocity) and to the thrust force, assuming that the other parameters remain fixed (drill tool and target rock are the same) during a testing session. This was also stated in theory in Chapter 5.4.1. The results are quite consistent with this theory, although it has to be noted that rock drilling tests here are very much empirical science, since it was not possible to monitor all possible affecting parameters (wear of the drill bit, debris in the drill hole, surface anomalies in the cutting surface etc.). No specific dependence between the rock type and the temperature rise (ΔT) was detected.

The main objective was to find drilling parameters that result in *too great temperature rise.* This objective was fulfilled, and the results are used to design the new drill concept, its operational scenario and performance requirements.

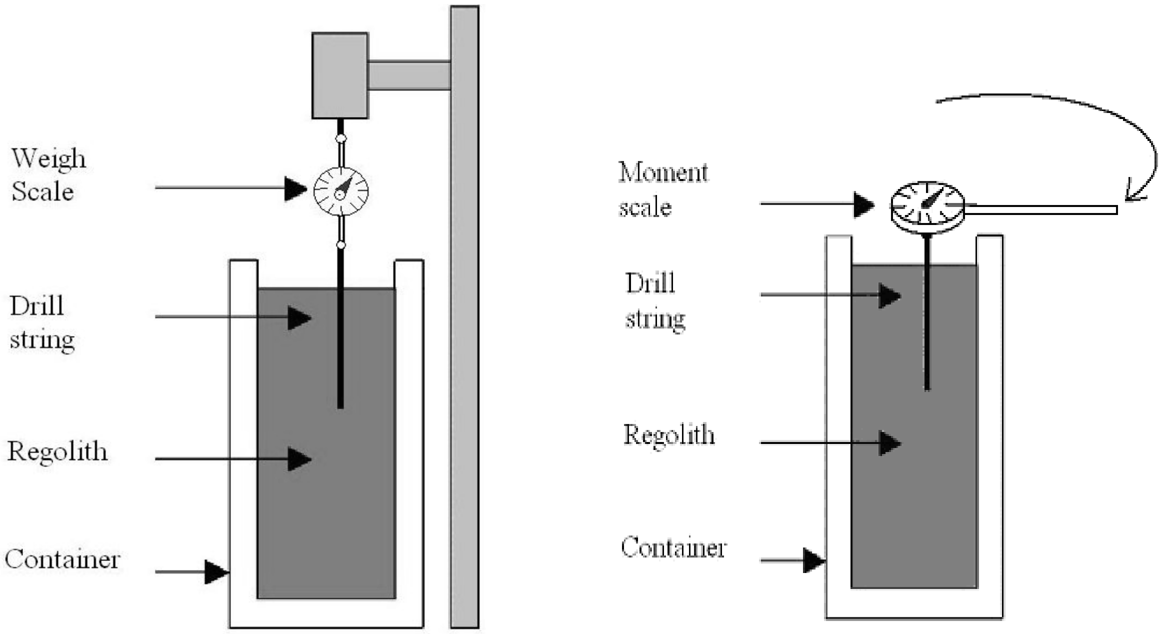
During the MIRANDA-2 tests, no specific drilling penetration tests were done. This was mostly due to the geometry of the NTC temperature sensor placement, which would have resulted in broken NTC too often. However, the calcite tests revealed the same penetration scale that was measured in the MIRANDA tests in 2003.

5.4.6 Results of the drill string friction tests

In addition to the temperature and drill efficiency tests explained above, two additional tests were conducted: drill anchoring force test and drill rotation friction test.

The ‘drill anchoring force test’ was conducted by drilling the drill string deep into the MIRANDA sand column, and then measuring the required force to lift the drill string without rotating it (Figure 84a). The results of this test are strongly dependent on the type of the terrain that the drill string is submerged, and on the drill string type. Therefore this test gave only the scale of the force, which is needed to lift the drill string from the ground (without rotation movement). However, on the other hand, this force could also be measured in Mars by the drill system, and thus new information would be gathered from the density and packing degree of the regolith. The test results of the MIRANDA sand column are shown in Table 26. The measurement accuracy was 10 N. The test was conducted by pulling the drill string straight up with the MIRANDA test bench's linear feed motor, and measuring the required lift force by a weight scale.

As seen from Table 26 and Figure 85, the results are far from linear when the drill is buried only 0-60 cm, even that the measurements were taken several times. This is due to the fact that the sand column is not homogenous, but layered with different type of materials. Also the surface layers are not packed very tightly, so the first half metre is pretty porous material, which does not bind the drill string very tightly. In addition, it is notable that although the lift force is given in Newtons, it is not directly proportional to the gravity, so lifting of the drill rod on Mars is not much easier than on Earth.



a) *b)*

Figure 84: Lift force (a) and rotation torque (b) measurement principles.

Table 26 and Figure 85 show also the results of the rotation torque tests. The test was performed similarly to the previous lifting test, but instead of trying to lift the drill string, a torque measuring wrench was used to determine the rotation friction of the drill rod (Figure 84b). As was the case with the previous lifting test, this rotation test was also were dependent on the regolith type and the drill string type. The results are still interesting, and again these could be measured in-situ by the drill instrument to attain more information about the terrain type.

Table 26: MIRANDA-2 tests: Second column shows the results of the anchoring force test of the drill string. The third column shows the results of the rotation torque test of the drill string. No difference in results was measured when the rotation direction was changed.

Length of the string that was under surface m	Required lifting force N	Required rotation torque Nm
0.2	~15	0.01
0.4	40	0.01
0.6	260	0.03
0.8	390	0.08
1.0	550	0.09
1.2	720	0.13

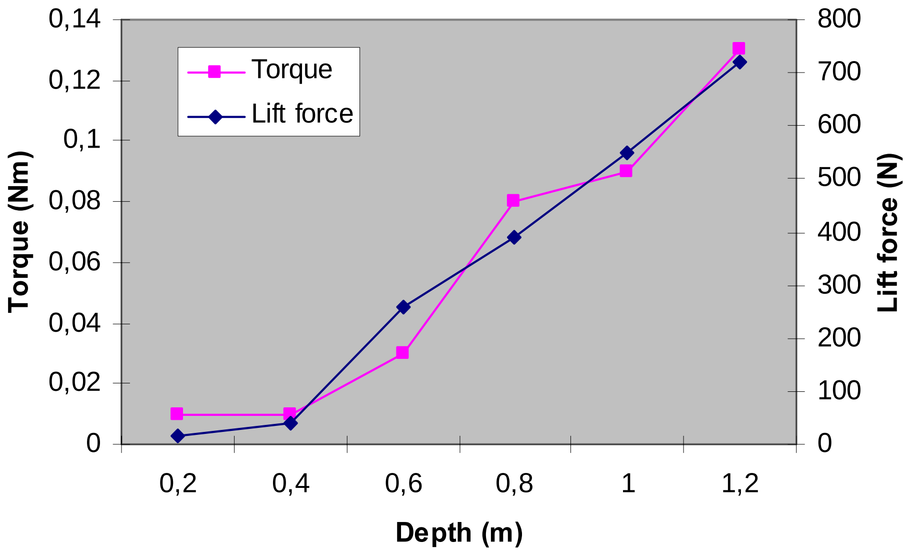


Figure 85: Results of the pulling and rotation tests.

While these tests are interesting, and the tests can be done also in Mars to reveal information about the terrain, it is notable that especially the rotation torque test is crucial regarding the functionality of the drill. The ExoMars drill must be able to drill down to 2 m depth; therefore it must be able to rotate the drill rod, which is buried deep in the regolith. It also has to be able to conduct the actual drilling, so there must be enough torque in the drilling motor/gears to sustain efficient drilling.

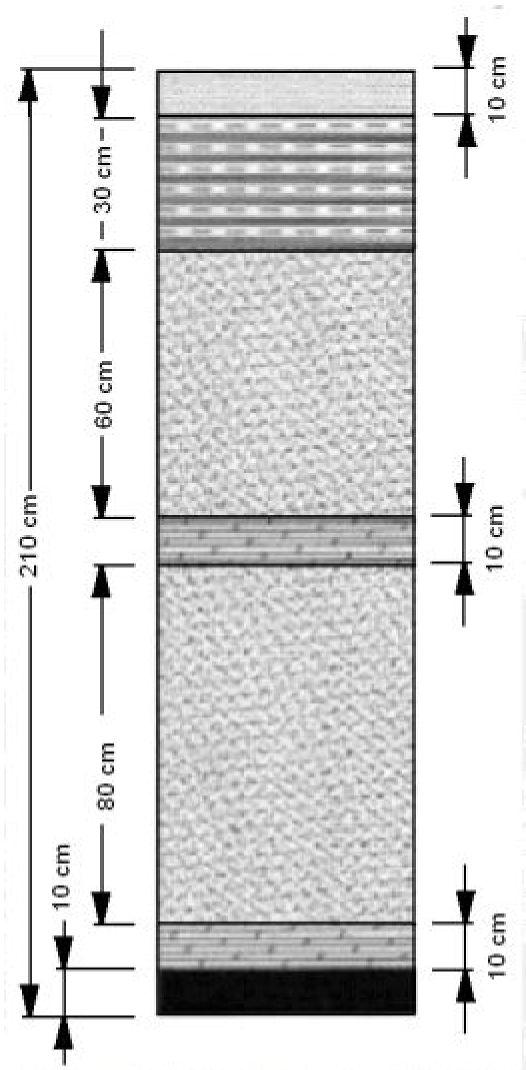
5.5 Other drilling tests

There have been several different drilling tests in the world, regarding planetary robotic exploration by drilling. However, only some of these are public and only some of these public tests can be referred here, due to lack of space or they might be irrelevant for this thesis.

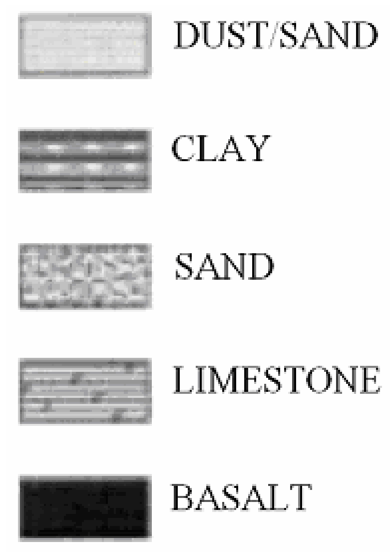
Two different drilling tests are explained in the following. They are the NORCAT/CSA drilling tests and the Tecnospazio's drilling tests. Also mentioned are the JPL's drilling tests and Open University's ice drilling tests. These tests are not in any order and there might be more relevant or better test results somewhere. In addition to these tests, a typical terrestrial drilling test with its results is explained. All errors explaining these tests are naturally the lack of knowledge of these tests by the author of this thesis. Also no detailed analysis is given except of the MIRANDA tests, explained previously. The idea is mainly to get a glimpse of other possible test setups.

5.5.1 NORCAT / CSA

Northern Centre for Advanced Technology (NORCAT), Canada, has constructed a simulated Martian 'sand box', which is 210 cm deep. The drilling test bed was built for an assignment given by the Canadian Space Agency (CSA) [31]. The test bed is seen in Figure 86 [31]. The actual drilling tests contained a simulated Martian terrain conditions (in a form of different materials to drill through), and a drilling device. The drilled media was a layered material which contained dust/sand, clay, sand (coarse), limestone and basalt. The reason for choosing these materials was that these should represent Martian environment accurately enough for this kind of drilling test. The author of this thesis has no accurate drilling test results to publish, but the main reason to introduce this test bed is to show the layered structure of the sand column. Similar layered test bed was used in the MIRANDA tests, explained in Chapter 5.3.



a)



b)

Figure 86: NORCAT test media layers (Image: NORCAT).

a) Test media layers shown in different depths of the 'sand box'.

b) Explanation of materials shown in Figure a).

5.5.2 Tecnospazio's drilling tests in 2001-2002

Tecnospazio (TS, Italy) has been introduced previously in this thesis e.g. in Chapter 3.4.2 about DeeDri drill. TS has also performed some interesting drilling tests, which are useful for comparing with MIRANDA test results. TS presents in ref. [53] drilling tests that were carried out during years 2001-2002. The TS drill tool had a completely different design than the MRoSA2 drill tool, and it drilled a hole 35 mm in diameter, and (upon command) acquired a core sample of 14 mm in diameter. Drilling force, torque and power were higher than those for the MRoSA2 drilling tests. The drilling tests were carried into several materials: sand, gas concrete, tuff and travertine. Table 27 presents the averaged test results and describes performance of the TS tool prototype.

Table 27: Tecnospazio's 35-mm drill tool performance in different materials [4,53].

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 rotary speed (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

TS used a specific variable for determining the cutting efficiency with respect to different drilling parameters (see Chapter 5.3.1). This new variable, 'Specific Drilling Power' (SDP, W/(mm/minutes), indicates directly how much power (W) is needed to achieve a corresponding speed of penetration (mm/min.). SDP depends on properties of target material, tool geometry, rotation speed, thrust, and drilling method (rotary, percussive or rotary-percussive). In the TS tests all other parameters were kept constant, but effects of drill rotation speed and feed rate were studied.

SDP multiplied by the depth of the borehole (mm) gives the energy needed for the sample (W-min. = 60 J). Table 28 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 [53].

Table 28: Tecnospazio's 35-mm drill tool performance in travertine with varying feed rates [4] [53].

Feed rate / (mm/min)	SDP / W/(mm/min)	Power input / W
0.3	37	12
1.1	23	26

5.5.3 Terrestrial drilling tests

While terrestrial drilling tests are usually greatly different than e.g. the MIRANDA tests, it is interesting to take a brief look of them also. Three main differences are usually present when comparing terrestrial drilling and planetary (robotic) drilling:

- Available power is far greater in terrestrial applications
- The drilling systems are more robust (especially in size) in terrestrial drillers
- Problem situations in terrestrial drillings can be handled by human operator in-situ, so there is no need for such an automated design.

In addition to these points, different techniques are used in terrestrial applications, such as drilling fluids and hardening of the borehole walls.

As for one example, the author refers to a one terrestrial drilling test [86]. The test compared two diamond drill bit types; one consisting of surface-set diamonds (Figure 87), and the other consisted of impregnated diamond bits. The tested target materials were high strength rock types including granite, quartzite and taconite [131]. Measured specific energy for drilling 150 to 400 MPa rock with a surface-set diamond bit was between 1 and 2 J/mm^3, while the specific energy for drilling with impregnated diamond bits is around 10 J/mm^3. The results are consistent with [132], which reports the specific energy of diamond-bit drilling in 200 MPa rock to be in the range of 1 to 10 J/mm^3.

Based on these results, the rate of penetration of a surface-set diamond bit (50 mm diameter) with 1.7 kW mechanical power in hard rock would be 1.5 to 3 m/hour. Note that the size of the drill bit is huge compared to MIRANDA tests, as is the drilling power.

Figure 87: Terrestrial drilling bits: Drills (left to right): water jet, mechanically-assisted water jet and 50-mm diameter surface-set diamond bit (Image: Tempress Technologies Inc.).

The referred test discuss also about [133] two drilling tests of black granite with a compressive strength of 280 MPa using a 38 mm diameter surface set diamond bit shown in Figure 87. At rotary speeds of 340-780 rpm and a thrust of 2200 N, the drilling rate was 1.8 - 2.9 m/hr. Measured drilling rates with an impregnated diamond bit were about 0.3 m/hour. Under normal terrestrial operating conditions, abrasive wear limits the bit life of diamond bits to less than 30 m in rock types such as granite, which have quartz content greater than about 20%. At low thrust and rotary speeds, a surface-set diamond bit is capable of drilling 30 m without significant drill bit wear.

The results, discussed above, are of course far from the MIRANDA tests, but the really interesting part is to compare the specific drilling energy per drilled material volume. For example, the first results (1.5 to 3 m/hour with 1.7 kW) above can be transformed to a volumetric value of 1.7-3.4 cm^3/Wh. The surface area of the MRoSA2 tool head (ring), used in the MIRANDA tests, is 1.63 cm^2, so to be consistent with these terrestrial drilling tests, the MRoSA2 drill head should penetrate ~1-2 cm/Wh. This is the case with carbonatite (see Table 21), but it is quite a soft material. For example, the diabase requires 5.8 Wh/cm (20.9 kJ/cm using MRoSA2 drill bits). Therefore it can be seen, that the MIRANDA tests gave worse drilling results than these terrestrial tests. The reason is simple: the thrust force was very low in MIRANDA tests, comparing to these terrestrial tests (>2 kN force). Taking this into account, it can be seen that the MRoSA2 drill tool is competent tool for rock drilling, and the results are similar for terrestrial, commercial drilling tests.

5.5.4 Examples of other drilling techniques

The tests described so far in Chapter 5 have all related to rock or regolith drilling for Mars drilling purposes, using rotary drilling. However, there exist other targets in space containing other kind of environments, and also there are also other means to penetrate a rock than rotary drilling.

NASA Jet Propulsion Laboratory (JPL) has developed an ultrasonic corer tool (USDC, explained in Chapter 3.4.5), which uses only percussion movement (without rotary movement). The USDC “hammers” the core tube into the target rock using power in a scale of 5-25 W [118]. Typical core tube diameter is 2 mm (core sample diameter) and 3 mm of outer diameter of the tool. Unfortunately, the author found no testing results that could be directly compared with the MIRANDA(2) results. A notable parameter of the USDC device is, that it requires very low axial preload (~10 N or less), while conventional (space) drills require load in a range of 100-200 N. Also the precession forces, which make the drill tip to “walk” in the target surface, are low; in a range of ~1 N, while precession forces are typically in a range of 10-100 N with rotary drills.

In addition to regolith/rock drilling in space, there is a need to test ice drilling in extremely low temperatures. Ice exists or may exist in Moon, Mars, Jupiter’s icy moon (i.e. Europa) and in comets. There are some tests already conducted regarding ice drilling. For example, the Planetary Sciences Research Institute (PSRI) of the Open University in England has conducted tests of cryogenic ice drilling [117] [119]. Water ice is very hard at cryogenic temperatures, and thus it is comparable to rock drilling. However, water ice has significant changes in its properties when the temperature alters during the drilling, so the drilling is more complex than ordinary rock drilling in case the ice melts, and particularly if the requirements state that the ice (if it exists) may not melt during the drilling.

5.6 Results and summary of the system and drilling tests

The tests for the MRoSA2 system and tests done in the MIRANDA test bench gave valuable information regarding the robotic drilling concept and the required power and energy values for sampling procedure. In addition, the comparison between the other test setups and drilling test results gave important and interesting perspective regarding the validity of the MIRANDA test bench and the results achieved by the author of this thesis.

The systems tests for the MRoSA2 were efficient in revealing the weaknesses of the different operations and mechanical solutions. The results gave valuable information in designing of the new MASA concept (introduced in Chapter 7), based on the MRoSA2 DSS. The MRoSA2 DSS is in level 3 in the TRL scale (Technology Readiness Level [138]).

The original 'sand box' of the MIRANDA test bench was designed already in 2002 (during the MRoSA2 project) by the author, and the construction was realized in 2003 during the MIRANDA project. The author received a structural design document of the NORCAT Drilling 'sand box' in 2003. It is interesting to compare these two different but similar designs. While there are no exact models of Martian subsurface structure, these test bench models are most probably adequate for testing the drill systems.

During both of the MIRANDA tests (1 and 2), the rock core sample tended to break occasionally. This was even more problematic in the MIRANDA-2 tests. Two reasons could be found, although both of them are more like 'educated guesses': 1) When the rock is more porous than another one, it breaks the core more often. 2) With greater rotational speed the core tends to break more likely. Breaking of the core is not necessarily a problem, if the breaking occurs near the end of the drilling operation, or if the breaking is done so completely that the remainings of the core are very small and transferred away from the bore holes bottom.

Figure 88: The MRoSA2 drill tool and five extracted core samples. Grid size of the paper behind the samples is 7 mm (Image: MA).

Figure 88 shows five different samples. The first sample (from left to right) in the picture is a full-size rock sample. The second and the third are also good samples, although they are not full in length. The fourth sample was broken in three parts because of the porosity of the rock. The last sample was broken (because of sponge-type structure of the calcite target rock) after the first 4 mm of drilling depth was reached.

In addition to the MIRANDA tests, also the MIRANDA-2 tests gave valuable information regarding the drilling efficiency values. The efficiency results of the MIRANDA tests are shown in Table 29. Chapter 7.7 explains possible drilling results by using the energy limits of the ExoMars mission and the drilling efficiency values of the MIRANDA 1 and 2 tests. It has to be emphasized that the drilling results are also a function of the tool geometry. These MIRANDA tests used the MRoSA2 tool, which has a cross-sectional area of 163 mm^2 (of the crown blade), and cross-sectional area of 227 mm^2 of the whole drill tool including the core area.

Table 29: Specific Drilling Energy values for test rocks of the MIRANDA and MIRANDA-2 tests.

Rock	Hardness MPa / Moh	Density kg/m^3	Energy / cm (MRoSA2): kJ	SDE kJ/cm^3	Notes
Mafurite	>250 / >6	2545	1555.2	954.1	M1
Calcite	~50 / 3	2710	6.5	4.0	M1 & verified in M2
Diopside	~120 / 6	3260	14.0	8.6	M2
Diabase	~220 / 5.8	3080	20.9	12.8	M1
Granite	~180 / 6.3	2580	66.6	40.9	M2 results, Table 25.

Note: The fourth column (Energy/cm) is calculated using the MRoSA2 tool. M1 = MIRANDA tests, M2 = MIRANDA-2 tests.

Chapter 5.4.5 summarized the MIRANDA-2 temperature tests. As mentioned, the main focus was to find drilling parameters for the MRoSA2 tool that result in too great temperature rise. The results are used to design the new drill concept, its operational scenario and performance requirements.

The MIRANDA drilling results are consistent in comparison of the MIRANDA-1 and MIRANDA-2 results, but it is also useful to compare the results with other drilling results, such as the Russian Luna drillings (see Chapter 3.2.1), the MER Rock Abrasion Tool (RAT, see Chapter 3.2.2) grindings and to one terrestrial (commercial rock drilling, see Chapter 5.5.3) test results. These tools are compared in Table 30, where also some of the previously mentioned VTT drilling test results (during the MRoSA2 project, see Chapter 5.1) are shown.

It is very difficult to calculate the SDE values for the old Russian Luna drillers, but some fairly good assumptions can be made. According to the references [78], the consumed energy was 700…900 W-min / 35cm sample. The sample diameter (including the drill structure) was 26 mm, and drilling power was 140 W. No exact SDE values can be derived without knowing the drill's cutting area, but an estimate was calculated to be about 15.5 kJ/cm^3, which fits well in the scale of the other test results. Similarly, the SDE value for the MER RAT tool was counted by using the limited information available [101,140]. The value ~28 kJ/cm^3 is well in the scale of the MIRANDA tests.

As stated in Chapter 5.5.3 about terrestrial/commercial drilling operations, typical specific energy values for a hard rock (granite etc.) drilling are in a scale of about 1.7-3.4 cm^3/Wh (1.1-2.1 kJ/cm^3 SDE). The MIRANDA test bench (used in both the MIRANDA and MIRANDA-2 tests) contains the drilling tool of the MRoSA2 drill. The drilling results are comparable to the commercial drilling results, as the results show similar scale in specific drilling energy values. However, one must remember that such parameters, as the drill tool design and target rock material have significant effect to the results. Also the power and force levels in commercial big-scale drillings are usually much higher than in these tests, which result in better efficiency (bigger cuttings from borehole are more energy-effective than gradually "pulverizing" the borehole bottom).

Table 30: Specific Drilling Energy comparison for known drilling studies.

Mission or test	Target material	SDE kJ/cm^3	Notes
MER RAT	Martian rocks	~28 kJ/cm^3	MER Spirit: the first abrasion spot.
Luna 16, 20	Lunar soil	~15.5 kJ/cm^3	Estimated from the known parameters
Commercial drilling tests	Granite	~1…2 kJ/cm^3	High-power drilling
MRoSA2/VTT	Marble (see Table 11)	38.5…470 kJ/cm^3	Tool geometry, force and rot. speed varied
MIRANDA	Various rocks	6.5…66.6 kJ/cm^3	Not counting mafurite
MIRANDA sand drilling	Medium-cohesive sand	<< 1 kJ/cm^3	Estimated result from various measurements. See also Chapter 5.3.4.

Table 30 shows clearly how much variation there are between different test setups, but the results are still in the same scale. It is also clearly seen that low-power drilling is not always very efficient, but using high force (which requires high power) leads to bigger chip size and better overall efficiency.

6. EVALUATION OF FUTURE NEEDS AND PERFORMANCE REQUIREMENTS

The key feature of planetary landers is the ability to analyse the surroundings. In early days of planetary exploration, the landers carried imaging systems, some atmospheric sounders and seismographic sensors. Some landers carried also surface analysis experiments, such as the Venera landers to Venus (Chapter 3.2.3) and Viking landers to Mars (Chapter 3.2.2).

However, all the surface analysis has been concentrated mainly to the surface layers; sand and rocks. There have been drills (Apollo (Chapter 3.2.1) and Venera (Chapter 3.2.3)) but not yet such a sophisticated instrument that could automatically extract deep soil and rock samples from the depths of 1-2 metres. This kind of instrument is an important addition to the payload for future landers and rovers, such as the ESA's ExoMars and NASA's MSL missions. These missions, their objectives and payload requirements, are covered in this chapter.

6.1 Upcoming missions: Their objectives and constrains

The main motivation for this thesis was the idea to design an instrument that could perform deep drilling and sampling in Martian environment. As seen in previous chapters, there have been a few drills in space already, and more in concept level. Some of them have been even worked in prototype level. However, no space drill has ever operated in Mars yet. The aim is to use the existing knowledge of concept instruments and prototypes, and to use the lessons learned from past missions to sketch a drilling and sampling instrument. This instrument should work in real mission and should satisfy the needs for the upcoming missions' requirements.

As this thesis is not a commercial project, the study done here is mainly for academic interests. Anyway, it is the most motivating to design the instrument towards a real mission. For this purpose, the ESA's ExoMars mission is taken as a target mission, and the aim is to fit the concept instrument in the ExoMars mission's requirements.

As for reference, NASA's MSL mission's drill system requirements are also explained to illustrate the differences between the sampling systems of the ExoMars and MSL rovers.

6.1.1 The guidelines in future Mars exploration

The major international space agencies, institutes and science groups have pretty much consistent vision for the future of Mars exploration. Both the NASA and ESA have preliminary plans for Mars sample return missions (MSR) and for human Mars missions.

These following fundamental principles form the future of Mars exploration [96]:

- Mars exploration will be scientifically balanced to the maximum extent feasible within resource constraints.
- The main objectives for Mars exploration are: Life, Climate, Geology and Preparation for human exploration

These points can also be seen as guidelines, which direct the mission objectives to:

- Continue searching for water
- Searching for past or present life
- Finding valuable resources for human missions

All of these objectives will involve deep drilling, so the drill development can be seen not only as a mission specific task (for ESA's ExoMars mission), but also as a mandatory preparation for upcoming missions.

6.1.2 ESA's plans for the 2009 launch window: The ExoMars mission

In early 2002, at its Concurrent Design Facility [21] (CDF), ESA embarked on a 4-month, 30-person design effort to define the first roadmap mission ('Flagship' mission) of the Aurora program; the ExoMars mission. The ExoMars mission will include a Mars rover, which will carry a set of instruments in the rover's payload.

As briefly introduced in Chapter 3.3.1, the ExoMars rover carries a payload called 'Pasteur'. One of the instruments in the payload is a drill, which is supposed to retrieve samples from the Martian regolith. The characteristics of the instrument in the Pasteur payload are shown in Table 31, highlighting the drill parameters:

Table 31: An overview of the instruments included in the Pasteur Payload design [21].

Instrument	Heritage	Mass kg	Dimensions mm	Power W	Operational Time
PanCam	MER Rover (NASA)	2	150x80 diam. camera head without mast	8 W average	5 min for 10 pictures
Subsurface Electromagnetic Sounder	ESA Mars Topical Team	1.5	1000x600x20 antenna on whole rover's underside	10 W	1 min for 8 firings
Drill	Rosetta, but more complex	11	500x160x160	average 10, peak 40, contingency 70	Many hours
SHPS	ESA EMF Phase A Study	5	650x350x150 envelope includes optics	10 W average, 30 W peak	30 min / sample
Microscope	Beagle 2	0.5	112x68x51 within SHPS	3 W average, 6 W peak	10 min / sample
Raman + LIBS	ESA GSTP	1.5	160x160x160 within SHPS	2.5 W average, 3.5 W peak	1.5 min for 200 runs
Oxi-GC/MS	Rosetta, but more complex	7.5	400x600x100	35 W average, 65 W peak	18 min for 3 runs
Life Marker Chip	New development	3	160x200x160	3 W average, 20 W peak	5 min for 2 runs

As mentioned in Table 31, the drill is conceptually a heritage of the Rosetta mission. There are no specific plans yet, but the MRoSA2 (Chapter 4) and the DeeDri (Chapter 3.4.2) drills are probably closer in design than the Rosetta's (Philae Lander's) SD2 drill (see Chapter 3.3.5). The mass allowance is 11 kg (inclusion of the 2-d.o.f. manipulator is uncertain at the current phase of design). Size allowance is 500 mm (height) x 160 mm x 160 mm. Maximum power in nominal operation should not exceed 10 W. Peak power limit is 40 W. The drill must be able to run for several hours during deep and/or hard rock drilling.

The requirements in Table 31 are pretty coarse, and more detailed Pasteur drill system requirements are given in the ExoMars Rover / Pasteur System Requirements Document (PSRD) [95] (see also Appendix IV). The main issues in the PSRD, which affects the conceptual design of the drill, can be summarized roughly as follows:

- Collect subsoil material from down to two-metre depth, and from the surface rocks (req. RM-1-4280 and RM-1-4300 in [95] (Appendix IV)).
- Preserve the physical and chemical properties of the sample.
- Deliver the sample to the Sample Preparation and Distribution Subsystem (SPDS, earlier called 'Sample Preparation and Handling System', SPHS).
- Drill system's mass, size and power are limited.

These scientific and functional requirements lead to other requirements, which are mainly technical issues (sensor knowledge, feedback, cameras etc.). 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.

These requirements form the cornerstone of the Pasteur drill design. The focus in Chapter 7 is to explain how to use the existing information and experience about drill systems to sketch a concept which fulfils the ExoMars' Pasteur drill requirements.

6.1.3 NASA's Mars Science Laboratory mission 2009

NASA's Mars Science Laboratory (MSL, introduced in Chapter 3.3.3), will not contain a drill, but a similar corer/abrader tool than the RAT (see Chapter 3.2.2). The Corer/Abrader will have the following performance stated in Table 32 when drilling rock whose compressive strength ranges up to and including that of hard, dense basalt.

Table 32: Mars Science Laboratory mission's Corer/Abrader tool's required properties [128].

Parameter	Value
Diameter of abraded spot	≥ 3.5 cm
Diameter of core	0.8 - 1.2 cm
Max Length of core	10 - 12 cm
Mass	< 4 kg
Peak power use (Abrading)	< 80 W
Peak power use (Coring)	< 80 W
Rate of Penetration (abrading)	≥ 5mm/hr
Rate of Penetration (coring)	≥ 5cm/hr
Average axial preload force (RMS over any 0.1 s)	< 80 N
Peak 3-axis reaction force to rigid mount	< 200 N
Average Reaction Torque (RMS of 0.1 s)	< 2 Nm
Peak 3-axis reaction torque to rigid mount	< 4 Nm
Maximum lateral force (e.g. when starting hole)	< 15 N
Operational temperature range at mounting I/F	-120C - +35C
Operational atmospheric pressure	1000 -6 mb (air), 6 mb CO_2
Lifetime	≥ 75 holes (10 cm deep), 75 abrasion sites
Depth of abraded spot	≥ 5mm

As the Corer/Abrader is not the main type of instrument concerning this thesis, no detailed explanation of the operation is given. Because the MSL's Corer and Abrader tool is in a relatively early stage of development, the capabilities described in Table 32 are focused on the primary functional requirements. The final, implemented design may bring additional capabilities. For example, the ability to re-enter a previously cored hole for further sampling or to enable access to only a subsurface segment is under definition yet.

In addition to the Corer/Abrader tool, the MSL has also another means to acquire surface and shallow subsurface samples. MSL will contain a scoop, which is expected to be capable of acquiring icy mixed regolith and pebbles from the Martian surface, and possibly scraping to acquire sample from exposed surfaces. The scoop would have minimal trenching or digging capability.

6.1.4 Examples of past drilling projects' requirements

While there have been several drilling projects in past, aiming to build a prototype or a concept study in paper only, a few of them are worth of more detailed study. Most of the requirements set to a particular project in past are hard to get, since they are either company-confidential information, or they simply do not exist in any public domain. What are even harder to get, are the results of these projects. A table/matrix showing clearly the achieved requirements, indicating also descoped goals and possible failures, would be very useful and informative, but unfortunately –and understandably – these are rarely published.

The MRoSA2 project's requirements and results are shown in Chapter 4.5 (Table 9). As can be seen, the requirements are close to the ExoMars missions' Pasteur Drill requirements (shown in whole in Appendix IV). Table 9 serves also as a basis for 'lessons learned' publication [1], which was written in 2002 by the author.

The DeeDri drill (explained briefly in Chapter 3.4.2) serves also as a good example regarding this thesis. DeeDri is very similar to the MRoSA2 and the concept of the ExoMars drill, and DeeDri was one instrument candidate to the NASA's 2003 Mars Surveyor lander mission. The 'Proposal Information Package' (PIP) [112], written in 1999, is public document, and states the following functional requirements for the drill instrument:

The Drill system will provide the following functionalities:

- *To collect core samples and deposit them into the Mars Ascent Vehicle (MAV) for sample return to Earth.*
- *To provide the collected samples to scientific instruments on board the Lander for in situ experimentation.*
- *To allow direct science at surface/subsurface by exploiting specific sensors included into the drill itself. Preliminarily, the following sensors can be considered: temperature, optical for stratigraphy, resistivity, radioactivity measurement.*

The Drill system will operate with a high degree of autonomy.

In addition to the high-level, functional requirements, the following system specifications were applicable (Table 33):

Table 33: DeeDri systems specifications for NASA's 2003 Mars Surveyor program [112].

Parameter	**Value**
drilling depth	0.5 m for the first mission (2003 mission) progressively increasing to TBD metres for the subsequent missions
dimension of collected samples	diameter 7 mm (TBC), length 25 mm (TBC)
Sample typology (powder, solid piece, partially grained,...)	core preferred, as allowed by the soil material consistency
number of collected samples	3 to TBD samples for MAV; TBD for other instruments
soil characteristics to cope with	from soft to very hard soil (basalt like)
sampling area	guided in a range of at least 0.5 m
number of locations to be drilled	any within the sampling area above defined

vertical force (thrust) for drilling	70 - 100 N
torque for drilling	1.5 - 2.0 Nm
power consumption and time to drill 500 mm	20 W, 1 hour to drill medium compressive strength soil (~10 - 20 MPa) 35 W, 5 hours to drill hard compressive strength soil (~100 - 150 MPa)
mass (excluding electronic unit and scientific sensors located in the drill tool)	<12 kg, goal 10kg
mass of electronic unit	<3 kg
dimensions when stowed	L 1360, W 175, H 362 (all TBC)
operational sequence	first operation: collection of the 3 samples for MAV second operation: collection of TBD samples for other instruments third operation: direct science by exploiting sensors accommodated within the drill

The DeeDri was never included in 2003 NASA's Mars mission, but still it is interesting to study these requirements and find similarities to the future missions. As can be seen from the Table 33, it describes very much different instrument that is explained in Chapter 3.4.2 about DeeDri drill. This is because the DeeDri is more like a program than a single project, and under the name 'DeeDri' there have been several drills, different in nature or updated from previous similar prototypes. What is also interesting to see, is that the requirements in Table 33 are similar to the ExoMars drill requirement (Appendix IV), but the ExoMars drill is clearly more challenging to build. The required depth is greater, and the drill dimensions are smaller.

6.2 Summary of requirements

The MSL Corer/Abrader requirements, presented in last chapter, are mainly shown as an example of requirements since it is not very close to the drill tool that is presented in the Chapter 7. The case with the drill tool's requirements of the ExoMars mission is more closely the topic of this thesis, as are the past MRoSA2 and DeeDri requirements.

To summarize the requirements that have been set in past projects, and for those that concern future missions, some similarities can be seen:

- Required drilling depth is in a scale of 0.5 - 2 m.
- Electric power is limited. The scale is few tens of watts.
- Core sample must be collected (from a rock), and the drill must be able to collect also porous samples (from soil). Multiple samples are needed by the same drill, but the tool may have to be changed.
- Drilling must not alter the composition of the sample.
- Drill must be mostly autonomous, accepting high-level commands from Earth.
- Drill must be small (size is in a scale of few tens of centimetres) and the mass is limited (usual scale is 5-15 kg).

All of the requirements, stated above, are typical for every planetary drilling instrument that have been made or studied, and only few differences are seen. The most relevant instrument concept regarding the driller presented in Chapter 7 is the ExoMars drill. This is because it is the newest drill, which is under definition currently, and it has the closest resemblance to the MRoSA2 drill, which is familiar to the author of this thesis.

7. A NEW MODEL OF A MARS DRILLER AND SAMPLE ACQUISITOR

Based on the requirements for the upcoming robotic Mars missions, especially for the ESA's ExoMars mission, the author has derived a concept of a drilling device, which would satisfy the needs for near-future robotic Mars exploration needs (regarding drilling instrument) and the systems requirements of the ExoMars drill. The main concept is named 'MASA', which is an acronym of 'MArs Sample Acquisitor'.

Despite the fact that there have been several drillers and samplers in space missions, and even more as a prototype or concept level, there are no publicly available concept designs yet available of a driller instrument that would satisfy the ExoMars/Pasteur Drill System needs.

The author presents the MASA concept in this chapter, and the emphasis has been in comparison against the ExoMars/Pasteur Drill System requirements, and the suitability of this drill for that mission. However, it is notable that the concept proposal for different commercial components, such as actuators and motors, contains mainly non-space qualified items. To qualify the concept prototype for space-use, a more detailed study is needed.

7.1 The MASA drill

The MASA drill is a revolver-type miniature deep-driller and sampler machine. Its main purpose is to be able to drill and sample all kinds of materials that could be found on Mars. The size, mass and power consumption are tightly budgeted, and still the system must be very reliable and robust.

The MASA is based on the MRoSA2 projects (including the original ESA GSTP project and the second ESTEC Purchase project "MRoSA2 Upgrade"), the MIRANDA tests at HUT and the current ESA's ExoMars requirements (based on the 2004 situation [95]). The main focus is to satisfy the ExoMars mission's requirements for offering a concept that could be used as the driller instrument in the Pasteur payload. The objective is not to compete with possibly existing commercial projects, but to offer one solution that is derived from past experience in drill systems and test results.

The MASA drill system constitutes of four modules or units, as shown in Figure 89:

- MASA Drill Unit (DU)
- Drill Positioning Unit (DPU), containing the 'robotic arm' (lever) and Pasteur mechanical and electrical interfaces
- Drill Electronics (DE)
- MASA Application Software (MASW)

The MASW is not a physical structure of the drill system, but it is an essential part of the instrument, as it contains all the functionality and algorithms of the MASA.

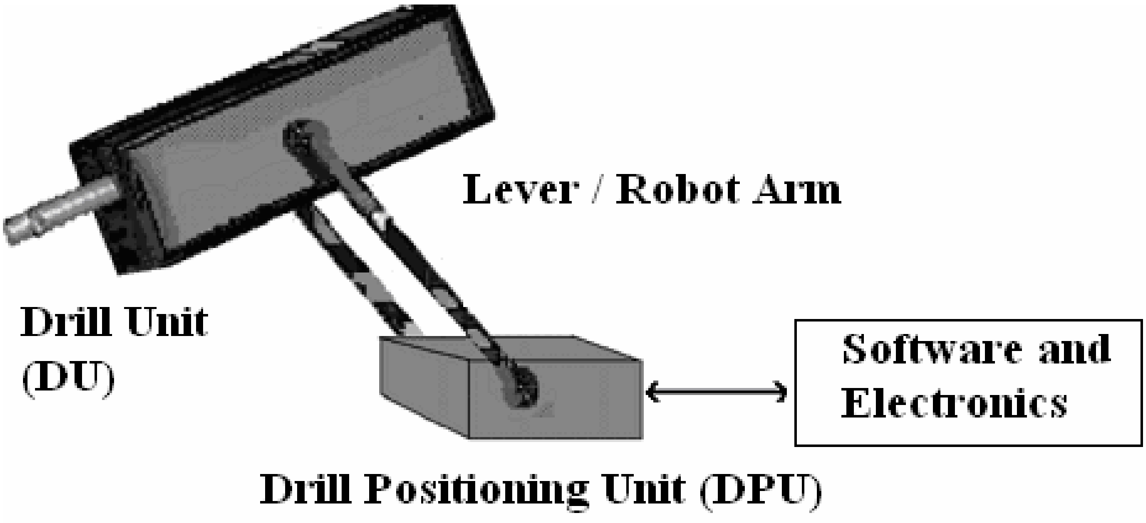


Figure 89: The structure of the MASA drill instrument (Image: MA).

7.2 Design requirements

The design of the MASA drill unit (DU) will be similar in principle to the MRoSA2 design. However, the biggest changes concern the robustness, power, size and mass of the drill unit. These changes are due to the technical and functional requirements set to the Pasteur Drill in the SRD [95], which also lists the complete list of requirements for the drill unit for the Pasteur payload. The same, or more stringent, requirements apply also to the MASA drill. The main functional requirements can be divided into scientific and technical requirements. This classification is explained in below, and the key points are discussed.

7.2.1 Scientific requirements

The scientific requirements determine the goals that are needed to achieve during the operational life of the instrument. In order to satisfy these scientific [95] goals, the MASA drill shall be able to:

- Support Pasteur payload science operations by collecting scientific samples and delivering them to the Sample Preparation and Distribution System (SPDS), and by allowing the precise positioning of the collection devices to obtain the sample from the right spot.
- Capable to collect and deliver samples to the SPDS for further preparation and distribution to other Pasteur instruments.
- Support the search for water in all forms (ice, permafrost, liquid water, water mixtures and solutions (brines), adsorption water, and possibly vapour) in the Martian subsurface. In addition, the Drill Unit shall preserve the possible water fraction in the sample in its original condition.
- Support the search for organic compounds in the Martian subsurface, and preserve the possible organic fraction in the sample.
- Support the search for oxidising agents in the Martian subsurface.
- In the process of obtaining and delivering a sample, the Drill Unit shall not induce physico-chemical degradation or alterations in the sample.
- Through the monitoring of its various sensors' information as a function of penetration progress, the Drill Unit shall support the determination/estimation of the soil's mechanical properties: density, porosity/compaction, hardness/cohesion, cementation, etc.
- The Drill Unit shall be capable to collect samples from within surface rocks.

7.2.2 Technical requirements

The technical requirements define the engineering aspects of the system in more accurate manner than can be derived from the scientific requirements. In brief, the main technical requirements that dominate the design process of the MASA Drill Unit are:

- Physical properties: Size: 160 x 160 x 500 mm, mass: 11 kg
- Drilling depth 2.5 m (Pasteur: ≥ 2 m)
- Multiple sampling (one at a time) from both loose soil and hard rock.
- Sample handling process (drill must not alter the sample)
- Drill will not contain a CPU, but the drill SW will run in the Pasteur CPU.

7.2.3 Functional design aspects

As mentioned, the design of the MASA drill is similar to the MRoSA2 drill, but several changes are proposed. Besides the engineering issues, which are covered from Chapter 7.3 on, there are some high-level design issues that are worth of mentioning:

- Accommodation of the drill unit
- Drilling methods
- Instrument autonomy
- Measurement while drilling capability
- Emergency situations

<u>Accommodation of the drill unit</u>

There are basically two ways to accommodate the drill: in a robot arm, or fixed to the rover chassis. Both of these options have then other variations, concerning mainly the degrees of freedom of the drill unit. Figure 90 illustrates the two accommodation possibilities.

a) *b)*

Figure 90: The two different methods to accommodate the drill unit (Images: ESA). In the left-hand side picture (a), the drill is accommodated directly to the rover chassis. In the second picture (b), the drill is in the end of a short lever ("robot-arm – type accommodation").

Both methods have their benefits and drawbacks. If the drill unit is rigid, i.e. it is mounted to the rover chassis, it has the most counter mass for the drilling operation. This mounting method also reduces the mass of the drill (due to the reduction of mounting accessories, robot arm etc.), and the complexity of the drill system. However, if the drill unit is situated in the end of an arm, it will get better access to different drilling locations within the reach of the mechanical arm. Figure 90b illustrates one concept, in which the drill unit is situated in the end of a lever-type arm, which has two degrees of freedom (d.o.f.). This concept is not much more movable than the rigid drill in Figure 90a, but the main advantage is that it can deliver the samples back to the rover. In NASA's Mars Exploration Rovers (see Chapter 3.2.2), the RAT grinder is located in the end of a very dextrous robot arm (the Instrument Deployment Device, IDD). The IDD has many advantages regarding mobility and reach compared to the robot arm in Figure 90b, but it may not be feasible in the ExoMars rover. The main drawbacks are the complexity, mass and available counter force of the IDD. The DU will be quite heavy and it needs adequate counter force during drilling. The mass budget is tight, and the complexity will increase also the price of the device. Therefore the choice has to be made between the rigid drill and the lever arm mounted drill. These two options will be compared in this thesis. The DU design will be about the same for both models, but there are a few discrepancies regarding for example the sample return after drilling. One most also remember that the choice does not have to be made precisely between these options, but there might also be variations of these both options.

The MASA drill concept includes the lever arm, as illustrated in Figure 91. In position a) (of Figure 91), the drill is stowed. Position b) illustrates horizontal drilling, which can be done in any given angle. One possible drilling attitude is also shown in Figure 91b. Position c) illustrates vertical drilling. Position a) is also one option to return the samples, in case the sample handling station is located in below of the DU.

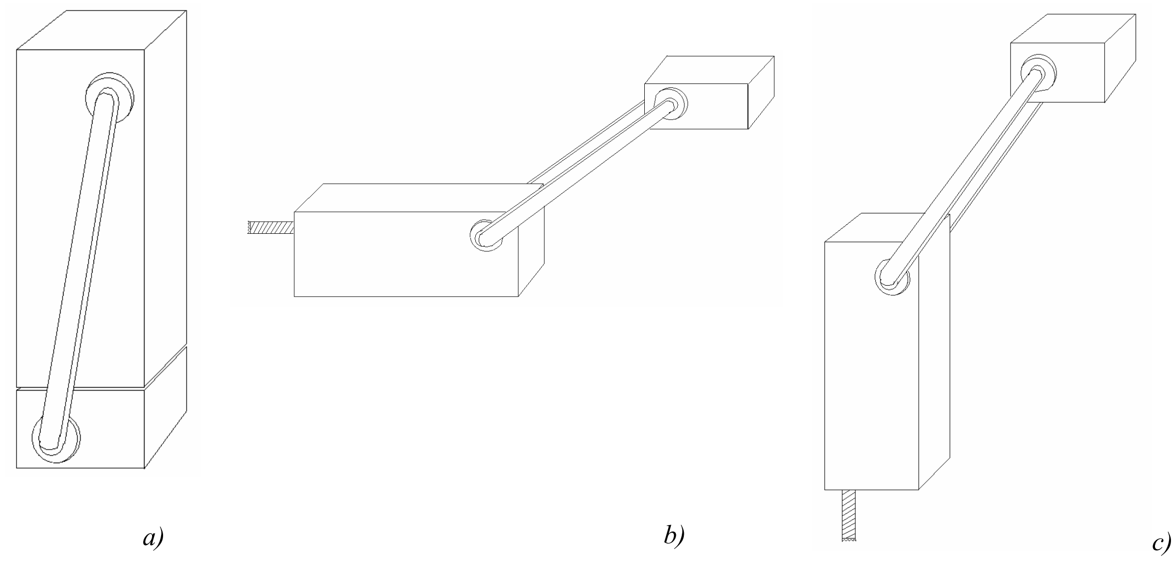


Figure 91: A simplified concept of drilling and sampling subsystem module, the MASA. In position a), the drill is stowed, b) it is lowered to drill in horizontal position, and c) it is lowered to surface for vertical drilling.

Drilling methods

Basically there are three possible drilling methods for this kind of drill: percussive (sonic/ultrasonic), rotary-percussive or traditional rotary drilling. The theory of rotary rock drilling was explained in Chapter 5.3.1. While there have been number of projects worldwide regarding all of these methods, the traditional rotary drilling is by far the simplest way for creating a borehole. Both NASA and the Europeans [108] have experience of ultrasonic devices, and especially NASA JPL has produced several prototypes of ultrasonic driller and corer devices [113]. The original plan was to incorporate a ultrasonic drilling tool to the MRoSA2 drill tool, but this plan was later abandoned due to financial reasons. However, no ultrasonic devices have ever flown yet. The percussive method can be counted to be as ‘brute force’ method, but by right control algorithm it will be much more effective than the traditional drilling. The drawback is always the complexity of the system, not to mention the mass, power and financial budgets.

Although ultrasonic drilling can be counted as percussive method also, in this context percussive drilling is much slower motion than ultrasonic vibration. The percussive drilling technique is based on generating periodic impact forces in order to enhance dynamic crack creation and propagation in the brittle type of drilled materials. In this case the periodic impacts opposite to the static loading can strongly increase the material fracture leading to significant improvement in the drilling rates. In case the amplitude of the impacts is appropriately controlled, the drill bit wear can be even decreased comparing to the rotary drilling method. ESA has plans to study percussive drilling (Appendix I) for future applications.

All the studies performed during the tests regarding this thesis have concentrated mainly on rotary drilling, using the MRoSA2 drill tool geometry. The same methodology is proposed also to the MASA drill instrument.

Instrument autonomy

Adequate autonomy is an essential ability for any kind of Mars drill system. Real-time teleoperation is impossible, since the time delay of two-way telecommunication between Earth and Mars varies from 7 to over 44 minutes, depending on the relative positions of the planets. Operating the drill from Earth would be very difficult and time-consuming, and therefore the rover must control the drill mostly autonomously, with only high-level commands from Earth. This will be covered in more details in Chapter 7.4.

Measurement While Drilling capability

Measurement While Drilling (MWD) instrument capability means that the drill shall be designed to allow either downhole science instruments or instrument heads, which can be used during the drilling operation or during short breaks while commencing the penetration. These instruments can be integrated into drill pipes or into drill tool. During the drilling, the system monitors drill actuator parameters, such as the motor current consumption. Also these parameters can be used to analyze the soil properties in some sense, but the MWD refers to instruments (or instrument heads) in the downhole. The drilling system must also provide a means of transmitting data from the instrument to the surface, either directly to the rover or to the drill unit.

Emergency situations

Recovery tactics from the following emergency situation categories must be considered in design:

- Drill module actuator failure
- Drill jamming and the pipe connection failures

The jamming of the drill string, or an actuator failure may lead to a loss of instrument, but the concept must be designed so, that in emergency situations and in permanent instrument damage situations there is still possibility to conduct some scientific measurements with the remaining capabilities of the drill system. The possible solutions to overcome technical difficulties are explained in Chapter 7.9.

7.3 Mechanical design

The mechanical design of the MASA drill unit (DU) will be similar in principle to the MRoSA2 design. The biggest changes concern the robustness, power, size and mass of the drill unit. Additionally, the mechanics must allow instrument positioning inside the drill pipe/tool, as well as the required wiring (electrical and optical).

7.3.1 General notes about hardware for space-flight environment

The purpose of the Chapter 7 is to introduce the new MASA concept in high architectual level, and the components of the concept are not necessarily *space-qualified*. This means that the actuators and sensors or other hardware are proven to exist in terrestrial or commercial applications, but there was no possibility to study space-qualified components due to the limited space in this study.

In principle, the components that are space-qualified, are more tested and proven to work in the space environment. Naturally all missions have their own requirements. In case of Mars, the components and systems have to be able to withstand the launch, cruise phase, entry/landing and Martian conditions. An overview of these requirements are given in below.

<u>Launch conditions, cruise phase, entry, descent and landing</u>

Launch phase, entry to Mars' atmosphere, descent and landing are the most violent phases of the mission to most of the Mars surface instruments. These phases cause typically G forces in a range of 3 to 10 G, with the maximum occuring at entry phase. The mechanics must have sufficient locking system to prevent it moving during these phases. In addition, if the landing is performed with a 'NASA style' airbag bouncing technology, the mechanics will be in real shock test. These issues are factors, that are greatly dependent on the landing type.

<u>Operational phase on Mars</u>

There are four major issues that affect the MASA instrument's operational phase on Mars: Temperature, pressure, dust and radiation. To qualify for Martian environmental conditions, the instrument must go through rigorous testing phase before the launch.

The temperature on Mars varies in average from -63°C to a maximum temperature of about 25°C and a minimum recorded temperature of -140°C [61] (Chapter 1.3.1). This is the scale, that will be defined in more details after the landing site has been selected. However, the qualification temperature is not the same than the operational temperature. Typical operational temperature range of mechanical instruments on Mars is in a range of -70°C to 45°C [90]. The instrument can also operate in lower temperature, providing that the critical components (e.g. actuators, gears, lubricants) are heated to the minimum operational temperature. For example the MER robot arm's operational minimum temperature is -70°C, but the outside temperature can be as low as -120°C [90].

The surrounding pressure on the surface of Mars is roughly 7 mbar (Appendix III), so it is not a vacuum, and thus somewhat easier environment to some pressure-sensitive components, such as lubricants. Even that the MRoSA2 drill was manufactured to operate in laboratory conditions, there where not much lubricants used. Mostly there were dry ball bearings or smooth plastic surfaces between dynamic components. This is also the case with the MASA drill. Some means of lubricants must be used, but most probably that will be graphite, plastic surfaces or dry ball bearings. Graphite can also be risky regarding the sample analysis, since graphite dust could mix with the sample, and raise false positive results in carbon analysis.

The dust is problematic for MASA drill. Dust accumulates to the mechanics and can cause serious problems. The instrument can not be made hermetically sealed, since the drill string must exit the drill unit. Therefore, there are basically only two methods to avoid dust deposition inside the drill: To have a shutter mechanism in the drill box hole (where the string comes out), or designing the system so that there is some way to clean the drill string when it is lifted back inside the drill box. The shutter mechanism might be needless, since it only prevents the wind-blown dust accumulation inside the box, and that amount of dust is not very much comparing to the dust intake of even one drill run. In addition, a shutter increases the complexity, mass and price of the system. The drill dust and debris are the most hazardous issues here. The drill pipes could be coated with a slippery material that prevents adhesive dust accumulation (passive method), or the hole of the drill box could be equipped with a small ring-shaped brush, which cleans the drill pipe when it is retracted (semi-active method, since there is relative movement between the drill string and the brush). Either way, the electrical and optical connections between the drill pipes and tools will suffer of dust accumulation when the drill is used, and this must be considered in the operational lifetime definition of the instrument.

For an instrument like the MASA drill, the radiation should be not of concern, since the drill itself does not contain sophisticated electronics. Some encoders, optical, inductive or magnetic sensors need to be qualified, naturally, but Mars is not very hostile place regarding radiation damages to larger electronical devices such as DC motors (especially in a time period of a few months only).

Planetary protection

Planetary protection requirements mean that the instrument must be adequately sterilized on Earth, so that it will not carry microbes from Earth to Mars. This requirement is particularly important for the Pasteur payload (including the drill), since the key objective is trying to find possible marks of extinct life. Earth-based microbes could pollute the environment of the rover, leading to false positive results in sample analysis. The planetary protection issue for the Pasteur payload is discussed in [21].

Summary

Summarizing the issues stated above, the MASA drill must withstand the conditions stated in Table 34. The drill must also be properly qualificated (qualification tests) before the instrument can be mounted to the ExoMars rover. These requirements concern in practise only the mechanics and the electrical parts, and in addition the software and electronics must be tested in proper ways also. However, especially the software tests are not dependent on the environmentally conditions, but mostly the dominating issue is the reliability in general.

Table 34: Environmental conditions that the MASA drill must be qualificated to withstand, and test limits for solving the key parameters.

Parameter	**Value**
Temperature	Minimum outside temperature: -120°C Minimum operational temperature: -70°C Maximum temperature: 45°C
Pressure	Minimum pressure: 0 mbar (vacuum) Maximum pressure: 1 bar (Earth atmosphere) Operational pressure: ~7 mbar
Environmental aspects	Dust accumulation tests to mechanics: - Testing of the mechanics with dusty test conditions. - Solving the “jamming” point: What are the weak points of the mechanics regarding the dust accumulation? - Pipe and tool connectors: How does the dust accumulation affect the electrical and optical connections?
Radiation	Radiation tests to the electrical and mechanical components.

Mechanical shock	Mechanical shock tests concerning the following issues: - Launch conditions - Cruise phase (long hibernation phase) - Entry, descent and landing - Nominal drill operations - Emergency operations (increased drilling force, excess load etc.)

There are several studies available on space-qualified hardware (e.g. [90]); some studies [38] are even dedicated to introduce possible hardware for drilling mechanics for Martian conditions.

7.3.2 Drill actuators

When determining the mechanical actuators and structures, the key issues are mass, power and size. On the other hand, the drill unit must be able to perform its duties in feasible time, so it must be powerful enough. The points that must be studied here, from “inside-out” are:

- Linear feed motor
- Rotation motor (power, mass, size, transmission etc.).
- Drill pipe and tool design (pipe type, connections, sampling tools, instrumentation etc.)
- Pipe carousel design
- Tool carousel design
- Clamping mechanism
- Sensors
- Chassis design
- Mounting design (lever arm or other possibilities)

The spindle mechanism (including pipe gripper) and the drill string system including the drilling tool design are explained in Chapter 7.3.3.

<u>Linear feed design</u>

The linear feed system consists of the feed actuator, ball screw rod, sledge (including the spindle system), bearings, sensors and supporting structures. Linear feed is the single most important function in the drill. In case of rotation motor failure the drill can be still used as a penetrator instrument (some penetrators were explained in Chapter 3.1), but in case of feed mechanism failure, the drill becomes useless. The linear feed system (Figure 92) of the MASA drill is basically similar to the MRoSA2 linear feed system, and the main changes concern the robustness and force of the mechanisms. The feed force transmission to the sledge is totally different than in the MRoSA2. This is explained further in this chapter where the sledge design is introduced.

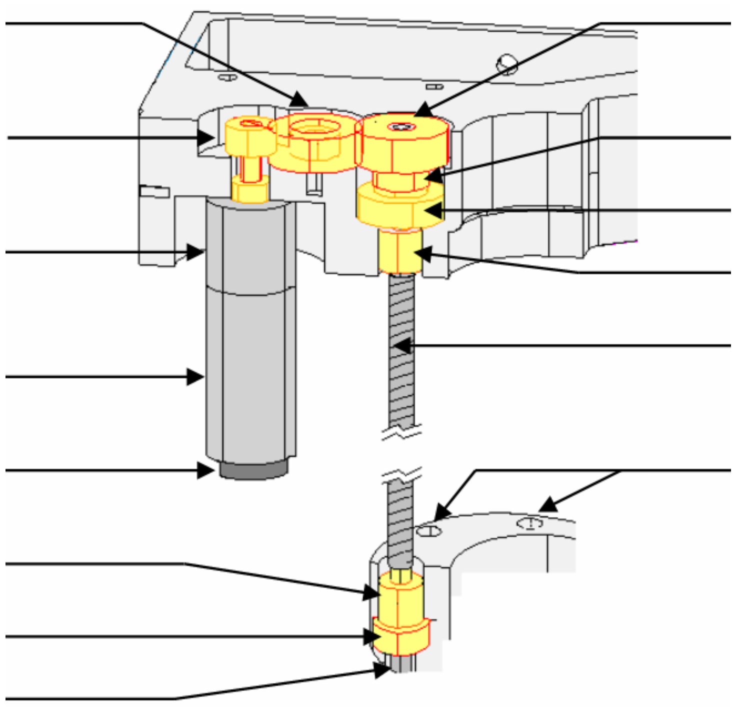


Figure 92: An illustration of the linear feed system of the MASA drill, which is similar to the MRoSA2 design. The image does not show the potentiometer, which indicated the feed position (Image: VTT, MA).

The most important design aspects when designing the linear feed system are the feed force, feed speed and the physical constrains; size, mass and available power. The target platform in this study is ESA's ExoMars rover. When determining the strength of the linear feed system, two different aspects must be considered: the drilling force (in all situations), and possible non-nominal situations.

Screw rod design

According to the drilling tests (Chapter 5.4.4), the maximum drilling force that can be used without generating too much heat due to the friction forces, is in a range of 200-300 N. This force is relatively high when compared to the drilling force of the MRoSA2 DSS (30 N nominal during drilling [89]). However, this force is needed to achieve drilling results in sufficient time. The pipe attachment/detachment force was determined to be 100 N in MRoSA2 project [1]. The maximum required drilling force is therefore defined to be 300 N in nominal situations. But this is not yet enough for the system to withstand in exceptional situations. The worst case scenario is that the rover would stumble or loose its balance during the drilling operation, and the whole weight of the rover would suddenly be faced by the drill string. This is defined to be the critical load, which determines the strength of the feed system (which will carry the load). This load is also called the critical *buckling load* (F_C) of the MASA drill feed system. This is grossly oversized for drilling force requirement (the weight of the ExoMars rover in Mars), but the reason for this is to protect the mechanics of the drill (this approach does not consider the forces to the robot arm). The mass estimate of the ExoMars rover in current phase of design is 220 kg [21], which results to a weight of 820 N in Mars (Mars' gravity is 38% of Earth's gravity). With 25% margin the critical buckling load is then 1025 N.

The critical buckling load determines the maximum force that can be applied by and to the feed system, without damaging the linear feed system's screw rod. The buckling load is calculated by using Euler's formula. Euler analysis applies to slender columns like the MASA drill screw rod. The formula for the critical axial concentric load that causes the column to be on the point of collapse for frictionless pinned ends (no bending moment at the ends) is given below:

$$F_C = \frac{E \cdot I \cdot \pi^2}{L^2} \qquad (9)$$

where:

F_C = critical load (N)
E = Young's modulus (GN/m^2)
I = second moment of area (mm^4)
L = length of the screw rod that carries the force (m)

The illustration of extending the critical load is given in Figure 93, where the drilling force (in –X axis direction) causes equal force to the screw rod (in X axis direction). This causes the screw rod to bend in ±Y axis direction in two-dimensional (X,Y) analysis.

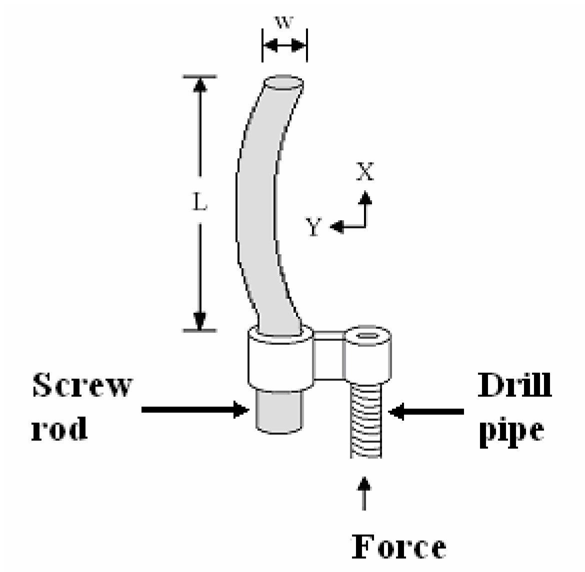


Figure 93: An illustration of the effect of the feed load to the ball screw rod (Image: MA).

The Young's modulus for steel is typically 200 GN/m^2 [130]. The length of the rod determines maximum linear distance of the feed system. The feed distance is 300 mm. It is formed based on the following factors: The MRoSA2 feed distance was 220 mm. The MASA DU has 50 mm longer pipes. In addition the feed has total of 20 mm more space (15 mm divided to upper and lower end as a margin, and 5 mm wider clampers to allow more friction). This result to 295 mm feed distance. The load calculations are made with value 300 mm to allow some margin to the result.

The second moment of area, I, can be used as a measure of how stiff a particular geometry of a structure is, or how well the geometry resists bending. For a cylindrical rod, the second moment of area is $I = \pi D^4/64$, where D is the diameter of the rod. Thus, the minimum diameter (D) for the screw rod is 5.6 mm. A possible ball screw is 'SKF SH 6x2', with 6 mm diameter, 180g/m mass and 1.2 kN dynamical load resistance [129]. The MRoSA2 DSS's screw diameter was 3.56 mm. There is no need for high linear speed, so it is reasonable to choose a screw with the smallest possible pitch. The bearings for the screw have to be fitted also to withstand the same forces than the screw rod.

Linear feed guiding system

There are four linear slides which guides the sledge in the MRoSA2U DSS. The slides are commercial 'NB SNS 5' [89] slides made of stainless steel (Ø = 5 mm). The mounting points of the slides are visible in Figure 92 and the slides are visible in Figure 95. The MASA drill requires longer slides that was used in the MRoSA2U, but the same product can be used (lengths up to 500 mm are available from the manufacturer). The slide-sledge-interface, the nut, is the same as was used in the MRoSA2U:

'SMS 5 Nut', made of stainless steel. The outer diameter is 10 mm and length is 15 mm. The mass of one slide and a nut is 80 g in the MASA concept, consisting of four 295 mm (the length of the movement of the sledge) slides.

Linear feed motor

The original motor-gear combination in the MRoSA2 achieved 600 RPM rotational speed of the screw. During the MRoSA2U (U = 'Upgrade') project, the transmission was increased by a factor of four, resulting to 150 RPM. MRoSA2 screw lead (screw lead during one revolution) was 1 mm. This resulted in 150 mm/minute, or approximately 88 seconds time for full feed distance of 220 mm (with no load). The theoretical force of the motor (not counting the transmission inefficiencies) was 400 N in the MRoSA2 Upgrade project, and 100 N in the MRoSA2 project.

The MASA drill's ball screw 'SKF SH 6x2' has a lead of 2 mm [129], resulting that the MRoSA2U DSS's feed motor-gear combination is not sufficiently powerful for the MASA drill. The MRoSA2U feed motor-gear combination would result in maximum theoretical feed force of 200 N, which is not enough. As mentioned earlier in this chapter, the required drilling force is 300 N, but the motor will have to be a bit stronger due to the transmission inefficiencies and to allow some margin for operation.

In the MRoSA2 DSS, the feed motor is in 'stall' while drilling, ensuring that the drill head follows the drilled surface level. However, this is very inefficient and power-consuming. In the MASA concept, the springs in the sledge system (see Figure 96) ensure that the drill head follows the target surface while drilling.

The motor for linear feed system does not have to be very strong. It is enough that it can (via reduction gears) deliver enough torque to the screw rod, which in turn delivers the force to the sledge (via spring system) and to the drill string. The motor does not have to very fast either, but fast enough to move the feed in sufficient time. In the MRoSA2 (the first project; ended 2001), the feed system moved from one end to another in 22 seconds. In the second project (MRoSA2U), the transmission was greater and the feed time was, as mentioned, 88 seconds. This was still fast enough. Keeping these numbers in mind, the time may be even doubled to fit the same motor to the MASA feed system (which needs two times the torque of the MRoSA2 feed), but the gear transmission have to be two times more than was in the MRoSA2U drill. While drilling, the maximum feed speed is not essential, but it makes only difference when the feed is driven long distances. This happens only in pipe change procedure. There has to be some compromises also. In the final design, a more powerful motor can be used if it is needed. As a baseline, the MASA feed system uses the same 'Maxon RE d10mm 118392' DC motor that was used in the MRoSA2U feed system. The gear transmission has to be doubled from the MRoSA2U's 'Maxon 110308' gear box. With this configuration, the calculated feed end-to-end time is ~200 sec. (±10 sec.), and the maximum feed force in both directions (up and down) is 400 N.

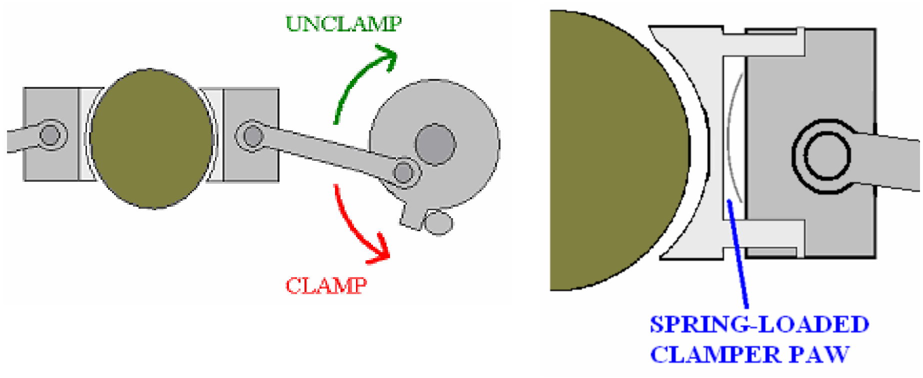
<u>Pipe and tool carousel motors and transmission</u>

The pipe and tool carousel motors are needed to rotate the tool and pipe carousel. The required torque is very small, but the system must be able to monitor the torque by some means (e.g. input current measurement) to find out possibly jamming or other physical wear. There was no need for encoders in the MRoSA2 design, because the position of the carousels was monitored with separate limit (micro) switches. However, the micro switches tended to brake easily, so the MASA concept will have different kind of sensors. The sensor type is not defined here, but one possibility is to use (inductive) resolvers or magnetic (Hall) sensors. Optical sensors are sensitive to dust, and therefore those can be used only if they can be accommodated in a way to minimize any contact with drilling dust. Because of the lack of available space, in tool carousel actuation it is necessary to use as small (in diameter) motors as possible. The MRoSA2 DSS had 'Maxon RE d10' DC motor with gear in the pipe carousel (starting torque 7 nMn) and 'Maxon 118383' DC motor with gear in the tool carousel (0.1 mNm, 0.75W), which are suitable (although not space-qualified) in type also for the MASA DU. It takes ~5 seconds to roll a carousel over (theoretical time without friction or load is 3.2 sec, 18.6 rpm). This is faster than needed, and a further reduction rate (~1: 2 to 1:5) in the gears should be used (to gain also more torque).

Pipe clampers

The pipe clamping device must provide a 100 N linear holding force (which is maximum specified connecting force for the pipe C-ring connections). With a friction coefficient of 0.25 (a pessimistic estimate) the needed clamping force is 400 N.

Because of the clearances the cam wheel cannot be rotated exactly to the dead point (see Figure 94). Basically the same motor and gear configuration than in the MRoSA2 clamping mechanism can be used, but the 'clamp lock' system has to be improved. In the MRoSA2U, the clampers were driven in stall to achieve the maximum holding force. In the MASA DU, the clampers will be equipped with strong leaf springs (Figure 94b), which will allow the clamping cam wheel (Figure 94a) to have some clearance. The MRoSA2 DSS clamping system used two independent 'Maxon RE d13 118430' DC motors and 'Maxon 110 316' gears.



a) *b)*

Figure 94: Clamper concept. In figure a): A mechanical dead stop position of the clampers' over-center-mechanism. In figure b), a spring-loaded clamper paw instead of elastic rubber-like material in the friction pad (Image: MA).

7.3.3 Sledge and spindle design

The sledge is the system that is driven by the linear feed and it contains the nut (the interface to the ball screw rod), the linear slide bushings, and the spindle system with rotary motor and transmission, and other associated subsystems.

Force transmission system

In the MRoSA2 DSS, the sledge was rigidly connected to the nut of the screw rod (see Figure 95). When the screw rod rotated, the sledge moved vertically. In the MASA DU, this system has changed. The nut presses a strong spring, which in turn transmits the push-force to the sledge (Figure 96). The nut can also be locked in a position where the spring has no tension. In this way the sledge can be driven up or down without using the spring system. The nut has a 'ball return' - ball bearing system, "ball nut", to decrese the friction. The sledge has a ball-locking system for locking the nut in one position (as shown in Figure 96). This lock is actuated by miniature linear piezo motor ('PI line M-661.4P0 [143]), which has dimensions of 25x20x8 mm and a mass of 30 g, including linear encoder (to resolve possible lock jamming). The locking force is 3 N and holding force 5 N. The Piezo system could also be replaced my DC motor. A similar system that was used in the MRoSA2U spindle grippers (a miniature DC motor) could be used in the ball-lock also. This would possibly result in less complicate accessory system (electronics), but more complicated transmission system. The spring is a commercial 'AS R C0420-063-0500*S' type spring [142] with two times the nominal wire diameter resulting in 451.4 N maximum compression force before going solid. The free length of the spring is 50.8 mm, solid length is 35.4 mm and outside diameter of 10.7 mm. Spring ratio is 31.89 N/mm.

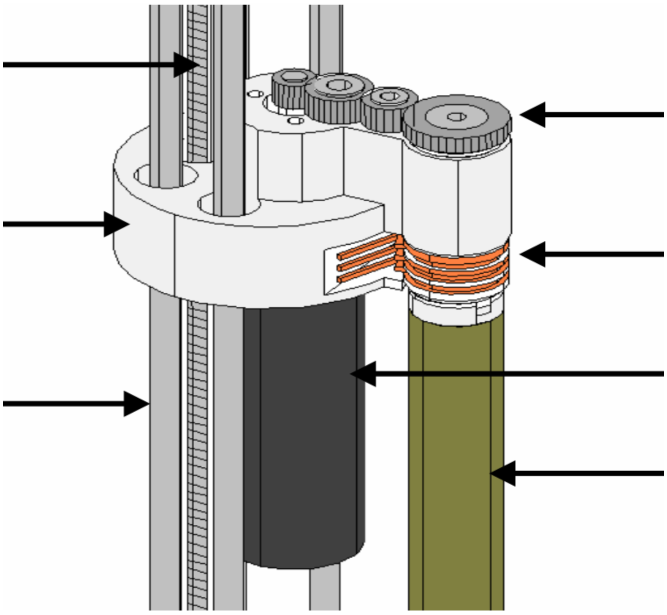


Figure 95: a) The MRoSA2 sledge and spindle principle, with a drill pipe connected to the spindle. (Image: VTT, MA).

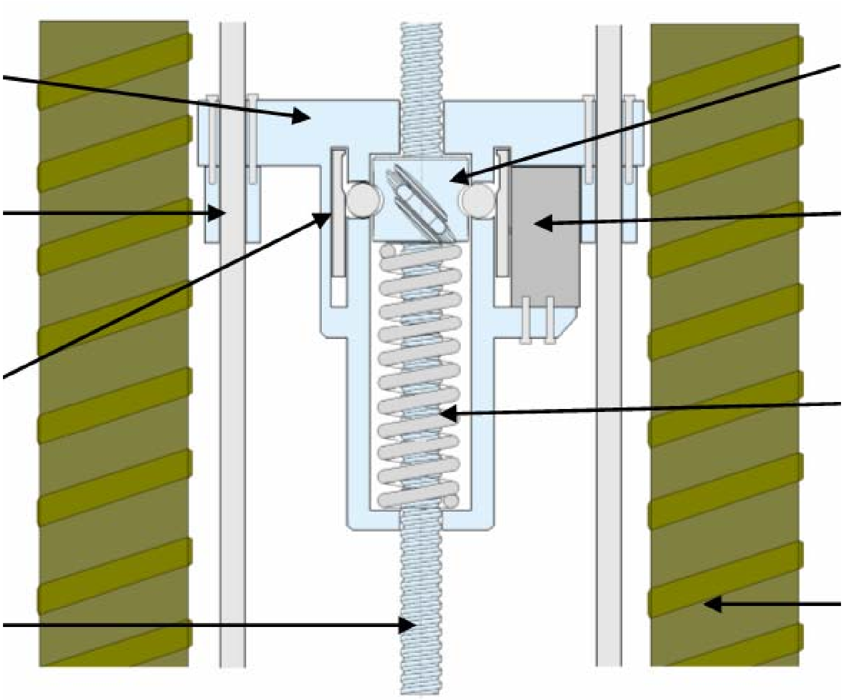


Figure 96: MASA Spindle/sledge design with energy storing spring mechanism. The rotary motor, transmission and spindle are not shown here (Image: MA).

Rotational motor

The MRoSA2U DSS has one DC motor to rotate the drill, and another one to establish the linear movement. The power of the rotation motor is 6 W (Maxon S-motor 2322.980-11.225.200) and maximum torque is 13.3 mNm. Diameter of the motor is 22 mm and length is 87 mm. In addition, an encoder detects the rotational movement (encoder size: 14 mm in length and ~20 mm of diameter). The motor is inside the pipe carousel, so there are bevel gears to transmit the rotation movement to the drill. The encoder was not used in the MRoSA2 or in the MRoSA2U project, since it was detected to be broken in an early phase of the project and too difficult and expensive to replace. In addition, it was not needed in the level of operation that the system was used.

The MASA DU rotational motor is far more powerful than the one used in the MRoSA2 project. The ExoMars/Pasteur SRD [95] states, that the nominal (average) drilling power is 10 W, while peaks may be up to 40 W, and the motor has to be able to deliver 70 W in emergency situations. Because the motor should not be used in over-voltages, the choice is then a 70 W DC motor (a suitable model: brushless Maxon "EC-Max 40", Ø40.0mm [144]) with a gearhead (Planetary GP 42 C Ø 42 mm, 3 - 15 Nm [145]) and a digital encoder (Maxon MR [146]). An estimated mass of the motor-gear-combination with associated structures and sensors is 650 g. The motor accommodation is shown in Figure 97. Note that two of the 12 pipes in the pipe carousel are reserved to include the 'push-rod' mechanism, explained in Figure 100b.

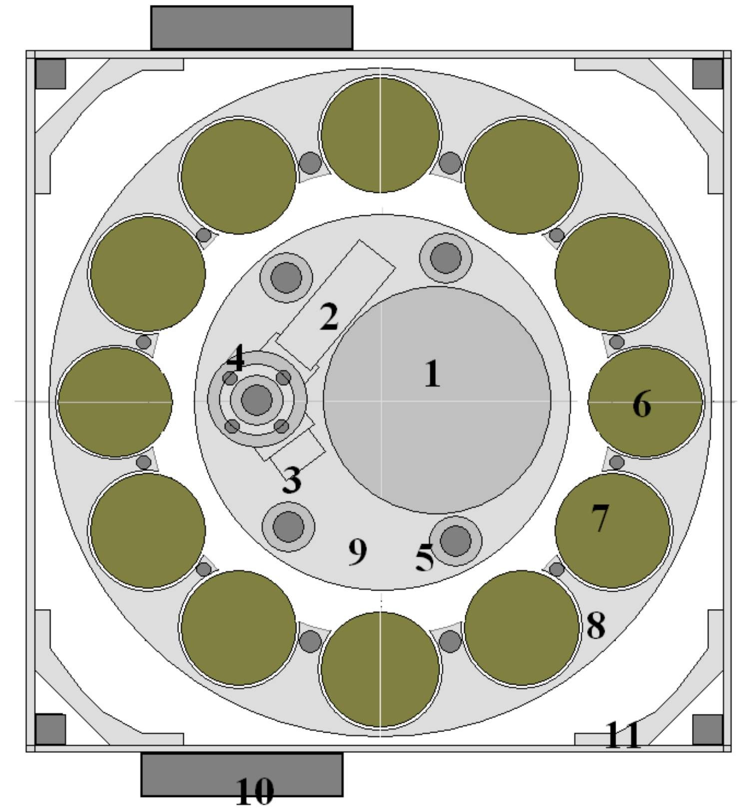


Figure explanation (a cross-section of the MASA DU):

1. *Rotational motor+gear, diam. 42 mm.*
2. *Piezo linear actuator for the ball-lock.*
3. *Position indicator for the ball-lock system.*
4. *Ball-lock system of the spring.*
5. *Linear slide and bushing (one of four).*
6. *The pipe that is currentlu used.*
7. *A pipe (diam. 20 mm) in the pipe carousel.*
8. *Pipe carousel chassis.*
9. *Sledge chassis, diam. 75 mm.*
10. *Robot-arm / lever interface*
11. *Drill box chassis*

Note: The spindle is not shown here, and it would be located on the place of the current pipe (marked with "6"). The width of the drill box is 140 x 140 mm, not including the lever interfaces (MRoSA2 width was 110 x 110 mm).

Figure 97: The rotational motor location in the sledge, inside the pipe carousel (Image: MA).

The maximum nominal rotational speed of the motor is 8100 rpm (max. allowed 12000 rpm), and stall torque is 510 mNm (max constant torque is 81 mNm). The ratio of 'speed/torque gradient' is 16:1 and it is almost linear throughout the power scale, so the motor fits ideally to this kind of application. It gives large torque also on low voltages. With planetary gearhead [145] the nominal drilling speed will be maintained in a level of 100-200 rpm (pipe rotational speed). However, there are no firm numbers for this, because the drilling parameters must be adjustable for different materials and situations, and based also on the feedback from the temperature sensors. This was a problem on the MRoSA2; there was no possibility to drill with high speeds, and even the highest speed (which was not very high really) was often needed to achieve enough torque for 'almost-stuck' situations.

Drill spindle design

The principle of the drill spindle will be the same than in the MRoSA2U. The biggest changes are the size and connection type (electrical and optical connections). The spindle includes a gripper mechanism, which locks the pipe to the spindle. This mechanism will remain the same that was used in the MRoSA2U design, although there has to be a simple position sensor inside the spindle to mark the positions 'open' and 'close'. This mechanism was shown in Figure 56 of Chapter 4.3.1. The spindle outer structure will be similar to the MRoSA2U's spindle, shown in Figure 95. Only visible difference, besides the size, is a fiber optic rotary joint (FORJ [147]). This FORJ will be connected to the spindle's aft end, after (on top of) the bevel gear (note that spindle head is facing down) as shown in Figure 98. This optical line is reserved for possible instrumentation. Besides the gripper mechanism, the spindle connection is similar to a normal pipe connection (Figure 102). The electric lines (three lines) are carried to the rotating spindle via a slip-ring design.

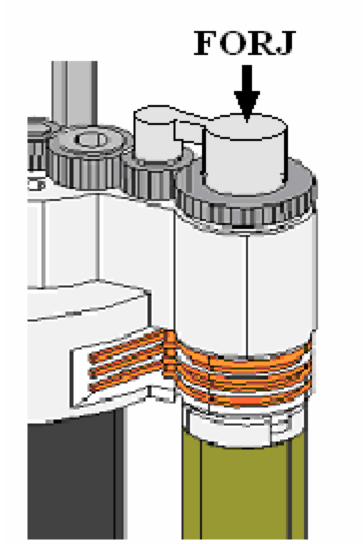


Figure 98: The MASA spindle principle, with a drill pipe connected to the spindle. The FORJ is seen above the spindle's bevel gear (Images: MA).

7.3.4 Drill pipes and tools

The MASA drill string system consists of three different subsystems:

- Drill spindle interface and pipe gripper mechanism.
- Drill pipes, including the connection mechanism.
- Drill tool, including sensors inside the tool.

The structural elements and functional issues, which are to be considered in the design, are:

- Drill pipe architecture
- Drill tool architecture including sample storage and delivering
- Drill spindle, pipe and tool connection mechanism
- Measurement While Drilling (MWD) -capability

The basic design is based on the MRoSA2 concept, but several changes are proposed, as described in the following subchapters.

<u>Drill pipe architechture</u>

The drill pipes are similar to the MRoSA2U design in principle. The inside diameter of the MRoSA2 pipes is 13 mm, outside diameter is 15 mm, and three-ended 'auger' outside the pipe has 17 mm outer diameter. The MASA drill pipes are 20 mm in outside diameter, and the other dimensions in width are also 3 mm wider than the MRoSA2 pipes, respectively.

The MRoSA2U pipes had permanent magnets inside, and the DSS chassis had magnets near the drill string shaft. This system prevented the pipes from falling to the shaft when the carousel rotated. This system was detected to be working, and it is also used in the MASA drill. However, the magnets have to be somewhat stronger in MASA design to improve the reliability, because the pipes are also heavier in mass. These magnets are not sufficiently reliable to be used during rest (not to mention e.g. launch conditions). When the drill is not in use, there must not be a drill pipe in the shaft section of the pipe carousel, or the pipe must be connected to the spindle. The MRoSA2 pipes had a mass of 60 g each, and the MRoSA2U pipes weighted 70 g each (because of the magnets). The MASA pipes are longer and contain the electrical and optical connections, which leads to total estimated mass of 90 g each. The length of the MRoSA2 pipes were 200 mm without the male connector, and the length of the MASA pipes are 250 mm each.

For transfer of a rock sample an additional dedicated drill pipe is used. This drill pipe is similar to the other pipes, but it does not contain the optical interface, but instead of the optical interface it contains a DC motor (and gear + screw rod to achieve the linear motion) driven push-rod (seen in Figure 100), which is used to push the core sample away from the tool. For redundancy, there are two of these push-rod pipes included in the baseline design. They can also be used similarly than normal pipes, but they do not have the optical connection. Later the tool itself is cleaned on a cleaning station of the DPU. In total, there are ten ‘normal’ pipes and two ‘push-rod’ pipes, totaling to 12 pipes in the pipe carousel, as shown in Figure 93.

Drill tool architechture and sample handling

The drill bits are different from the MRoSA2 design. The bits are larger in diameter (MASA 20 mm, MRoSA2 17 mm), and in length (MASA: 60 mm, MRoSA2: 36 mm). This increase in diameter is due to the need of active or passive instrumentation inside the pipes/tools, and the need of electrical and optical connection between the pipes. The increase in tool length is due to the 40 mm sample-length requirement of the ExoMars SRD [95], and the hatch-design of the sample chamber. Also the electrical connector requires more space that was available in the MRoSA2 tool. This increase in size and functionalities leads naturally to an increase of mass too. The mass of the MRoSA2 drill tool was 20 g and the estimated MASA drill tool mass is 45 g. The mass increase is not an issue when considering one tool, but there are ten tools in the MASA drill unit. Note that even though the outer diameter has grown by 3 mm, the core inlet diameter remains in 10 mm. The crown-blade dents have steeper angle to cut more rock away. This consumes more energy, but if the core would be larger in diameter (and thus consuming less energy to cut the ring-shaped hole), it would be far more hard to cut it broken from the rock. This in an important issue, which leads to compromises between low energy consumption and high probability of acquiring good samples.

The comparison of the MRoSA2 and MASA drill tools are shown in Figure 99. As seen, the MRoSA2 drill bit did not have any active sensors or moving parts. In addition, there was never a solution to the problem *how to get the sample out from the drill bit once it was acquired*. This problem was not solved during either of the MRoSA2 projects, since it was not required in the statement of work. The MASA drill tool has an openable hatch in the top of the sample chamber. The core blade is attached on the other side of the hatch and the doors of the hatch are spring-loaded to keep the hatch closed. The center part of the electrical connector is hollow, and the hatch can be pushed to open-position via the center-hole of the tool (this is explained in further below). The inner walls of the MASA drill bit’s sample chamber have ‘steel hairs’, which form a trap for the core sample. As explained in Chapter 5.6, the MRoSA2 drill tool did not always manage to keep the core sample inside, but sometimes it was dropped away. To prevent this, the steel hairs form friction between the sample chambers walls and the core sample. This mechanism works also for porous samples, as long the soil is cohesive or rough-grained enough to stay inside the sample chamber. The clear benefit in this sample chamber design is that the concept is passive in operation. It does not require any electric motor –driven parts or big mechanisms inside the drill pipe (as e.g. the DeeDri design in Chapter 3.4.2, Figure 39b), but the core sample removal must still be done with an active operations (the push-rod shown in Figure 100b).

Some drill tools can be reserved to acquire soft samples only (soil samples). These tools would be similar to the other tools, but including a ‘trap-door’ or ‘mechanical diode’ in the tool bit’s tip. This one-way door would allow soil to come in, but prevent it going out. The ‘push-rod’ would then push the thin metal foil doors open (in downward) direction when the sample is delivered to the SPDS. These kinds of tools were also designed to the MRoSA2 project by VTT Automation (Finland).

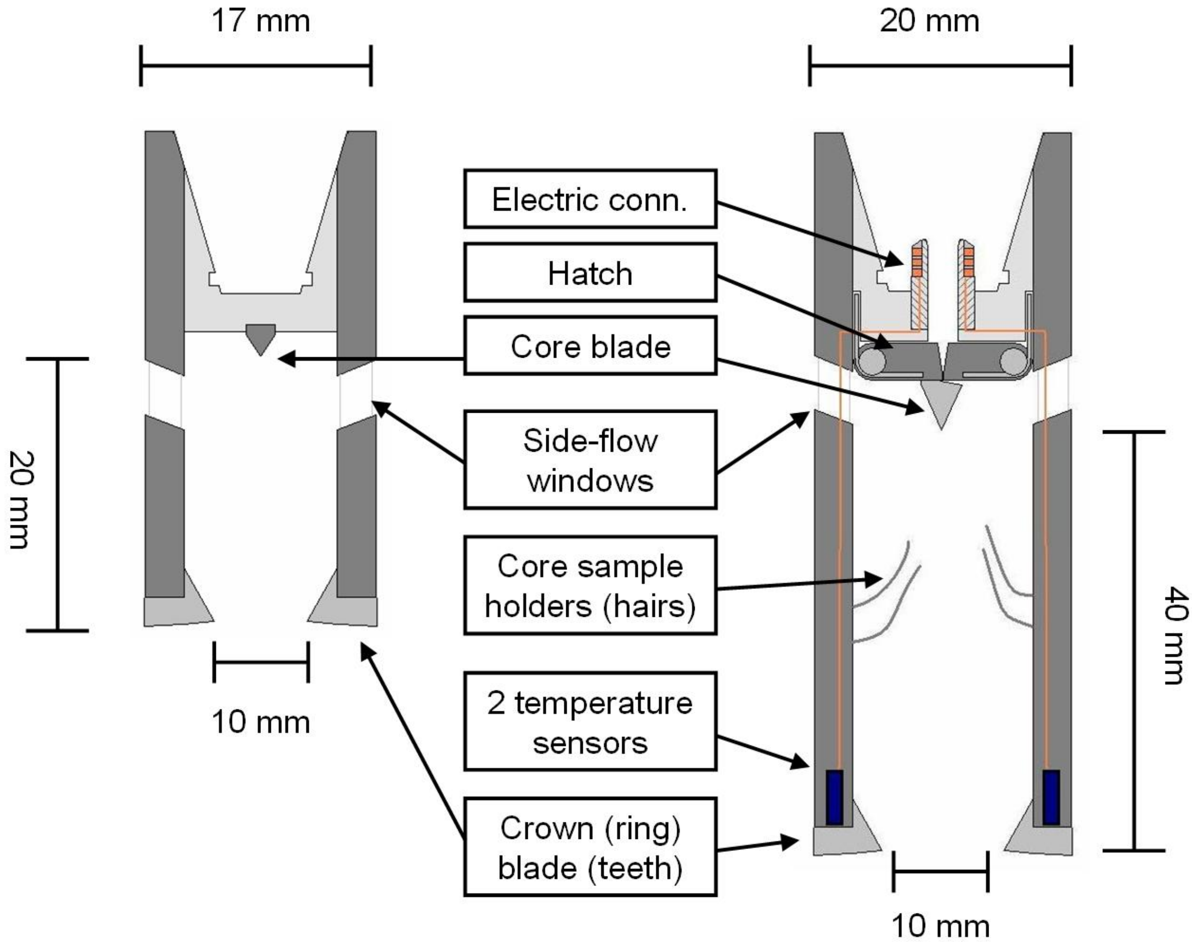


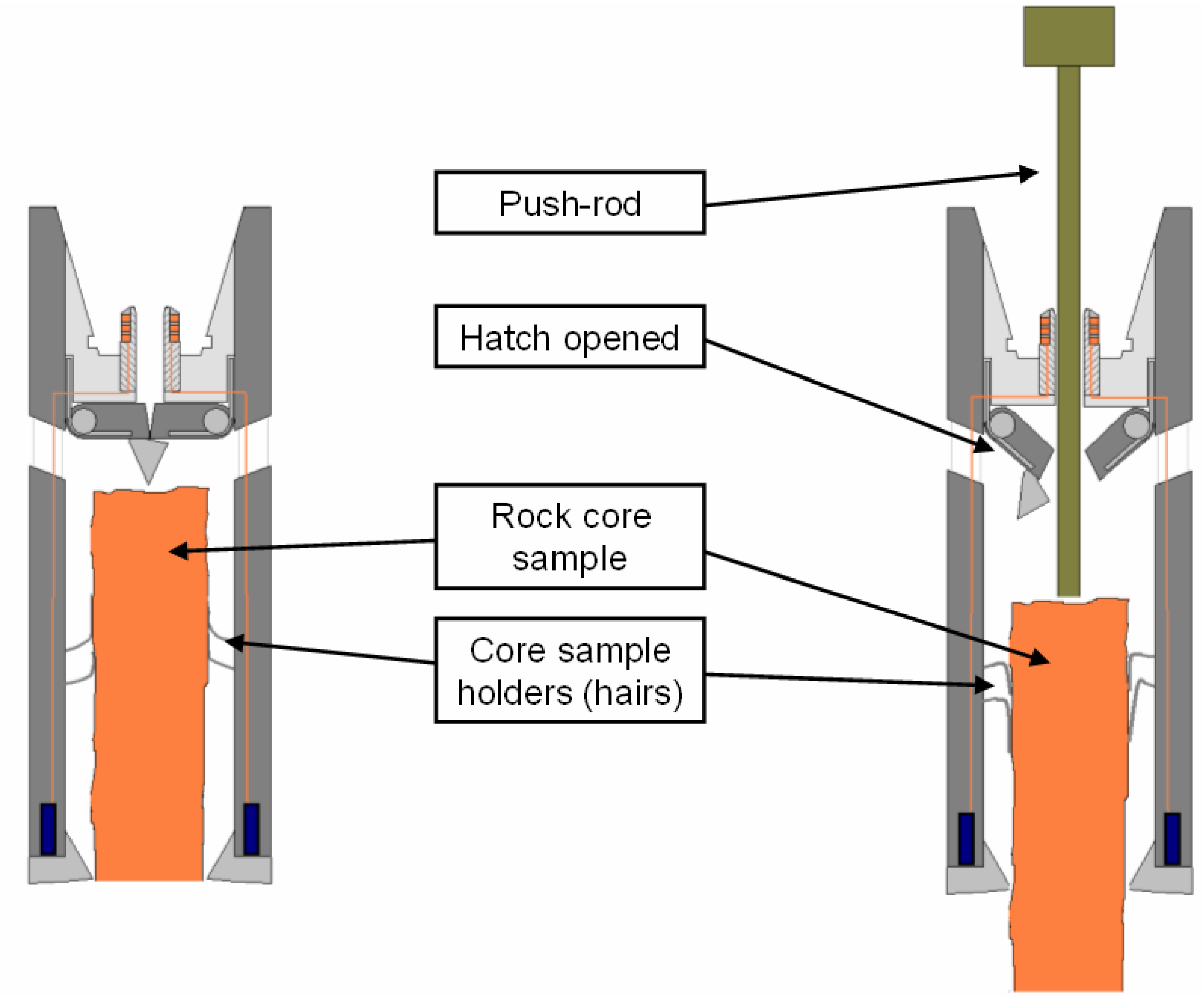
Figure 99: Comparison of the MRoSA2U drill tool (left) and the MASA drill tool (right) (Images: MA).

The design includes also two temperature sensors, which are embedded near to the drill teeth (the "crown blade"). They are being used to monitor the temperature of the sampled material (to avoid too high temperature, which would lead e.g. ice melting), and they are required in the ExoMars/Pasteur SRD.

No definition of the electrical design is offered in this thesis. The solution might be direct analogue contact (with common ground) to the electrical connections, or a micro-chip –based TC/TM data connection. As a baseline, the drill tool is not equipped with an optical connection. There remains a possibility to use optical data devices also in the drill tools, because the pipes have optical connections. There also remains an option for using different types of MWD (Measurement While Drilling) functions, as the drill tools or pipes might be equipped with various kinds of sensors. The tools might also be equipped *only* with sensors, leaving the sample capturing chamber away. This design would turn the drill into a penetrating soil-properties investigation instrument without a sample capturing capability.

As shown in Figure 99, the samples are stored inside the drill bits when the drill is lifted back to the surface. The drill bits are then stored in the slots of the tool carousel of the MASA drill. Since the instrument does not necessarily have the information on sample properties, the sample containers (tool slots) must be able to receive all types of samples; hard rock or loose soil. When returning a sample (and a tool), the drill string (containing one pipe and a tool) is elevated above the tool carousel and desired sample container is selected by rotating the tool carousel.

As mentioned before, a dedicated drill pipe is used for delivering the samples from the drill bit to the SPDS. This delivery mechanism is shown in Figure 100.



a) *b)*

Figure 100: MASA drill tool while sampling. a) Drill bit with full-sized rock core sample. b) Rock core sample being delivered by pushing it out from the drill bit (Images: MA).

Drill spindle, pipe and tool connection mechanism

Being able to rotate the drill also to the counterclockwise (CCW) direction is essential. As seen in Chapter 5.4.6, the drill string might be impossible to pull out from the borehole, and therefore the CCW rotation gives additional lift force during the lifting of the drill string deep from regolith. If the drill pipe connections are typical threaded connections, CCW rotation risks opening a drill string connection. In addition, the CCW rotation is needed in tool exchange operation and in core sampling. Thus, the threaded connection method is not allowed in drill string design.

Threaded connections are usual in terrestrial industrial applications and they were used also in the Apollo mission's ALSD (Chapter 3.2.1, Figure 15). Even though the ALSD drill string outer structure was quite similar to the MRoSA2/MASA drill string, the astronauts needed to use a jack (Chapter 3.2.1, Figure 14) to lift the drill string back to the surface because of the substantially high friction force of the Lunar regolith. The same problem is expected to exist in Martian drilling.

In the MASA drill, as well as in the MRoSA2 drill, the coupling between the drill pipes and between the pipe and spindle is realized with a conical connection that also provides a geometric constraint to transfer torque. The connection is locked with a split ring ('C-ring'), which needs several tens of Newtons' force to be opened (MRoSA2 connections: 30 N). The connection between the spindle and the top-most pipe is further secured with a DC-motor driven locking wedge that anchors the spindle head into the pipe's split-ring interface, thus providing high holding capacity of connection. Electrical and optical connections for sensors and instruments are located concentric in the middle of the spindle and pipe cone using a plug (Figure 102). The MASA drill connections should be able to take 50 N pull-force before opening. This is enough to secure the connections even when lifting the drill string, because the lifting operation is helped with CCW rotation. This leads a little stiffer C-ring design, but the general principle remains the same.

The ends of the pipes include also electrical and optical connectors, as shown in Figure 102. The MRoSA2 connections (Figure 101) were also to have electrical coaxial connector, but the design was later abandoned, because there was no need to include any instruments or sensors to the drill pipes or tools. The MASA drill pipes have one optical fibre running through the pipe, and the pipe ends have optical fibre connectors. The female pipe connector has male electric connector (Figure 102), and an optical connector. The optical connector is spring-loaded to form tight connections with the other pipe’s optical connector. A spline connects the optical fibre to the optical connector. Optical connection is needed for possible instruments in the pipes or in the tools, but the instruments are not specified in the MASA baseline design. One example of potential instrument is the DIBS [135]. The electric connectors are used for reading the drill bit’s temperature sensors.

Optionally, the pipes and/or the drill bit may be equipped with micro chips to be used for different purposes. In this case, the electric lines form a TC/TM data gateway, which is also used for power transfer. If every pipe is equipped with a micro chip, the system can better detect the connections between the pipes. In the baseline design (the electric lines transmit analog temperature data from the drill bit), the system is aware of the overall connection (connection is “on/off” from the spindle to the drill bit).

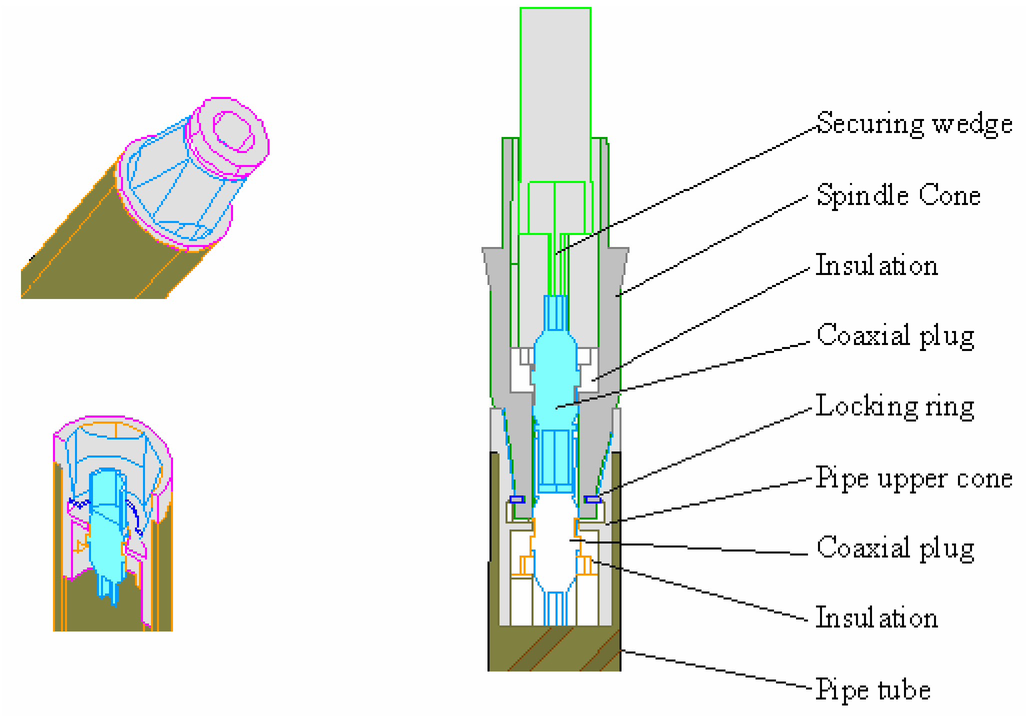


Figure 101: The MRoSA2 pipe connections (left), and the spindle-pipe connection (right). The electrical connection was not used in the final design of the MRoSA2 DSS (Images: VTT, MA).

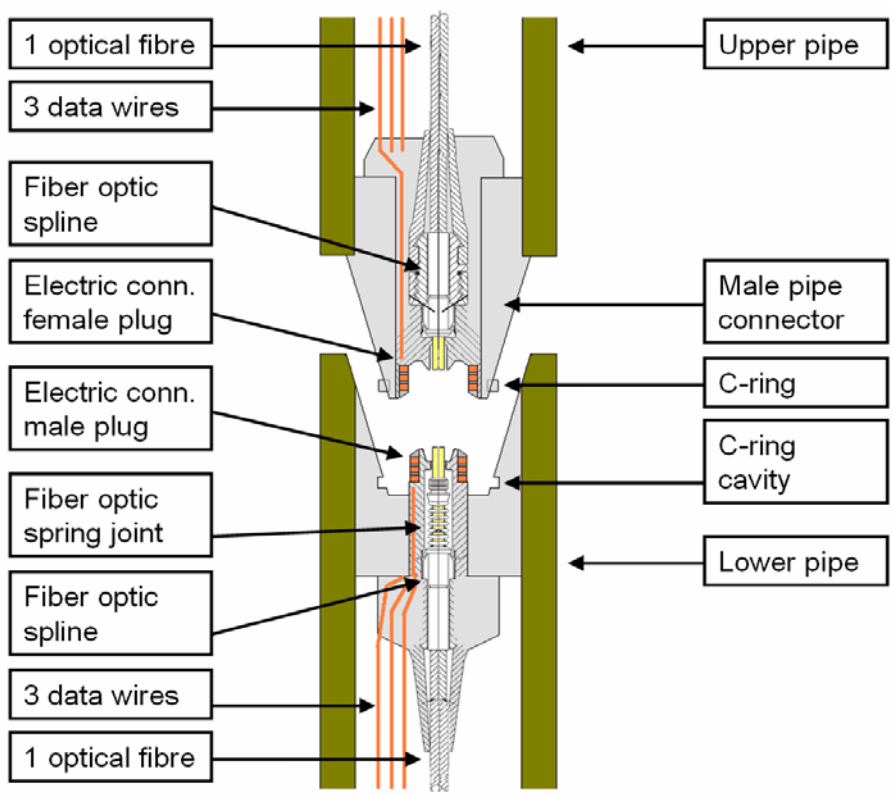


Figure 102: Pipe connection with electrical and optical joint (Image: MA).

<u>Measurement While Drilling (MWD) instrument capability</u>

The MWD principle was introduced in Chapter 7.2.3. The electric lines in the drill string are needed for two purposes in the baseline design: 1) to sense the drill bit temperature (from two independent temperature sensors), and 2) to power the push-rod drill pipes (which are used to deliver the core sample). In addition, there is one optical fiber running through the drill-string, which can be used for several purposes, such as for the DIBS instrument [149]. The temperature readings are monitored throughout the drilling process, but in addition there might be several instruments or instrument heads ("instrument front-end" design, IFE) included in both the drill pipes and/or in the tool.

7.3.5 Drill Positioning Unit design

The Drill Positioning Unit (DPU) is not the topic of this thesis, and thus it is not covered in details. A short introduction is given in below.

The DPU consists of two main parts; the 'DPU box' (interface to the rover), and the lever ('robot-arm'), which is interface to the MASA DU. The ExoMars/Pasteur SRD [95] calls for a DPU that has 2 d.o.f. (degrees of freedom). However, it should be studied whether it would be feasible to use 3 d.o.f. DPU, as shown in Figure 103. The azimuthal rotation may be replaced by rotating the whole rover instead of the DPU only. Whatever the final design, the DPU will not be as dextrous as the MER IDD (Chapter 3.2.2), because the mass limitations of the DPU are strict, and the development of a full-scale robot-arm would be very hard. The main challenge is the rigidity of the design, since the robot-arm needs to offer seceral hundred Newtons counter-force to the drill while drilling.

It would be necessary to equip the DPU with a cleaning station (Brush Station, BS), if it is needed to use the same tools for several times. This BS would be stationary 'hole', with a 'dummy core' inside it. The 'core' and the hole walls would be brush-like material, which would clean the drill tool while it is rotated inside the BS. However, the BS might not be able to clean the drill bit so effectively that the cleaned bit would be free of cross-contamination problems. Therefore a reused bit would always be somewhat 'more dirty' than a non-used drill bit.

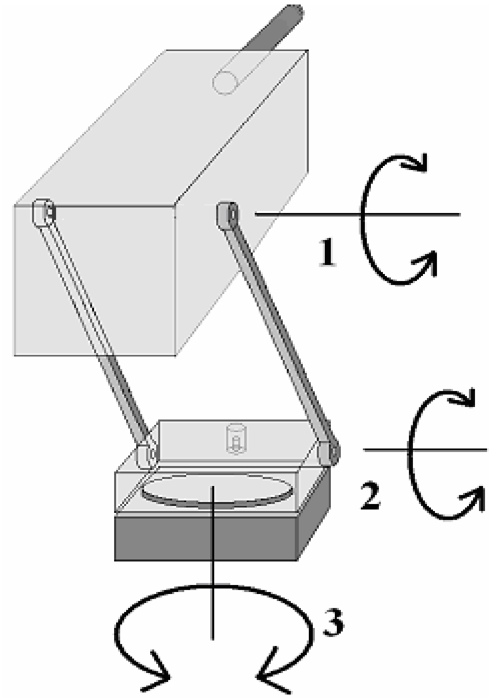


Figure 103: Schematic view of the Drill Positioning Unit (Image: MA).

Figure explanation:

1. *Rotation axis in elevation angle 1.*
2. *Rotation axis in elevation angle 2.*
3. *Rotation axis in azimuth angle.*

Note: The DPU box has a brush station visible. The drill tool is parked to the brush station hole and rotated for cleaning of debris and dust. The lever is shown in a schematically way only. There are no structural elements or actuators shown.

If the Drill Positioning Unit (DPU) has unlatching devices (pyrotechnics etc.) to release the whole DPU module from the Pasteur payload, the rover could go on the mission without the drill in case of severe jamming (possible multiple actuator failure in the drill module). This option should be considered in the design process of the DPU.

7.3.6 Size and mass estimates

Exact dimensions of the MASA drill are estimates in the current phase of design. The width of the MASA DU is 140 x 140 mm, based on the inner structure of the sledge and the surrounding pipe carousel. The the height is longer than the MRoSA2 was. The MRoSA2 was 350 mm in height. The MASA DU contains 50 mm longer pipes and 24 mm longer drill tools. In addition, the sledge should move a little higher and lower in the linear feed's ends to allow some more margins (estimated total increase 15 mm in total, adding another 5 mm for wider clampers to allow more friction). This results to 444 mm total height of the MASA DU.

Mass estimate is very hard to give, but the mass is roughly equivalent to the volumetric increase. The total volume of the DU is 8.70 liters, which is about twice of the volume of the MRoSA2 DSS (4.24 liters). Therefore the estimated mass of the MASA drill would be 9.2 kg. A mass breakdown was also made to the MASA DU, and the results are shown in Appendix VII. As seen, the 9.2 kg mass estimate seems to be very accurate. This value could be played in both directions by using different materials and chassis structural design. The most important issue is that the mass estimate is well within the limits of the Pasteur Drill System SRD, which requires the Drill System be at most 11 kg of mass. The mass and size estimates for the DPU and lever are not given here, since they were not studied in detailed manner.

7.4 Electronics and software design

As the whole MASA drill design is in concept level, the electronics and drill software (MASW) are also explained here in high-level only. The following main issues dominate the design process, based on the references [21] [95]:

- The Drill Unit (drill box) and the Drill Positioning Unit (DPU) can not include the main electronics board(s) (due to the size constrains), and thus not also the software. Therefore the electronics board must be located in the Pasteur payload.
- There is a single interface (I/F) with the rover:
    - The rover sees the Pasteur payload as a single unit with a unique interface (functional/electrical, power, science data, telecommands (TC), telemetry (TM) and housekeeping (HK)). The reason for this approach is the need to test and qualify the package as an independent system during the development process of the payload.
- Rover interaction with Pasteur through macro-commands and telemetry packets.
- Single control unit (CPU) to manage all experiments:
    - It is foreseen to have a fully autonomous facility, able to operate after receipt of macro-commands from the rover. A single control unit will be in charge of communicating with the rover and managing the drill, the SPDS and the other instruments through a CPU.
- Capability of partial or complete reprogramming the Pasteur task list from the Earth:
    - Pasteur will work through a predefined task list, which describes a standard set of operations and scientifical experiments. The list will be reprogrammable from Earth through the interface with the rover.

7.4.1 Drill System electronics

There are two main drivers for the MASA drill system's electronics design: The MRoSA2 (and MRoSA2 Upgrade) project and the requirements for the ExoMars' Pasteur payload [95]. Since they are the closest equivalencies for the MASA drill purposes, they will also be considered here as references.

The requirements document [95] for Pasteur payload states the system requirements, including the requirements concerning the electronics. The Pasteur payload is a set of instruments, and Pasteur communicates directly with the rover computer (CPU). Since the Pasteur payload could be compared to a spacecraft (S/C) bus (satellite main computer system) with a set of instruments (containing their own CPU which communicates with the S/C CPU), it would be quite usual to include CPU's to each of the Pasteur's instruments. This would simplify the logical structure of the Pasteur and reduce the CPU load of it. However, the instruments will not have their own CPU, for the reasons mentioned in [21] and [95]. Having own CPU in payload and other one in rover allows autonomy during testing and redundancy during operations. Figure 104 shows the CPU concept such as the ExoMars/Pasteur concept.

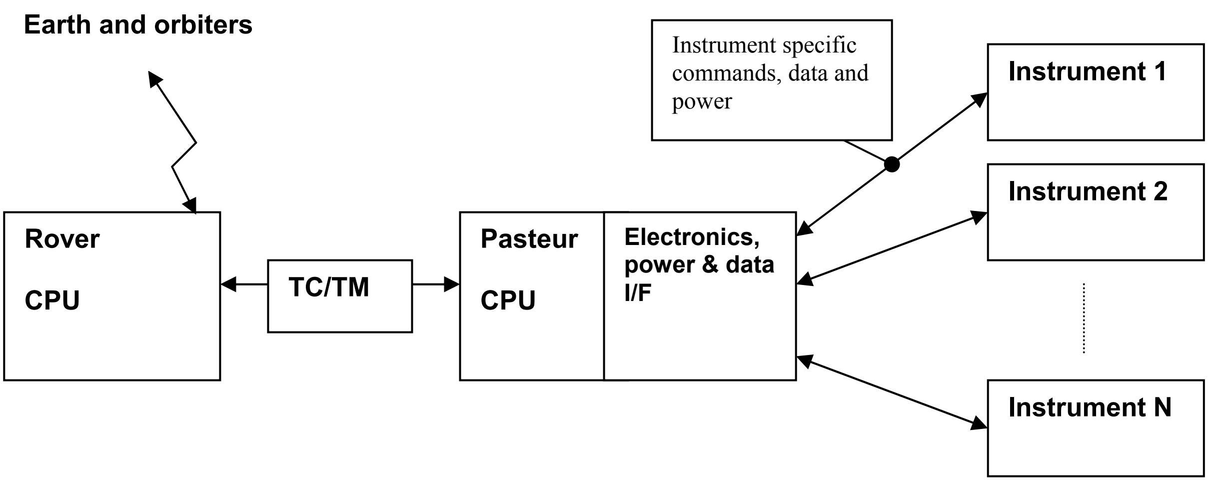


Figure 104: Schematics of the electronics interfaces for the Pasteur payload.

7.4.2 Drill System software

As stated above, there is no dedicated Central Processing Unit (CPU) board for the MASA DU, but the drill is commanded through the Pasteur CPU. There is an electronics board for the drill, which is situated in the Pasteur electronics box. Thus the MASA DU control program runs on the Pasteur CPU.

The functions of the rover control program, the MASA Application Software (MASW), are quite complex. The software:

- Obeys high-level commands from the ExoMars rover's CPU to run the MASA DU.
- Controls the MASA DU for automatic drilling, positioning (by the DPU), and sample delivery, using several motors and mechanisms concurrently.
- Sends housekeeping, monitoring and reporting telemetry (TM) to the ExoMars rover's CPU.
- Includes Failure Detection, Isolation and Recovery (FDIR) functions.
- Enables low-level commands for each single actuator use and sensor readings.
- Enables complete patching and re-programming procedures for the drill SW.
- Enables On-Board Control Procedures (OBCP), which are a set of 'macro commands'.
- Enables testing during the drill and/or rover development phase.

The MASW will be similar to the MRoSA2 control software, presented in [3] by the author, but the autonomy and FDIR capabilities must be improved. Mainly these issues concern autonomic operations due to the long time-delay between Earth and Mars. These issues were noted in the MRoSA2 project, but there was no need to implement them because the MRoSA2 project was more like a technology demonstrator project than a project to implement SW to real Mars mission. However, the MRoSA2 software already includes the ESA Packet Utilization Standard (PUS) services, which are needed in the Pasteur Drill System software also. These PUS services form the baseline structure of the TC/TM communication between the application software and the S/C CPU (the ExoMars rover's CPU in this case).

The expected size of the MASW is a bit larger than the MRoSA2 DSS's control software was, since the MRoSA2 SW did not contain much autonomy. It is not possible to estimate the exact size of the required code memory, but an estimate of one megabyte is accurate enough for the binary image of the compiled MASW code. This is based on the size of the MRoSA2U binary code size (486 kilobytes).

7.5 Alternative concepts derived from the baseline concept

The term 'baseline concept' means the MASA drill concept design that has been introduced in the previous subchapters. The baseline design is shown in Figure 86, and it consists of similar drill module than the MRoSA2 DSS. There are some possibilities to modify the baseline design if needed. These modifications are explained in below.

7.5.1 Tool and sample carousel location

The MASA Drill Unit (DU) consists of all the mechanics that are needed for drilling. The Drill Positioning Unit (DPU) box contains the mechanics that are needed to rotate the drill unit in horizontal direction, and the robot-arm (lever) interface. However, there is also possibility to include the tool and sample container carousel to the DPU, if the DU mass is of concern. However, this would not reduce the total weight of the system. It would possibly lead to a bit more time-consuming drilling, if multiple samples are to be acquired before delivering them to the Sample Preparation & Distribution System (SPDS). This is still an issue to be kept on mind, if the robot-arm (lever) design calls for reduced weight for the DU.

This thesis does not consider the design of the DPU. It is still assumed that it contains at least two mechanical actuators, each responsible for one degree of freedom. The first d.o.f. is the horizontal rotation movement and the second d.o.f. is the lever vertical movement. An additional actuator is on the drill-end of the lever, which is responsible for another vertical movement of the DU.

In addition to the actuators for lever movement, the DPU should include a Brush Station (BS). This BS would be used to clean the used tools from drilling debris. It would still be very difficult to make the BS so effective, that it could clean the tools so completely that no traces of previous samples would exist, and therefore the cleaned tools are considered to be less clean than unused ones.

Chapter 7.3.5 introduced a general conceptual design of the DPU including the BS unit.

7.5.2 Active drill tools and instruments in the drill bit

The basic drill tool model consists of a cutting head and sample chamber and two redundant temperature sensors. The sampling system of the tool might vary if there is a need to sample reliably both loose soil and rock cores. The MASA drill string design is equipped with three copper cables and one optical fiber, which are used for optional additional instrumentation inside the pipes or the tool. One can get great amount of additional information or save energy by using active drill tools, which may contain for example:

- Sensor head (or multiple heads)
- Instrument (one or several)
- Active drilling systems (drill in drill –design)

These drill tool models are discussed in below.

Instrument-in-borehole design and in-situ analysis

The most important function of the drill is naturally the sample retrieval. After the sample has been retrieved, the on-board laboratory will analyse it. In case of ESA's ExoMars rover, the drill will deliver samples to the Pasteur payload's sample handling and preparation system (SHPS). Instead of, or in addition to, analysing the sample in the payload laboratory, it is also possible to make preliminary analysis in-situ in the borehole. If the drill tool (or drill pipe) is equipped with analysis system, some preliminary measurements will be possible without retrieving the sample.

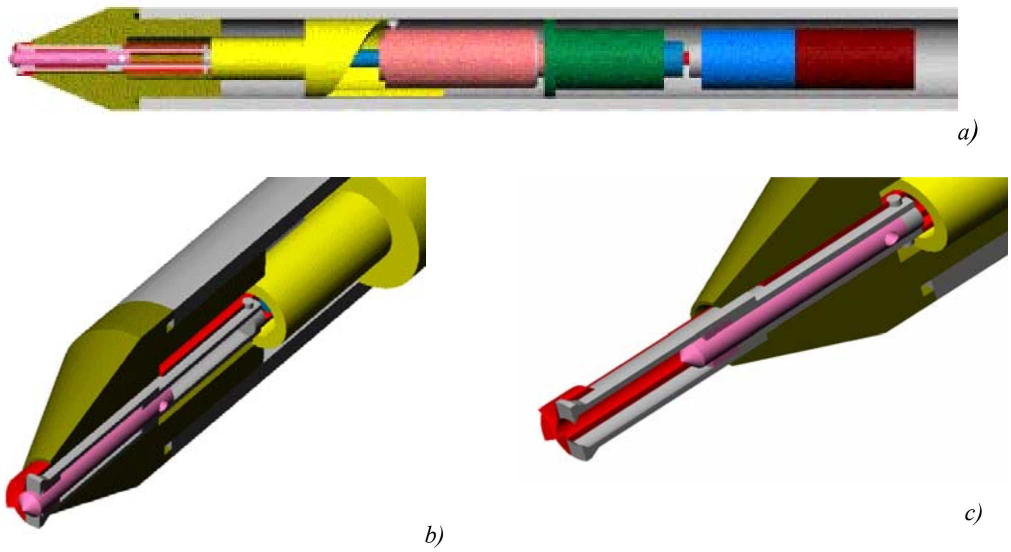
The drill will be lifted up anyway, even if there will be made no analysis in the borehole, so it will not save any time for retrieval operation. However, in-situ analysis has the following benefits:

- Analysis may reveal, whether it is worthwhile to proceed drilling deeper, if the near-surface analysis reveal no interesting measurements (e.g. when trying to find ice). It is notable that drilling to deeper layers may require very much time and energy.
- The sample can be analysed already in-situ (if it isn't needed to make more thorough analysis in payload laboratory), and the same drill tool can be used in the next borehole (the old sample, especially in case of loose material, will flow through the drill tool in next drilling action) without bringing the sample to the laboratory, thus saving some time and energy.
- In-situ analysis will add information from local terrain, like: temperature in subsurface layers, possible moisture, mineral composition, thermal conductivity, electric properties etc. depending on the instrumentation in the drill tool. Even some optical analysis (microscopic photographing) has been studied [135].
- Downhole analysis adds redundancy in case drill retrieval turns out to be unsuccessful.

The first point above is essential regarding the power budget of the Pasteur payload in ExoMars, and similarly in any possible planetary drilling. Even when there is available enough power for drilling so, that the power budget is not critical (such as in case of RTG power source), it will take some time to drill deeper holes even to loose soil. For example, the MRoSA2 drill penetrated approximately 15 cm per minute with no resistance. In addition to this time, one must count also the time to attach the additional drill pipes. Every additional pipe took about 6 minutes to drill (Chapter 5.2.2). In total, even when drilling with no ground resistance at all (drilling in air without anything to penetrate) it will take almost 60 minutes (Table 19) to extend the whole MRoSA2 drill pipe system (which is 2 metre long). Then there will be the retracting time also, which is in this case (nothing to penetrate) about the same than the time taken for drilling. Naturally this time will be far more when drilled in to stiff soil or to a rock. However, the time (and energy) is not the only points to focus here. The *reliability issue* is at least as important. If the drilling is to be made in to deep to regolith, the amount of attachment and detachment phases increases. With autonomous robot technology in Mars, this has to be counted as an important factor too. As an example, using the MRoSA2 DSS to drilling and not counting the influence of penetrated material, a drilling procedure to two metre was demonstrated in Table 19. As it should be noted that the relatively poor reliability in the MRoSA2 Upgrade tests concerns a prototype drill and not a flight model drill, the basic idea is still visible. Even with higher success rate of single operations, the risk of getting stuck or having a malfunction increases drastically with increased amount of single operations (especially in this revolver-type drilling machine).

Drill-in-drill design

There are several design concepts to use a miniature drilling device inside the actual drill tool. One of these concepts, the ´Drill-in-Drill´concept [139], was introduced during the MRoSA2 project. Drill-in-Drill was developed for VTT Finland by the Hong Kong University since VTT was at that time the contractor of the MRoSA2 DSS system. The mini drill is supposed to fit inside a larger drill for subsurface coring. The mechanism is able to core a small rock sample when the drill string faces underground rock. The design is seen in Figure 105. The little core sample is stored inside the drill tool and retrieved back to the surface with the drill string.



a)

b)

c)

Figure 105: The Drill-in-drill design (Image: VTT / T.C. Ng). a) Conceptual image of the system. b) Drill tool tip in ´hidden´position. c) Drill tool tip in core sampling position.

This ´Drill-in-Drill´concept is just one example of the potential instruments inside the drill tool. Naturally larger instruments reservers more space, resulting to the fact that the MASA drill tool can not accommodate all possible instruments. If larger instruments are needed, then one or more drill pipes can be dedicated to act as a drill tool.

Active sample capture chamber

Also the drill tool’s sample chamber may be active in operation. The Drill-in-Drill design (above) contains a sample chamber that is closed before the sampling depth is reached. For loose soil samples, the sample chamber may contain an electric motor driven shutter that is opened and then closed after the sampling depth has been reached.

The list above is not exclusive. There are several issues that might be considered as alternatives in operational and functional design. One issue, for example, is the percussive drilling mode. This is also in ESA's interest (Appendix I).

7.6 Operational concept

The main components of the MASA drilling system are in principle the same as in the MRoSA2 DSS. These subsystems and components are:

- Drill system chassis and interfaces to the robot arm (mechanical and electrical interfaces)
- Tool carousel (ten tool containers and one "empty" slot to drill through)
- Pipe carousel, containing ten pipes (+ two active 'push-rod' pipes, including possibly other type of active pipes/tools also for scientific purposes)
- Drilling motor to rotate the drill string (located on the sledge)
- Linear slide and electric motor to move the drilling motor on its slide with a lead screw.
- Clamping device
- Sensors and electronics.
- Drill Positioning Unit (DPU), including the lever ("robot arm").
- Camera system (as required in the ExoMars SRD). The camera system is not specified in this thesis.

The drilling and sampling function are integrated into one tool bit which is connected to the extendible drill sting. The drill is basically the same that was used in the MRoSA2 project (drill tool image was shown in Chapter 4.2.3, Figure 57), but several changes are proposed regarding sensor technology and sample capturing functionality (see Chapter 7.3.4). In addition to the drilling tools, some drill pipes can be dedicated to serve as an active drilling tools or to contain sensors inside of them.

The drilling function has two degrees of freedom (d.o.f.):

- The first one is the rotary movement of the drill string, which is actuated with an electric motor (Chapter 7.3.3).
- The second d.o.f. is the linear movement. The rotary motor is located on a linear slide to enable the linear feed of the drill actuated by another electric motor with a lead screw and a nut (Chapter 7.3.2).

The carousels both have one rotary degree of freedom and one electric motor each. Also the clamping device, which is used for holding the drill string during the extension or detachment phases, has one degree of freedom.

7.6.1 Initialisation of the MASA Drill

A drilling operation starts with the drill unit (DU) initialisation. The initialisation is done to check the status of all actuators and moving components of the DU. The initialisation was realized to the MRoSA2 DSS during the Upgrade project. In the MASA DU, the initialisation phase consists of:

1. SW/system status check: The main initialisation expects to begin in 'no-pipes-in-shaft' –situation.
2. Electrical systems check: Check all circuits and sensor readings.
3. Pipe gripper status check: Verify that the lock is unlocked.
4. Linear feed position check: Verify that the feed is in top position.
5. Feed spring-system position check: Verify that the spring-ball-lock is on and spring untensed.
6. Pipe carousel check: Verify that the carousel can move, and count the pipes and their places.
7. Tool carousel check: Verify that the carousel can move, and count the tools and their places.
8. Clamper check: Verify that the clampers can move and verify that they are in unclamped position.

Naturally the initialisation sequence might be started from any arbitrary situation, i.e. in a case that the system has been restarted by some reason. In this case, the drilling SW must be able to run the initialisation from the current state on.

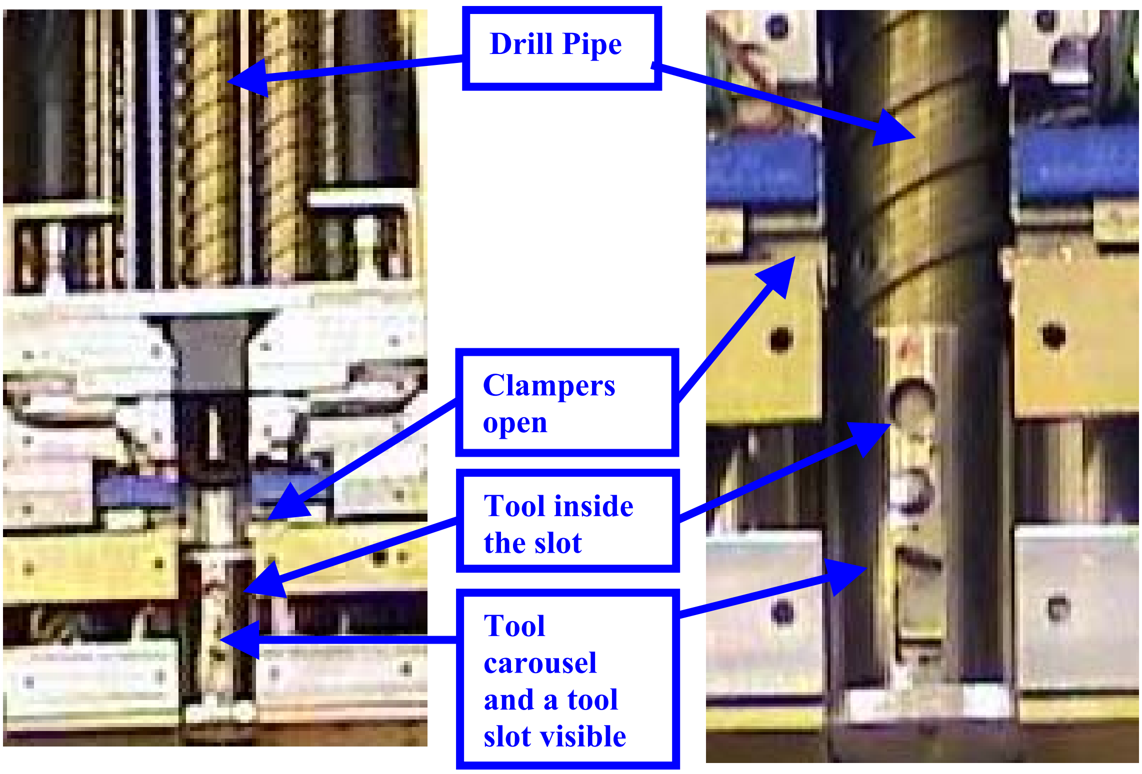
7.6.2 Drilling operation

The drilling operational scenario of the MASA DU is similar to the MRoSA2U DSS operational scenario. The main changes and improvements of the MASA drill concern specifically the issues that make this same operational scenario more reliable and more effective. Taking also into account the fact that the MASA drill is a concept design, not a prototype, it is feasible to take a look of the MRoSA2(U) operational phases (shown in Figure 106). The operational phases while drilling down are shown in Table 35 (more detailed explanation is explained in Appendix II) and in Figure 106:

Table 35: The operational scenario for drilling down (as of the MRoSA2 DSS).

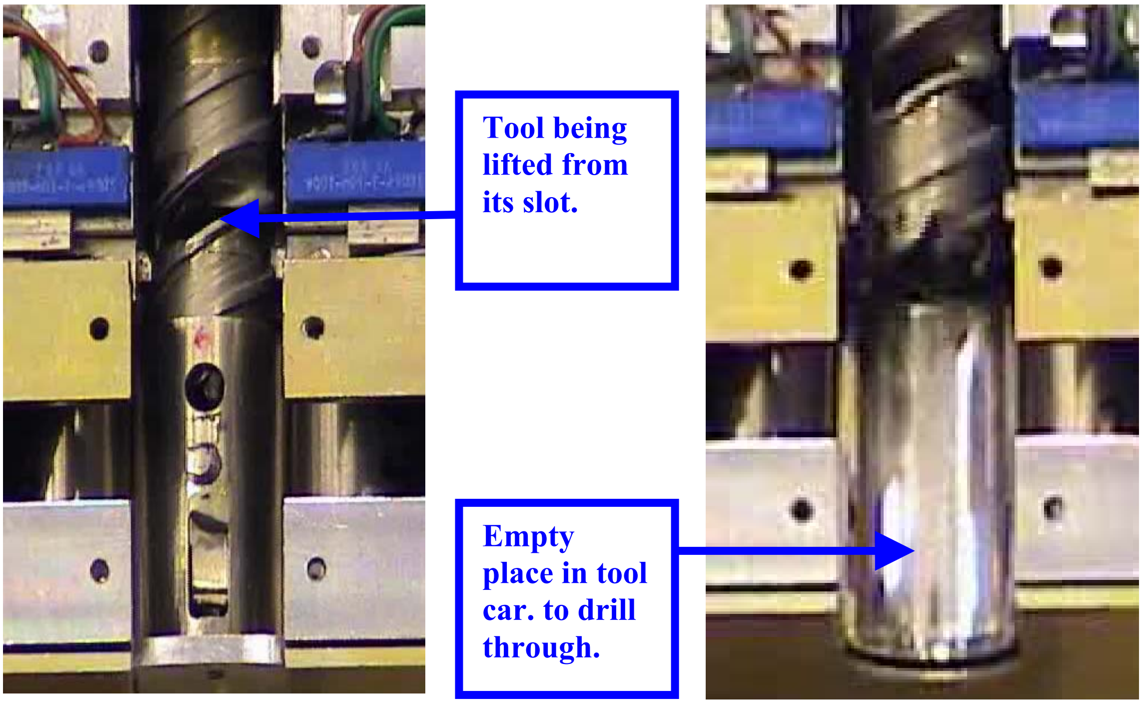
Phase # / Pipe #	Description of the operation
0 / Pipe 0	Initialize the Drill Unit
1 / Pipe 1	Select the first pipe
2 / Pipe 1	Select the first tool
3 / Pipe 1	Connect pipe to tool and spindle to the pipe.
4 / Pipe 1	Lock pipe gripper (to lock the spindle to the pipe)
5 / Pipe 1	Raise tool from its slot from the tool carousel.
6 / Pipe 1	Select ‘tool no. 0’ (which is the empty place in the tool carousel to ‘drill through’)
7 / Pipe 1	Begin drilling until linear feed system reaches its lower limit.
8 / Pipe 1	Clamp drill pipe
9 / Pipe 1	Unlock pipe gripper
10 / Pipe 1	Lift feed to up limit
11 / Pipe 2	Rotate new pipe to the shaft
12 / Pipe 2	Connect the new pipe to the drill string and the uppermost pipe to the spindle.
13 / Pipe 2	Lock pipe gripper
14 / Pipe 2	Open clampers
15 / Pipe 2	Begin drilling until linear feed system reaches its lower limit.
16 / Pipe N	(Continue this way until the desired depth is reached)

Figure 106 below shows these phases with references to the Table 35:



a) Initialize the Drill Unit, find pipe and find tool. Phases 0-2.

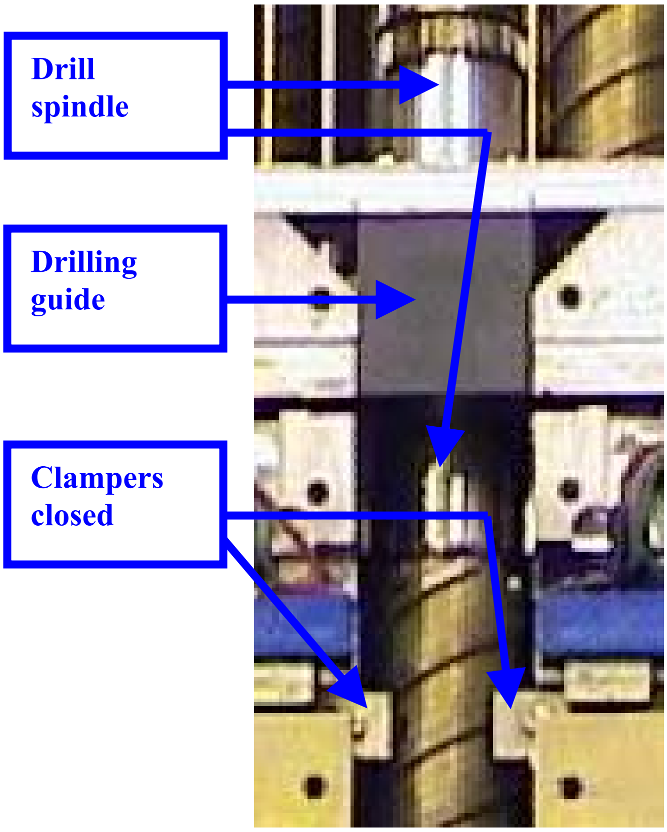
b) Connect Spindle+Pipe+Tool. Phases 3-4.



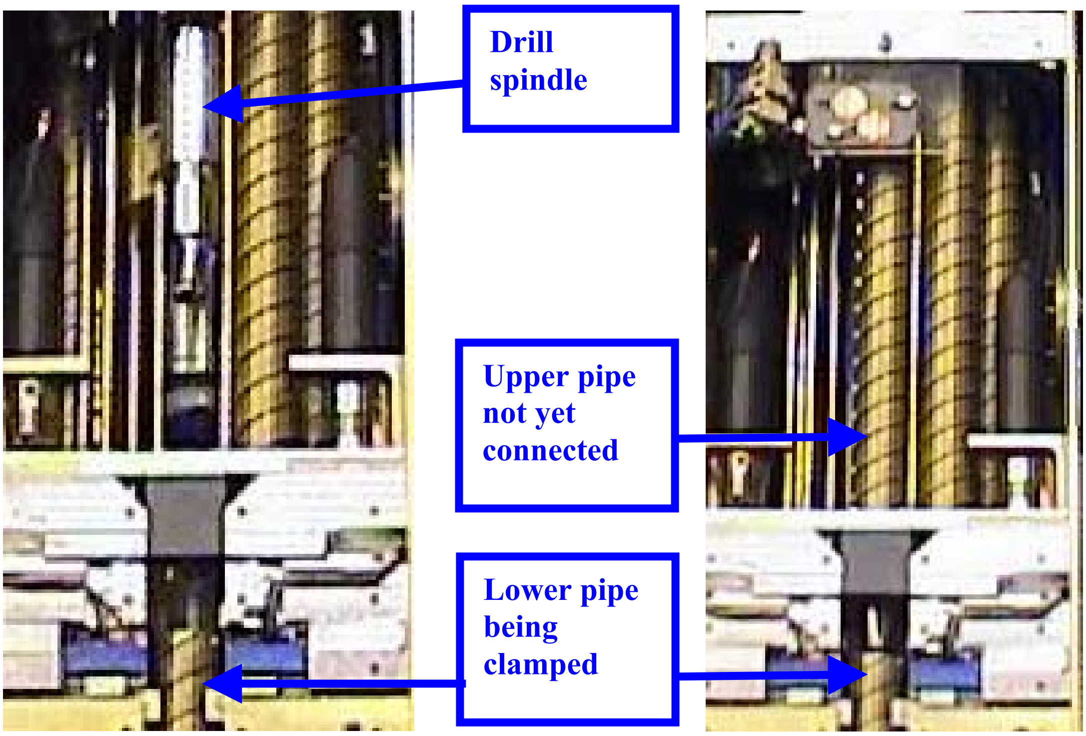
c) Raise tool from the tool carousel. Phase 5.

d) Rotate tool carousel to allow drilling. Phase 6.

g) Begin drilling until feed is down. Phase 7.

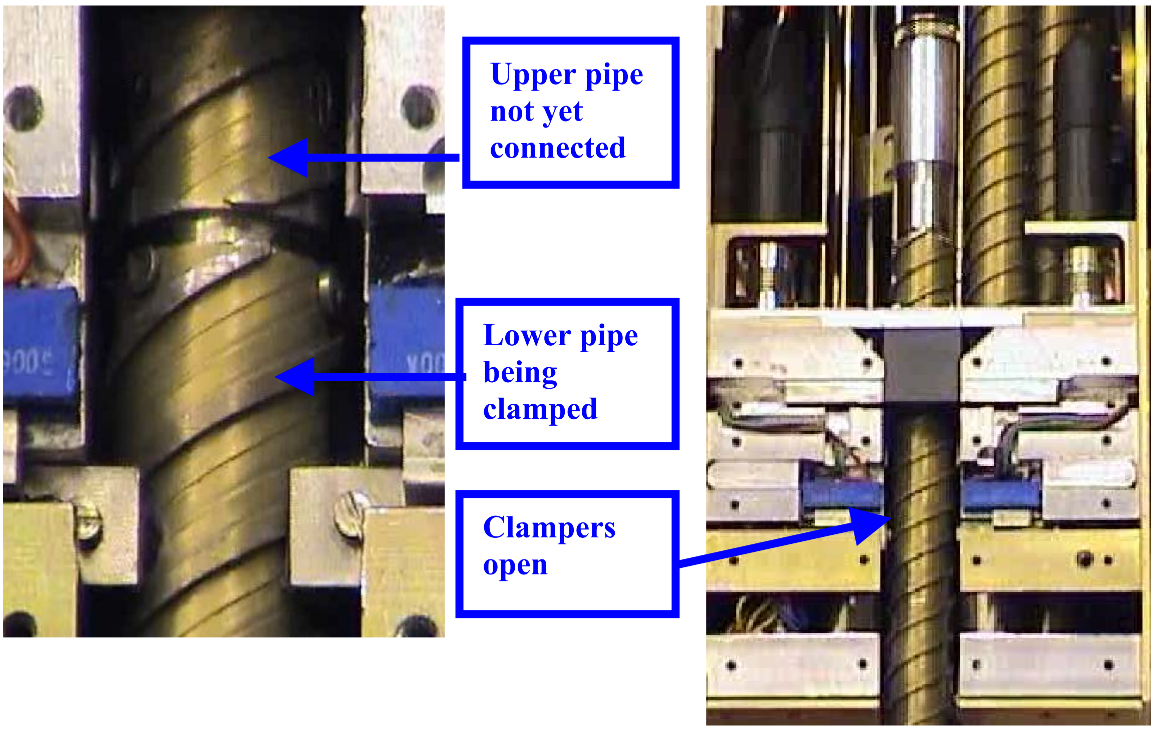


h) Close clampers, open gripper. Phases 8-9.



i) Lift feed up. Phase 10.

j) Find new pipe. Phase 11.



k) Connect pipe to the string and connect spindle to the uppermost pipe (not visible). Phases 12-13.

l) Open clampers, commence drilling. Phases 14-15.

Figure 106: Drilling operational scheme. Images are taken of the MRoSA2U system, and therefore they are not precisely like the MASA drill, but the operational concept remains the same (Images: MA).

Figure 106 above (phases a – l) presented the phases when the drill goes down. When the targeted sampling depth has been reached, the drill rotation direction turns to counter-clockwise direction. This will break the core (if the core has not broken yet spontaneously). Figure 107 illustrated the situation, where the MASA drill tool has reached 50 mm depth and the rock core has not yet been extracted. Retrieving the sample, i.e. lifting the drill, goes in the same manner, but in the opposite way. A used drill tool, containing the sample, is returned to the tool carousel which stores the samples until they are distributed to the Sample Preparation & Distribution System (SPDS). The drill tool can also be returned straight to the SPDS if needed.

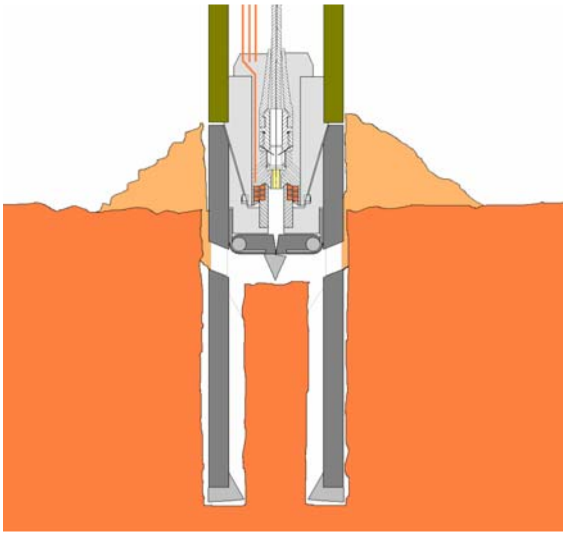


Figure 107: Schematic view of the drill tool in 50 mm depth, while the core sample is still connected to the bedrock (Image: MA).

7.6.3 Sample distribution and handling

The Sample Preparation & Distribution System (SPDS) study was not a part of this thesis, but a short introduction is still given here. After the DU has retrieved the samples and placed them into the tool carousel, inside the tools, they are being stored until bringing them to the SPDS.

As the ExoMars/Pasteur SRD [95] mentions, the objective of the SPDS is to receive samples from the Drill Unit, to prepare them, and to present them to the various analytical instruments of the (Pasteur) payload for study. The SPDS is fundamentally important system, because the quality of the scientific results of the mission depends foremost on the sample being adequately prepared.

The expected SPDS overall mass in Pasteur payload (including all devices, mechanisms, sensors, and their related internal harness), is approximated to be ≤5 kg. Average power consumption is less than 10 W. The next chapter (Chapter 7.7) discusses about the sampling performance. One important term is a ‘measurement cycle’. According to the reference [21], one (ExoMars/Pasteur) measurement cycle is defined as: “the acquisition of a sample by the drill unit and a full set of measurements being performed by all the instruments, working in sequence, each one taking the minimum number of pictures/runs that is considered acceptable from a scientific and statistical point of view”. The average energy required to complete one measurement cycle on each drilled sample is approximately 591 Wh (specified value, equal to 2.1 MJ). Figure 108 presents the sample processing flow in the Pasteur payload [135].

Schematic view of sampling and sample delivery were shown in Figure 107 and Figure 100, respectively.

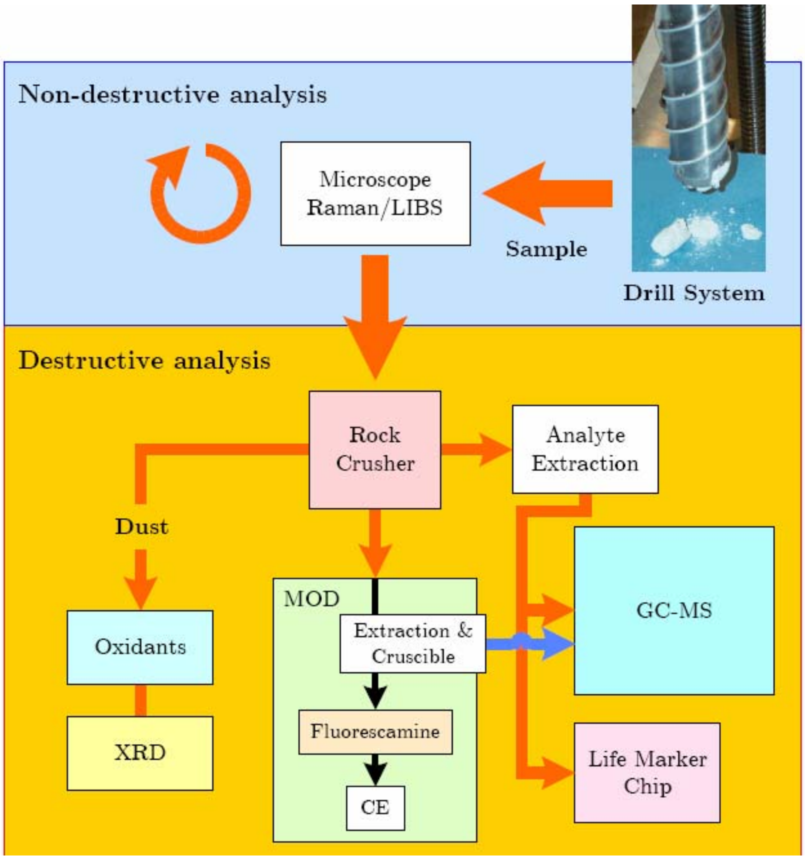


Figure 108: Sample processing flow in the Pasteur payload (Image: ESA).

7.7 Performance calculations

For the 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. On the other hand, there is limited power and energy available for the drill system.

The maximum available drilling power is limited by the capacity of the energy storage and power distribution system of the platform (the ExoMars rover in this case), and the overall power/energy limit is function of to the power distribution unit capacity, the size and efficiency of the solar cells of the platform (or radiothermal generator, RTG, output if the RTG would be used), and the available drilling time.

According to the 'CDF Report 2002' [21], ExoMars rover's Pasteur payload can offer 120 Wh/run for drill unit. This energy is equal to 432 kJ/run, but one must remember that this is just an estimate until the design process of the ExoMars is in more detailed level. A 'run' is defined to be conducted during one 'measurement cycle', which includes also the procedures for handling and analyzing the sample.

Chapters 5.3 and 5.4 about the MIRANDA drilling tests explained the required energy levels to acquire a regolith sample or a rock core sample. The ExoMars SRD [95] calls for a core sample of 10 mm of diameter and 40 mm of length (SRD Req. RM-1-4330). In addition, the SRD states that "When collecting samples from within surface rocks, the Drill System shall be capable of penetrating beyond the weathering rind (estimated to be less than 10 mm) to retrieve the sample". Thus, the minimum sampling depth in nominal cases for acquiring a 'full-sized' sample is 50 mm.

The MIRANDA tests were done using the MRoSA2 drilling hardware, which can exctract a core sample of 17 mm in diameter and 20 mm of length. To fit these different sizes for forming an approximation of MASA drill capabilities (which has similar sampling tool dimensions than the

ExoMars/Pasteur Drill System), a Specific Drilling Energy values are used (see Chapter 5.3.1 about the SDE determintion). The exact design of the ExoMars/Pasteur Drill System's sampling tool is not yet determined, so the calculations here use the MASA drill tool dimensions, which are equal to the Pasteur drill tool dimensions in the current phase of design. The MASA drill tool is 20 mm in outer diameter, 10 mm in core sample chamber diameter, and collects a core of 40 mm in length (as stated in the ExoMars SRD).

The surface area (area of cut) of the crown blade of the MASA tool is then:

$$\begin{aligned} A &= \left(\pi \cdot r_{outer}{}^{2}\right) - \left(\pi \cdot r_{inner}{}^{2}\right) \\ &= \pi\left(10^{2} - 5^{2}\right)\ mm^{2} = 235.5\ mm^{2} = 2.355\ cm^{2} \end{aligned} \tag{10}$$

To extract full 40-mm length core, the volume of cut is:

$$\begin{aligned} V &= d \cdot A \\ &= 40\ mm \cdot 235.5\ mm^{2} = 9420\ mm^{3} = 9.42\ cm^{3} \end{aligned} \tag{11}$$

The volume of rock or soil, corresponding 1 cm of depth and cross-sectional area of the 20-mm diameter MASA drill string, is 3.14 cm^3. This is the volume that must be excavated in every additional centimetre of depth after the drill has reached the depth of 40 mm (corresponding the core sample length). Thus, the volume V of excavated material from a borehole of a depth of D (where D ≥ 4 cm), using the MASA drill, is:

$$\begin{aligned} V &= \left(d \cdot A\right) - V_{core} \\ &= d \cdot A - 3.14\ cm^{3} \end{aligned} \tag{12}$$

where V is in [cm^3], A is in [cm^2] and D is in [cm].

Energy consumption for excavating material volume of V is then:

$$E = SDE \cdot V\ , \tag{13}$$

where SDE is the Specific Drilling Energy (in [J/ cm^3] units).

The SDE values for the MIRANDA tests' target rocks were shown in Chapter 5.6 (Table 29). Based on these values, the energy consumption for MASA drill to acquire a rock sample from a specific rock type and from a given depth is as shown in Table 36 (where 'reaching energies' mean the energy that is needed to go down to a given depth):

Table 36: Estimated sample reaching energies (kJ) for different depths and rock types. Bold font indicates values that exceed the energy limit of a drill run (one run = 432 kJ).

Equivalent rock type	4 cm (1)	5 cm	10 cm	20 cm	50 cm	100 cm	200 cm
No target, just extend drill string (2)	0.25	0.25	0.3	0.4	1.5	5.5	11
Sand	0.50	0.55	0.9	1.6	4.5	11.5	23
Calcite	38	50	113	239	**616**	**1244**	**2501**
Diabase	121	161	362	**764**	**1970**	**3981**	**8002**
Granite	385	**514**	**1156**	**2441**	**6296**	**12721**	**25570**
Mafurite (3)	**8994**	**11991**	**26978**	**56952**	**146874**	**296743**	**596483**

(1) = Depth of 4 cm means that the top of the sample is on the surface level. (2) Based on the MRoSA2U systems tests (Appendix II). (3) Mafurite was very hard to drill, and this example should be noted as 'worst case scenario' for extremely hard target.

Table 36 does not yet show the total energy of retrieving the sample, since the sample must also be lifted to the surface. This lifting operation is not very dependant of the rock type, but merely it is a function of time. In the MIRANDA tests, a value of 10 W-min / 10 cm was used (Chapter 5.3.4), which corresponds to 0.6 kJ per each 10 cm of depth (+ drill pipe detachment operation energy for each pipe). This approximate does not consider the difference of drilling in shallow or drilling in deep layers of soil. However, the energy that is needed to change a pipe must be added.

In case the available energy per sol is, as mentioned in the ExoMars SRD [95], 120Wh/run (432 kJ/run), and if one 'drill run' is considered to be done during one sol (sol = Martian day), it is clearly seen that there is no possibility to acquire deep hard rock samples very often. The energy limit might be possible to divide over several sols, giving the drill *an average* daily energy of 120 Wh/sol. In this case the drill could be used for harder/deeper drilling for one sol (while halting other energy-consuming instruments), and to rest for a few sols after hard, energy-rich sol of drilling.

The cross-sectional area of the MRoSA2 drill was 227 mm^2. MASA drill's cross-sectional area is 314 mm^2. This larger diameter of MASA drill is mainly for accommodating possible instruments or sensor heads inside the drill. However, this leads also to the drawback that the MASA drill needs more energy for penetrating, since the drilled unit volume is 38% larger (ratio: 314/227). If the design would use the MRoSA2 drill tool dimensions, the energy values stated in Table 36 would be 28% less (ratio: 227/314).

The available energy is not very much then. For comparison, the NASA's MSL rover (Chapter 3.3.3) offers 200 Wh/sol [148] for rock coring device, and some scientists have proposed even 600 Wh/sol to be used (for MSL) [6]. The ExoMars rover's expected lifetime is 180 sols [21], which includes 20 to 30 measurement cycles (each lasting six or more sols).

Currently, as shown in Table 36, the MASA drill (by using the energy limits of the Pasteur Drill System) could acquire e.g.:

- one surface sample of granite (4 cm hole depth), or
- one sample of diabase (10 cm hole depth), or
- one sample of calcite (30 cm hole depth), or
- soil samples from depth of whole range (0.. 250) cm.

This is adequate, but not very much. One potential solution to enhance the sampling ability is to decrease the sample length from 40 mm to 20 mm. This would greatly save the energy and reduce the sampling time. However, the sample length depends on the amount of sample material that is required to the sample processing facility, and will be defined in a further phase of the design.

7.8 ESA's ExoMars Requirements vs. MASA Drill Design Matrix

The MASA drill design has been explained in the previous subchapters. The design driver was to maximize the scientific feedback by acquiring good quality samples from the Martian soil and rocks. On the other hand, the focus was to design the instrument concept to fit into the ExoMars/Pasteur requirement frames.

Chapter 4.5 described the MRoSA2 project results against the requirements that were set to the system before the work began. As similar manner Table 37 describes the MASA drill system properties against the ExoMars/Pasteur Drill System requirements, but taking into account that the MASA drill is a concept level.

The first column is the content of the ExoMars/Pasteur requirement stated in the SRD document [95]. The second column is the author's statement whether the MASA drill fulfils the current requirement. A possible longer and more detailed explanation is referred as [RCM-{number}], where 'RCM' indicates to 'Requirement Correspondence Matrix' (Table 37) and the explanation is given in below after the Table 37. The third column is the requirement trace number in the SRD [95].

Table 37: Requirement Correspondence Matrix.

ExoMars/Pasteur Drill System's requirement description	Requirement fulfilled by MASA drill?	ExoMars/Pasteur Drill System req. number [95]
General Functional and Performance Requirements		
Because of the degrading UV and oxidant environment on the Martian surface, analysing protected subsurface material is the only way to ensure scientific results from unaltered samples, particularly important in search for life research. The main objective of the Pasteur Drill System is to collect the samples that will be studied by the Pasteur analytical instruments.	OK [RCM-1]	Requirement has no trace number.
However, the Drill System is also an instrument itself, as it integrates sensors to ensure the "good quality" of the retrieved sample, and others that provide valuable data on soil properties. The Drill System includes the drill(s) proper and all associated sensors.	OK [RCM-2]	Requirement has no trace number.
It is expected that the Drill System's overall mass shall not exceed 11 kg, including margin.	OK [RCM-3]	Requirement has no trace number.
It is expected that the Drill System's power consumption during operations shall not exceed the following values: ≤10 W average, ≤40 W peak, with an extra capability ≥ 70 W to be used solely in case of emergency, if the drill gets stuck and needs to be dislodged.	OK [RCM-4]	Requirement has no trace number.
Specific Functional and Performance Requirements		
The Drill System shall support Pasteur payload science operations: By collecting scientific samples and delivering them to the Sample Preparation and Distribution System (SPDS).	OK [RCM-5]	RM-1-4210 a
The Drill System shall support Pasteur payload science operations: By allowing the precise positioning of the collection devices to obtain the sample from the right spot.	PARTIALLY OK [RCM-6]	RM-1-4210 b
The Drill System shall be capable to collect and deliver samples to the SPDS for further preparation and distribution to other Pasteur instruments. *C: The sample shall be in a suitable condition to undergo the following analysis: optical/morphological, chemical, mineralogical, isotopic, and search for signs of present and extinct life.*	OK [RCM-7]	RM-1-4220
The Drill System shall support the search for water in all forms (ice, permafrost, liquid water, water mixtures and solutions [brines], adsorption water, and possibly vapour) in the Martian subsurface.	PARTIALLY OK [RCM-8]	RM-1-4230
The Drill System shall preserve the possible water fraction in the sample in its original condition. *C: e.g. ice, permafrost.*	OK *As in req. RM-1-4230.*	RM-1-4235
The Drill System shall support the search for organic compounds in the Martian subsurface.	OK [RCM-9]	RM-1-4240
The Drill System shall preserve the possible organic fraction in the sample.	OK *As in RM-1-4240/1.*	RM-1-4240 *(double-numbered req. / similar content)*
The Drill System shall support the search for oxidising agents in the Martian subsurface.	OK [RCM-10]	RM-1-4250

In the process of obtaining and delivering a sample, the Drill System shall not induce physico-chemical degradation or alterations in the sample. *C: This implies, for example, that the sample collection and delivery operation must be completed in a short time to minimise the sample's exposure to reactive substances, present either on the Martian surface or atmosphere. Of particular concern is the possible degradation of organics due to the action of putative oxidants.*	OK [RCM-11]	RM-1-4260
Through the monitoring of its various sensors' information as a function of penetration progress, the Drill System shall support the determination/estimation of the soil's mechanical properties: density, porosity/compaction, hardness/cohesion, cementation, etc.	OK [RCM-12]	RM-1-4270
The Drill System shall be capable to collect subsurface samples down to ≥ 2-m depth. *C: It is recognised that the maximum depth attainable at a given location may depend on a number of factors, such as soil stratigraphy, cohesion/hardness of the various layers to be perforated, available energy, time to operate, etc.*	OK [RCM-13]	RM-1-4280
The Drill System shall be capable to collect samples from within surface rocks.	OK [RCM-14]	RM-1-4290
When collecting samples from within surface rocks, the Drill System shall be capable of penetrating beyond the weathering rind (estimated to be less than 10 mm) to retrieve the sample.	OK [RCM-15]	RM-1-4300
The Drill System shall be capable to penetrate into the subsurface with physical characteristics as modelled in Annex 4 (*Appendix V*).	OK [RCM-16]	RM-1-4310
A Drill sample shall consist of a small cylindrical core (if allowed by the soil material), plus powder material from the same location where the core is obtained. *C: Most instruments require a dust or powder sample. The process of drilling already produces particulate material. This dust/powder, however, may still require further processing before it can be distributed to other instruments.*	OK [RCM-17]	RM-1-4320
The average dimensions of the cylindrical core sample shall be: 4 cm (TBC) in length by 1 cm (TBC) in diameter. *C: It is recognised that the ability to retrieve a small core depends on the hardness of the material; and that in some cases the resulting core may be brittle or fragmented.*	OK [RCM-18]	RM-1-4330
The Drill System shall include redundant temperature sensors capable to estimate the temperature of the sample at the bit contact point.	OK [RCM-19]	RM-1-4350
The Drill System shall be capable to monitor and control its torque.	OK [RCM-20]	RM-1-4360
The Drill System shall be capable to monitor and control its thrust.	OK [RCM-21]	RM-1-4370
The Drill System's operations shall not cause the melting of possible ice inclusions in the sample.	OK [RCM-22]	RM-1-4380
The Drill System shall be capable to monitor and control its penetration depth.	OK [RCM-23]	RM-1-4390
In case a Drill gets stuck and repeated attempts to execute the emergency dislodge manoeuvre are unsuccessful, it shall be possible to release the blocked Drill unit.	PARTIALLY OK [RCM-24]	RM-1-4400

The Drill System shall include a close-proximity camera at its base to help position the bit in the right place to start drilling.	PARTIALLY OK [RCM-25]	RM-1-4410
The Drill System's close-proximity camera shall also be capable to monitor the soil mound formed around the drill shaft at regular intervals. *C: This will permit having a look at the material being excavated by the drill as it progresses into the soil. It provides visual information of the material encountered by the drill bit, and complements the data provided by the other sensors.*	PARTIALLY OK *As in req. RM-1-4410 and in [RCM-25].*	RM-1-4420
Based on information from one or more PanCam images, from the navigation cameras, and with the assistance of the Drill System's close-proximity camera, from a distance of 3 m from the desired target, the rover/ Drill System shall be able to position the drill bit with an accuracy of 1 cm in all directions in a single operation (this means without requiring a further iteration cycle with mission Ground Control).	PARTIALLY OK *As in req. RM-1-4410 and in [RCM-25 and RCM-26].*	RM-1-4430
The Drill System, in its stowed position, shall fit within the rover/descent module's available envelope.	OK (Size is as in SRD)	RM-1-4440
Under no circumstances shall any of the Drill System's deployable elements interfere with the rover's progress on the Martian terrain when executing a traverse.	OK Chapter 7.2.3 about accommodation.	RM-1-4450

Referenced points of the RCM:

[RCM-1] This is also the main purpose of the MASA drill.
[RCM-2] Drill actuator sensors and drill tool sensors are used to determine the soil properties.
[RCM-3] Mass estimate is 9.2 kg, as stated in Chapter 7.3.6
[RCM-4] Maximum rotational power is 70 W. Nominal power is determined by the operator and could be even less than 10 W if needed.
[RCM-5] This is also the main purpose of the MASA drill.
[RCM-6] This ability is performed mainly by the Drill Positioning Unit (DPU). The drill SW is aware of the feed system's vertical position.
[RCM-7] Drilling is done in a way to minimize the alteration of the extracted sample.
[RCM-8] The drill will not melt ice, but the vapour and liquids are sampled only if the tool is compatible to that. This thesis does not go into very details of the sampling tool analysis, but the main purpose is to analyze the concept design of the drill system in whole.
[RCM-9] Drilling is done in a way to minimize the alteration of the extracted sample. The drill bits are not made of carbon-rich material, and the drilling temperature is monitored.
[RCM-10] The drilling temperature is monitored, and the sample should not be exposed to outer environment (especially UV radiation) for a long time.
[RCM-11] As [RCM-9] and [RCM-10].
[RCM-12] Drill actuator sensors and drill tool sensors are used to determine the soil properties.
[RCM-13] Theoretical maximum depth is 2.5 m (10 pipes, 25 cm each). This could even increased to 3.0 m if the both 'push-rod pipes' are used (10+2 pipes, 25 cm each).
[RCM-14] As in [RCM-13] and explained in Chapter 7.7
[RCM-15] As in [RCM-14].
[RCM-16] As in [RCM-14].
[RCM-17] As explained in Chapter 7.3.4.
[RCM-18] As in [RCM-17].
[RCM-19] Drill tool sensors are used to determine the soil properties. See Chapter 7.3.4.
[RCM-20] Drill actuator input parameters are monitored.
[RCM-21] Drill actuator input parameters are monitored, and the feed system has a load cell unit.
[RCM-22] Drill tool sensors are used to determine the temperature.
[RCM-23] The feed system parameters are monitored.
[RCM-24] As in Chapter 7.9.
[RCM-25] Camera design is not included in this thesis. The MASA drill concept does not prevent using a close-proximity camera to aid drilling.
[RCM-26] Camera design or operational use (close-proximity or PanCam) is not included in this thesis.

With the remarks above, the MASA drill concept is compliant with the ExoMars/Pasteur Drill System requirements.

7.9 Operational risks and emergency situation analysis

As with all mechanical devices, failures and malfunctions are not only possible, but also highly probable in some phase of the instrument's life cycle. Even though there have been scoops, corers and even drills before in planetary missions, this MASA drill would be by far the most complex sampling instrument ever on Mars. The complexity is not the only problem, but the small dimensions combined with dusty and dirty environment leads to probable minor or major malfunctions. The problems might be possible to overcome in-situ by intelligent drill application software, or in the most severe cases the ground controllers might find a solution to recover the situation.

7.9.1 Emergency management and recovery plan

In general, recovery tactics from the following emergency situation categories are considered:

- Drill module actuator failure
- Drill jamming and the pipe connections

Drill module actuator failure

There are several electric motors and actuators in the drilling system. Any failures of them affect to the system functionality in some level. The most severe actuator failure is the failure of the feed motor, which ends the drilling operations, because it is not possible to drill or handle samples. The ability to use the drill as a penetrator instrument depends on the drill string length at the moment of failure, and the capabilities of the robot arm. In case the rotary motor fails, the drill will still be capable to be used as a penetrator for shallow soil sampling, possibly not deeper than using one drill pipe's length.

The effect of the pipe carousel failure depends on the conditions:

1. If the carousel is in a position that there is a pipe in the position of the drilling shaft, it will be possible to take many samples, but maximum drilling depth is the length of one drill pipe.
2. If the previous failure happens during drilling, the pipes which are in the borehole can be retrieved, if the length of the string is relatively small (e.g. 1-3 pipes) with respect to the local terrain type and current ground clearance. However, most probably all but one pipes are lost (the top-most pipe can be saved, and used with the other tools in the tool carousel).
3. If the carousel is stuck in a position between pipe slots and the spindle is up, the drill become useless.

The effect of the tool carousel failure depends on the conditions:

1. If the carousel is in a position that there is a drill bit/sample container in the position of the drilling shaft, it will be possible to take one sample at a desired depth by *drilling through the tool carousel's bottom*; however, this is a contingency operation and leads possibly to metal chip remaining in the drill bit's sample container. Only one sample can be delivered to the analysis.
2. If the carousel is in a position that there is an empty bit/container place in the position of the drilling shaft, the drill will become useless.
3. If the carousel is stuck in a position between bit/container places, the drill will become useless.

Jamming of the drill

The drilling tool may jam because of e.g. tool bit failure, drill tool freezing (melted ice re-freezes) or collapse of the borehole. In case of jamming it is important to be able to somehow solve the problem and continue the mission, even with limited resources.

The connections between the motor spindle, drill pipe sections and the drill tool are critical to the function of the drilling system. If the drill bit/sample container is stuck to the drilling shaft, then it is not possible to take any new samples or deliver them to the sample receiver interface, but the sample being drilled can be delivered. In case there are other tools left, the jammed bit-pipe-combination can be abandoned and take a new pair taken into use.

If the connection between two pipes is stuck, then the bit and stucked pipes must be abandoned (if it is possible to detach the spindle–pipe connection). If only a few drill pipes (if the length of the string is relatively small, e.g. 1-3 pipes) are in the drill hole it may be possible to rescue the sample by lifting the linear feed to the top position and lifting drill system box of the rover by using the robot arm.

In any kind of drill actuator or pipe connection failure, there should be no effect to the operation of the ExoMars rover, if the drilling and sampling mission is not counted. The vehicle must be freed from the drill strings in case of total jamming, by releasing the connection between drill motor and drill string, or disconnecting the drill pipes by pulling. The robot arm, which holds the drill system, must have enough lift capability to pull open the connection between two pipes. In case the drill gets totally stuck (e.g. total ice re-melting) in the borehole, when there is just one pipe in the string, and the pipe gripper fails in locked position, there will be no possibility to release the ExoMars rover from the site. If the drill system has pyrotechnic (or similar) unlatch devices to release the whole module, the rover could continue its mission without the drill. This should be considered when the drill module's interface to the rover (Drill Positioning Unit, DPU) is being designed.

7.9.2 Summary of potential technical problems

An explanation of possible system failures are listed in Table 38 below. The list of potential failures is based on the lessons learned of the MRoSA2 operations and it covers mainly situations that are faced during the drill operation due mechanical or functional reason. Possible software reasons are not covered, but some failures are due to the fact that the drill software is unaware of the status of the drill actuator current position (due to other operational reasons).

The first column is the problem description. The second column is a possible reason. It is notable that there might be tens of possible reasons to some problems, and therefore the list covers only the most common reasons. The third column is the approximated severity of the problem in a scale 'mild' (easy to overcome), 'severe' (possible to overcome) and 'fatal' (loss of some/all functions of the drill). A possible solution is given in the fourth column. A possible longer and more detailed explanation of some description is referred as [S-{number}] ('S' = 'Solution'), and the explanation is given in below after the Table 38.

Table 38: Potential failures in drill operation.

OPERATIONAL PHASE / problem description	**Possible reason**	**Severity**	**Solution**
DRILL SYSTEM INITIALISATION			
Feed does not move	1. Carousels not aligned properly. 2. Clampers not properly open and drill string is connected to the spindle. 3. Feed actuator problem.	1. Mild 2. Mild 3. Fatal	1. [S-1] 2. [S-2] 3. [S-3]
Carousels do not move	1. Drill string is connected to the spindle. 2. Carousel actuator problem.	1. Severe 2. Fatal	1. [S-4] 2. [S-5]
Rotation is not working	*See "ROTATING DRILL" below.*		
Pipe gripper is not moving	1. Drill string is connected to the spindle and has tension. 2. Gripper actuator problem.	1. Mild 2. Fatal	1. [S-6] 2. [S-7]
ATTACHING PIPE			
Pipe attachment unsuccessful, but detected.	Pipe alignment and thrust force not compliable.	Mild	Retry operation

Pipe attachment unsuccessful, left undetected. → Drill string connection lost.	Error while determining electrical connection.	Severe	[S-8]
Electrical/optical connection failure	Debris/dust in connectors.	Severe	Retry operation
ATTACHING TOOL			
Tool attachment unsuccessful, but detected.	Tool alignment and thrust force not compliable.	Mild	Retry operation
Tool attachment unsuccessful, left undetected. → Tool connection lost.	Error while determining electrical connection.	Severe	Possible loss of tool → Get new tool
Tool acquisition jammed (from the tool carousel).	Jammed slot (sand etc. debris)	Severe	Possible loss of tool → Get new tool
ROTATING DRILL			
Stiffness in rotation even without drilling.	1. Carousels not aligned properly. 2. Clampers not properly open 3. Dust in rotation actuator transmission	1. Severe 2. Mild 3. Mild	1. [S-9] 2. Re-open clampers 3. Ignore and monitor
Rotation does not work	1. Carousels not aligned properly. 2. Clampers not open 3. Dust in rotation actuator transmission 4. Rotation motor damaged	1. Severe 2. Severe 3. Mild 4. Mild	1. [S-10] 2. [S-11] 3. Ignore and monitor 4. Loss of drilling capability
CLAMPERS			
Clampers can not hold pipe string while attachment	1. Clamping force problem 2. Clampers stuck 3. Clamping actuators not working	1. Mild 2. Severe 3. Fatal	1. Retry 2. Retry 3. [S-12]
Clampers do not close.	1. Clamping position sensors not working. 2. Clamping actuators not working	1. Severe 2. Fatal	1. [S-13] 2. [S-14]
Clampers do not open.	1. Clamping position sensors not working. 2. Clamping actuators not working	1. Severe 2. Fatal	1. [S-15] 2. [S-14].
DETACHING PIPE			
Pipe gripper gives in	1. Pipe gripper was not properly locked 2. Pipe gripper is broken	1. Severe 2. Fatal	1. [S-16] 2. [S-17]
Pipe is permanently stucked to another pipe.	Melted and re-frozen ice or possible debris which blocks the C-ring.	Severe	Ditch pipes.
DETACHING TOOL			
Tool is permanently stucked to the pipe.	Melted and re-frozen ice or possible debris which blocks the C-ring.	Severe	Ditch tool and the last pipe.
Tool is left to tool carousel without pushing it properly down to its slot. Realized when the tool carousel jams.	Error in feed position resolving.	Severe / Fatal	[S-18]
RETRIEVING SAMPLE			

Tool is permanently stucked in the borehole.	Melted and re-frozen ice or possible very adhesive soil or tight rock (jamming).	Severe	Ditch tool and retrieve the pipes by pulling strongly first.
Sample acquisition not successful.	1. Trying to acquire loose sample by a rock sampling tool 2. Sample core does not brake.	1. Mild 2. Mild	1. Change tool. 2. Retry.

Referenced items in Table 38:

[S-1] Carousel position sensors might be misaligned. This has to be verified by several tests.
[S-2] Clamper position sensors might be misaligned. This has to be verified by several tests.
[S-3] In case the feed actuator is broken, the instrument is lost. If the drill string is deep in the borehole, the rover might try to detach the pipe connections by driving away, and resuming other operations without the drilling functionality.
[S-4] The system might be unaware of its current state. This has to be verified by several tests.
[S-5] In case the carousel actuator(s) is broken, the drilling can be done only with the existing drilling configuration, which has to be evaluated in case-by-case basis.
[S-6] Gripper position sensors might be misaligned. This has to be verified by several tests. If the position sensor is the only flaw, the system can be used as before by ignoring the gripper sensor readings.
[S-7] In case the gripper actuator is broken, the instrument is basically lost. Some penetrating measurements are perhaps possible to a loose soil, but the drill string cannot be lifted anymore.
[S-8] If the drill string drops down, the system can try with a new drill string. If the drill string remains in the borehole and the system is axially aligned, the robot arm can possibly be used to reach the drill string. This has to be evaluated in case-by-case basis.
[S-9] Retry carousel alignment
[S-10] As [S-1].
[S-11] As [S-2].
[S-12] The drill string can not be increased or decreased in length. Future operations have to be evaluated in case-by-case basis.
[S-13] Re-adjust the clamping system position sensor limits in the drill SW.
[S-14] Loss of drilling capability. Only current drill string configuration can be used anymore as a drill or penetrator instrument.
[S-15] As [S-13].
[S-16] As [S-6].
[S-17] As [S-7].
[S-18] Try to rotate the tool carousel back to its previous position, and push the tool properly down.

Table 38 above is not exclusive, and as said, it consists mostly of the problems that were encountered during the MRoSA2 and MRoSA2 Upgrade project and documented by the author. Some problems were not faced in the MRoSA2 projects, but they are possible on Mars (such as the tool jamming due to the ice melting and re-freezing).

Mostly the problem severity estimation is classified as 'Severe', which means that the problem is possible to overcome by using ground operator assistance. The 'Mild' cases are not a significant problem and the drill SW should be able to deal with them. The main emphasis in the design phase must be given to the problems that are classified as 'Fatal', because those cases are the real constraints to the instrument operation. As seen in the table, these cases are mainly concerning the situations that have been happened due to an actuator (motor) break-down. This should be kept in mind while designing the motors for the drill unit. The most common reason to break a motor is to drive it in stall mode for extended periods. To prevent these break-downs, the motors should be slightly oversized in current-tolerance. On the other hand, the actuators should not break even when using them in 'wrong time', e.g. trying to move the pipe carousel while drilling.

7.10 Summary of the MASA drill concept design

The MASA Drill Unit (DU) is a revolver-type miniature deep-driller and sampler machine. Its main purpose is to be able to drill and sample all kinds of materials that could be found on Mars. The size, mass and power consumption are tightly budgeted, and still the system must be very reliable and robust. The main platform for the MASA DU in this study has been the ESA's ExoMars rover's Pasteur payload. There is no dedicated Central Processing Unit (CPU) for the MASA DU, but the drill is commanded through the Pasteur CPU. There is an electronics board for the drill, which is situated in the Pasteur electronics box. The drill software (SW) runs on the Pasteur CPU.

In principle, the MASA DU is similar to the MRoSA2U Drilling and Sampling Subsystem (DSS), but several changes have been designed based on the past experience with the MRoSA2 and MRoSA2U DSS and several drilling tests made during the MIRANDA projects. A new concept has been proposed to the drill unit, but the associated SW and hardware, such as the Drill Positioning Unit (DPU) and electronics, have been introduced only in a high-level design.

Exact dimensions of the MASA drill are estimates in the current phase of design. The width of the MASA DU is 140 x 140 mm, and the height is 444 mm. The total volume of the DU is 8.70 liters, and the estimated mass is 9.2 kg (mass breakdown shown in Appendix VII). This value could vary significantly in both directions by using different materials and design. The most important issue is that the mass and size estimates are well within the limits of the Pasteur Drill System SRD [95], which requires the Drill System be at most 160 x 160 x 500 mm of size and 11 kg of mass. The mass and size estimates for the DPU and lever were not studied nor estimated.

The MASA Drill Unit has one optical fiber and three copper wires in the drill string. These copper wires can be used either in analogue, 'traditional' manner in the temperature measurements, or then the pipes and/or tools might be equipped with TC/TM-line relays.

This thesis presents the MASA DU as a potential candidate for the Drill System of the Pasteur payload of the ExoMars rover. There are other possibilities also for the Pasteur Drill System, and hence it would be fair to make a brief comparison of them. However, the most of other "competing" drills' technical details are confidential information until the systems are built ready. The most probable choises to choose for a 'fit-to-Pasteur' furnishing work would be the DeeDri (Chapter 3.4.2), The SAHS (Chapter 3.4.3) and the Honeybee Robotics' One-meter Drill (Chapter 3.4.4). Because there is not enough information available of them, it is not reasonable to make a thorough comparison.

It is also worth to mention the issues that are important in the design process, but were not mentioned here due to the lack of space and resources. These issues are:

- *How to ensure the Drill System's operational inside temperature?* There is no reserved power budget for the heaters. Of particular concern are the actuators of the drill, which may need to be heated prior to operation. This issue has not been discussed in this thesis. A potential solution for this is the MER IDD –like thin-film heating element, bonded to the DC-motors and gears. Typical power consumption is 2-4 W (per each) for Martian conditions and operational time is in a scale of one hour (heating time prior actuator use, heating the motor from -120°C to -70°C).
- *Drilling tactics*. In case the drill manages to melt ice (in case there is such an amount of water ice present underground), the drill must not stop while the water is in liquid form, because halting of the drilling would almost certainly lead to a jamming of the drill string (water will 'glue' the drill rod to the borehole). This is another reason why the drill bit's temperature must be monitored during drilling. This was discussed in high-level design, but the detail design must be included in the drill SW. Considering this problem, there is a need to implement a feedback loop to prevent drill either melting the ice in the first place or letting it freeze again. This feedback loop would regulate the speed of rotation.
- *The drill bit's estimated temperatures must be calculated in simulations* to form a basis for the drilling tactics.

Table 39 below summarizes the comparison of the MASA drill and the ExoMars/Pasteur requirements for the Drill System.

Table 39: MASA drill compared with the Pasteur Drill System requirements.

Drill System	Mass kg	Dimensions mm	Max. Power W	Depth cm	Efficiency / notes
MASA	9.2 (1)	140 x 140 x 444	70 (2)	250-300 (3)	Full-size sample of a hard-rock, at 5 cm depth: ~160 kJ (~45 Wh). Full-size sample of a hard rock, at 10 cm depth: ~360 kJ (~100 Wh). See also Chapter 7.7 for detailed analysis of sampling energies depending on the depth and rock type.
Pasteur requirement	11.0 (4)	160 x 160 x 500	70 (5)	200	Max 120 Wh/run (432 kJ/run)

1) without margin, 2) max. rotational power that can be used. Drill can be operated in even only few watts of power, 3) can be increased to 300 cm, if the two 'push-rod' pipes are also used, 4) including margin, 5) nominal power 10 W, peak power 40 W, maximum available 70 W.

Table 40 below summarizes the technical parameters of the MASA Drill Unit, which were not mentioned in the comparison in Table 39.

Table 40: The MASA DrillUnit technical parameters.

Parameter	Value	Notes
Drill torque	Dependent on the transmission (1)	Motor stall torque 510 mNm, max constant torque 81 mNm.
Rotational speed	120 – 300 rpm max (1)	Motor nominal max speed 8100, peak max 12000 rpm.
Feed speed	1.5 mm / sec	Not counting the time needed for pipe exchange.
Feed force	50-200 N nominal, 400 N max.	Structural strength limit ~1000 N.

1) Note that the transmission rate has not been fixed yet. The estimate for the ratio is 1:40 ... 1:100. This will be defined when the design phase is in more detailed phase. Approximated transmission gear efficiency is about 50-60% based on the MRoSA2 design. The maximum rotational speed is thus in a scale of 120-300 rpm.

8. CONCLUSIONS

Planet Mars has been under study for thousands of years, but just over last four decades the exploration has begun to take its shape. This thesis has covered all missions to Mars' surface. The key question has been ruling the exploration regardless the other objects of the missions: has Mars ever been hospitable to life in some form? Recent studies are revealing the ancient presence of water, which raises the likelihood of being able to find traces of extinct life. If Mars once had liquid water, it is compelling to ask whether any microscopic life forms could have developed on its surface. But if there has been any life, the surface processes have wiped away all traces. The thin atmosphere of Mars does not give much shielding against the Sun's ultraviolet radiation, and the windblown dust has eroded the desert-like surface. There is a need to access the subsurface regolith to acquire samples from rocks and soil. The surface layers have protected the deep layers, which might reveal important information of the Mars' past. In addition to finding evidence for past life, exploring Mars will enhance our knowledge of the Solar System's history, and the formation of the planets, including the Earth.

There has never been an instrument on Mars, which can acquire truly subsoil samples. A drill, which could be accommodated in a very small space, would consume little power, and still would be able to penetrate deep layers of Martian soil and rock, is difficult to make. This thesis has explained several past missions which have included a drill instrument, but none of them is suitable for the demanding frames of the ExoMars missions. More detailed studies and tests are needed to qualify an existing concept or prototype to a flight level instrument. The MRoSA2 project could only begin this empirical study.

As a potential solution for this challenging problem, a new concept was presented to satisfy the needs of near-future robotic Mars exploration missions. This instrument, the MASA drill, is a heritage of the MRoSA2 drill. MASA is strongly based on the lessons learned from the two MRoSA2 projects and the MIRANDA drilling tests, and it satisfies the requirements for the Drill System instrument of the ExoMars project.

The main emphasis in this thesis was given to the following issues:

<u>Chapters 1 and 2:</u>

An explanation of the exact motivation for this thesis and what was the author's contribution to this study.

<u>Chapter 3:</u>

What kind of other sampling and drilling projects there have been, and what can we learn of them? Is there already an instrument, either a flown one or only a concept that could possibly be used in the ExoMars mission? All drills and samplers that have been sent to other celestial bodies than Earth were studied. None of them is suitable for the Pasteur payload, but they offer still important advice about different kinds of clever technical solutions, and especially the problems that were encountered during design or operation phases give valuable information.

<u>Chapter 4:</u>

The author was involved in the MRoSA2 projects, which were precursor of the ExoMars/Pasteur drill. The project team manufactured and tested successfully a prototype of a drilling and sampling instrument. There were still much to do to gather the results and to evaluate them for forming a guideline for designing an instrument that could satisfy the strict requirements for a flight model instrument.

No critical (especially self-critical) studies of existing drill prototypes have been published yet. This thesis presents these studies in Chapters 4.3 and 4.5, and the results were used to form the basis of the MASA drill system.

Chapter 5:

The system and drilling tests revealed important information about the technical and functional design of a drill instrument. Several kind of drilling tests have been conducted by different institutes and companies, but the design process of upgrading the MRoSA2 design to fit the Pasteur payload of the ExoMars rover required dedicated testing.

The test results gave not only necessary information for designing the instrument, but they also gave invaluable information how to perform the drilling and sampling to maximize the scientific return of the studies, and to perform the drilling operation in most safe manner to guard both the instrument and the sample. Most of the test results are in line with other tests, conducted by several other companies worldwide. These results can also be utilized in drill developments for other possible missions.

However, some of the test results gave values that were not in line with the estimates. Through these 'tries and errors', several problem situations were noticed that the space drill need to be prepared for.

Chapter 6:

As said, there has never been a drill on Mars yet, and no past instrument has had such a tight list of requirements that have been set for the ExoMars drill. After careful study of these requirements, the design process of the new drill concept was aimed to fulfil these requirements. As a reference, the MRoSA2 Drilling and Sampling Subsystem's, and NASA's Mars Science Laboratory corer tool's system requirements were presented.

Chapter 7:

The MASA drill is a complex instrument, which was designed on a basis of the results of evaluating past and current projects, tests and studies. The aim was to design a concept of a drilling and sampling instrument for the Pasteur payload of the ExoMars mission.

In general, the tests revealed also important results regarding the ESA's ExoMars rover's operations. As mentioned in Chapter 7.7, the energy budget for the sampling system is very tight. Drilling and sampling of rocks consume very much energy, and the harder rock types are difficult to sample. As the current phase of design requires 40 mm long and 10 mm in diameter rock core samples from rocks, the author strongly suggests the length requirement to be dropped down to 20 mm (as it originally was in the earlier phase of design). Other option is to increase the available energy per drill run. Currently there is simply not enough energy to use for sampling of harder rocks when the drill needs to penetrate through rocky surface layers, and the Martian rocks are known to be igneous and thus quite hard to penetrate. The soil samples should not be of concern.

The temperature issue is also very important. Chapter 5.4.5 discussed the results of the MIRANDA-2 tests. These tests revealed that the temperature increase can quite easily be so big, that possible underground ice will melt and mix the sample's structural composition. In addition, some carbonates can be destroyed if the drill bit runs on too great temperature.

The MASA drill, presented in Chapter 7, was compared against the ExoMars/Pasteur Drill System's requirements in Chapter 7.8. Table 37 states that the MASA drill is compliant with the current ESA's Drill System requirements. This was also summarized in Chapter 7.10.

The MASA DU is a *method* to reach the subsoil material. The idea was not to specify a *scientific instrument*, but to offer a tool for accommodating these scientific experiments. The MASA drill can be used as it is to collect samples and also to gather some scientific data, mainly regarding soil properties during the drilling operations. Actual detailed measurements are to be made from the acquired samples, or by the instruments that will be accommodated inside the MASA drill string. For this reason the MASA drill includes for example an optical fiber throughout the drill string, but no instrument has been specified to use that (except some ideas, e.g. the DIBS).

The MASA design fulfils the ExoMars drill requirements. In addition, the instrument concept is scalable and potential for using in other missions, such as the future sample return missions.

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APPENDICES

Appendix I: ESA ITT Documents

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ANNEX II: Descriptions

Science / Robotic Exploration Preparation

AURORA

Ref. Number T213-03MM
Activity Title Sampling drill tools for rocky and granular soils
This activity will develop and demonstrate three alternative tool designs (ca. 20 mm in diameter) to be mounted on a drill, to collect soil samples (sand or rock) at a desired drilling depth, the Mars surface being considered as reference. Operation of the soil sampling tools is based on opening and closing the sample chamber in the tool at the desired depth. Operation of a rock sampling tool is based on a wedge-type core cutter ring or a conical core catcher. A combined rock and granular soil sampling tool will be able to sample both sandy and rocky soil with negligible losses. Tool actuation force will be traded-off: it may be generated either by electric actuators (motor, solenoid, shape memory alloy), or it may passively take advantage of drill rotation or reversal of the drill rotation.
Deliverables Tools breadboard.

Ref. Number T213-06MM
Activity Title Imaging Lidar Technology
Nowadays Imaging Lidars can perform measurements up to few kilometres at typical distance resolutions of a few centimetres at a rate of a few kHz. Imaging Lidars can support a number of space applications on orbiter modules, landers and planetary rovers like surface mapping, hazard avoidance and safe landing, navigation, multiple spacecraft operations (rendez-vous and docking), target properties recognition. However, since most of these systems rely on complex scanning mechanisms, they are bulky and often too heavy for future solar system exploration missions. The recent emergence of novel and advanced technologies like new 2-dimensional detector arrays (APD or CMOS arrays) and optical micro components (like MEMS and MOEMS) will bring a new trend in the development of compact, high resolution and multi-task sensor Imaging Lidars. This activity shall study the use of these novel technologies, assess the impact on the Lidar performances and develop an Imaging Lidar proof-of-concept breadboard that validates these technologies, making the Imaging Lidar a feasible instrument for space applications in the frame of AURORA.
Deliverables Imaging Lidar breadboard.

Ref. Number T213-07MM
Activity Title Down-hole hammering mechanism for a planetary drill
The objective is to develop a high-energy (0.5-2 J/impact) hammering system, that can be placed inside the drill string (20-40 mm in diameter). Power generation can utilize an electric motor, but shape memory alloys and piezo-elements (operating in an inch-worm manner) can be considered as an option. An optional passive mechanism to take impact power directly from the drill rotation (without any additional power sources and power feed-through) can also be considered. Impact frequency will be limited by the power of the actuator; however, impact energy must be kept at a level high enough to provide the desired effect.
Deliverables Breadboard of a drill- hammering device.

Appendix II: MRoSA2 Upgrade project's time/energy consumption test results

This drilling test was conducted in Helsinki University of Technology premises by the author in May 2003. The drill experienced no counter force during drilling, since the drilling was conducted to air instead of drilled-material. For this reason, all energy values here describe only the required energy to move the parts of the drill itself, but the values do not include the power consumption for drilling itself. The drilling test includes the phases from start to down to 60 cm (three pipe's length).

Pipe	Total Energy Ws	Energy Ws	Power W	Duration s	Start min:sec	End min:sec	Operation phase
Pipe 1	10.1	10.1	0.72	14	0:00	0:14	Init Pipe Carousel + select a pipe
	17.3	7.2	0.72	10	0:16	0:25	Init Tool Carousel + select tool no. 5
	83.3	66.0	3.00	22	0:32	0:54	Connect pipe to tool + rotate
	104.9	21.6	1.20	18	1:12	1:30	Lock pipe gripper
	182.6	77.8	2.16	36	1:38	2:14	Raise tool from it's slot
	187.0	4.3	0.72	6	2:15	2:21	Select tool no. 0
	210.7	23.8	1.08	22	2:22	2:44	Drill down: 50% power + max rotation
	381.4	170.6	2.16	79	2:44	4:03	Drill down: 100% power + max rotation
Pipe 2	384.7	3.4	1.68	2	4:11	4:12	Clamp drill pipe: passive mode clamping
	409.9	25.2	1.20	21	4:24	4:45	Unlock pipe gripper
	656.9	247.0	5.04	49	4:49	4:50	Clamp drill pipe: dynamic mode clamping start
	745.4	88.6	2.16	41	4:51	6:32	Lift feed to up limit (at 5:38: change
	745.4						clampers to passive clamping mode)
	752.6	7.2	0.72	10	6:43	6:53	Rotate new pipe
	969.4	216.7	5.04	43	7:00	7:01	Clamp drill pipe: dynamic mode clamping start
	1026.4	57.0	3.00	19	7:02	7:21	Connect pipe to pipe + rotate
	1026.4				7:42	7:43	Change clampers to passive clamping mode
	1054.0	27.6	1.20	23	7:45	8:08	Lock pipe gripper
	1057.3	3.4	1.68	2	8:15	8:16	Open clampers
	1105.9	48.6	1.08	45	8:31	9:16	Drill down: 50% power + max rotation
	1239.8	133.9	2.16	62	9:16	10:18	Drill down: 100% power + max rotation
Pipe 3	1243.2	3.4	1.68	2	10:30	10:31	Clamp drill pipe: passive mode clamping
	1274.4	31.2	1.20	26	10:32	10:58	Unlock pipe gripper
	1521.4	247.0	5.04	49	11:00	11:01	Clamp drill pipe: dynamic mode clamping start
	1724.4	203.0	2.16	94	11:02	12:36	Lift feed to up limit (at 11:21: change
	1724.4						clampers to passive clamping mode)
	1731.6	7.2	0.72	10	12:53	13:03	Rotate new pipe
	1953.4	221.8	5.04	44	13:06	13:06	Clamp drill pipe: dynamic mode clamping start
	2013.4	60.0	3.00	20	13:08	13:28	Connect pipe to pipe + rotate
	2013.4				13:50	13:50	Change clampers to passive clamping mode
	2041.0	27.6	1.20	23	13:51	14:14	Lock pipe gripper
	2044.3	3.4	1.68	2	14:29	14:30	Open clampers
	2088.6	44.3	1.08	41	14:31	15:12	Drill down: 50% power + max rotation
	2209.6	121.0	2.16	56	15:12	16:18	Drill down: 100% power + max rotation

Appendix III: Mars fact sheet and Mars/Earth Comparison

The information in this Appendix has been gathered mainly from NSSDC/NASA sources [47] and from [48] through [50].

1. Bulk parameters

(Mars/Earth)	Mars	Earth	Ratio
Mass (10^{24} kg)	0.64185	5.9736	0.107
Volume (10^{10} km^3)	16.318	108.321	0.151
Equatorial radius (km)	3397	6378.1	0.533
Polar radius (km)	3375	6356.8	0.531
Volumetric mean radius (km)	3390	6371.0	0.532
Core radius (km)	1700	3485	0.488
Ellipticity (Flattening)	0.00648	0.00335	1.93
Mean density (kg/m^3)	3933	5515	0.713
Surface gravity (m/s^2)	3.71	9.80	0.379
Surface acceleration (m/s^2)	3.69	9.78	0.377
Escape velocity (km/s)	5.03	11.19	0.450
GM (x 10^6 km^3/s^2)	0.04283	0.3986	0.107
Bond albedo	0.250	0.306	0.817
Visual geometric albedo	0.150	0.367	0.409
Visual magnitude V(1,0)	-1.52	-3.86	-
Solar irradiance (W/m^2)	589.2	1367.6	0.431
Black-body temperature (K)	210.1	254.3	0.826
Topographic range (km)	30	20	1.500
Moment of inertia (I/MR^2)	0.366	0.3308	1.106
J_2 (x 10^{-6})	1960.45	1082.63	1.811
Number of natural satellites	2	1	

2. Orbital parameters

(Mars/Earth)	Mars	Earth	Ratio
Semimajor axis (10^6 km)	227.92	149.60	1.524
Sidereal orbit period (days)	686.980	365.256	1.881
Tropical orbit period (days)	686.973	365.242	1.881
Perihelion (10^6 km)	206.62	147.09	1.405
Aphelion (10^6 km)	249.23	152.10	1.639
Synodic period (days)	779.94	-	-
Mean orbital velocity (km/s)	24.13	29.78	0.810
Max. orbital velocity (km/s)	26.50	30.29	0.875
Min. orbital velocity (km/s)	21.97	29.29	0.750
Orbit inclination (deg)	1.850	0.000	-
Orbit eccentricity	0.0935	0.0167	5.599
Sidereal rotation period (hrs)	24.6229	23.9345	1.029
Length of day (hrs)	24.6597	24.0000	1.027
Obliquity to orbit (deg)	25.19	23.45	1.074

3. Mars Observational Parameters

Observed	Parameter
Discoverer	Unknown
Discovery Date	Prehistoric
Distance from Earth	
Minimum (10^6 km)	55.7
Maximum (10^6 km)	401.3
Apparent diameter from Earth	
Maximum (seconds of arc)	25.1
Minimum (seconds of arc)	3.5
Mean values at opposition from Earth	
Distance from Earth (10^6 km)	78.39
Apparent diameter (seconds of arc)	17.9
Apparent visual magnitude	-2.0
Maximum apparent visual magnitude	-2.91

4. Mars Mean Orbital Elements (J2000)

Element	Value
Semimajor axis (AU)	1.52366231
Orbital eccentricity	0.09341233
Orbital inclination (deg)	1.85061
Longitude of ascending node (deg)	49.57854
Longitude of perihelion (deg)	336.04084
Mean Longitude (deg)	355.45332

5. North Pole of Rotation

Right Ascension	317.681 - 0.108T
Declination	52.886 - 0.061T
Reference Date	12:00 UT 1 Jan 2000 (JD 2451545.0)

T = Julian centuries from reference date

6. Martian Atmosphere

Surface pressure:	6.36 mbar at mean radius (variable from 4.0 to 8.7 mbar depending on season) [6.9 mbar to 9 mbar (Viking 1 Lander site)]
Surface density:	~0.020 kg/m^3
Scale height:	11.1 km
Total mass of atmosphere:	~2.5 x 10^{16} kg
Average temperature:	~210 K (-63 °C)
Diurnal temperature range:	184 K to 242 K (-89 to -31 °C) (Viking 1 Lander site)
Wind speeds:	2-7 m/s (summer), 5-10 m/s (fall), 17-30 m/s (dust storm) (Viking Lander sites)
Mean molecular weight:	43.34 g/mole

Atmospheric composition (by volume):

Major (%)	Carbon Dioxide (CO_2) - 95.32%
	Nitrogen (N_2) - 2.7%
	Argon (Ar) - 1.6%

	Oxygen (O_2) - 0.13% Carbon Monoxide (CO) - 0.08%
Minor (ppm)	Water (H_2O) - 210 Nitrogen Oxide (NO) - 100 Neon (Ne) - 2.5 Hydrogen-Deuterium-Oxygen (HDO) - 0.85 Krypton (Kr) - 0.3 Xenon (Xe) - 0.08

7. Satellites of Mars

	Phobos	**Deimos**
Semi-major axis* (km)	9378	23459
Sidereal orbit period (days)	0.31891	1.26244
Sidereal rotation period (days)	0.31891	1.26244
Orbital inclination (deg)	1.08	1.79
Orbital eccentricity	0.0151	0.0005
Major axis radius (km)	13.4	7.5
Median axis radius (km)	11.2	6.1
Minor axis radius (km)	9.2	5.2
Mass (10^{15} kg)	10.6	2.4
Mean density (kg/m^3)	1900	1750
Geometric albedo	0.07	0.08
Visual magnitude V(1,0)	+11.8	+12.89
Apparent visual magnitude (V0)	11.3	12.40

*Mean orbital distance from the center of Mars.

Appendix IV: Pasteur Drill System Requirements

The following requirements are taken from the ExoMars Rover / Pasteur System Requirements Document (Aurora/MW/KC/006.03, September 16, 2004) (SRD [95]) and they concern the drill unit. The requirements presented here are from SRD Chapter 3.1.5.3.5 concerning the Pasteur drill system. This SRD references to Annexes, which all are not shown here. Annexes 2 and 4 are shown in the following Appendices, as they are relevant to the Drill System Requirements.

Drill System Requirements

C: Because of the degrading UV and oxidant environment on the Martian surface, analysing protected subsurface material is the only way to ensure scientific results from unaltered samples, particularly important in search for life research. The main objective of the Pasteur Drill System is to collect the samples that will be studied by the Pasteur analytical instruments. However, the Drill System is also an instrument itself, as it integrates sensors to ensure the "good quality" of the retrieved sample, and others that provide valuable data on soil properties. The Drill System includes the drill(s) proper and all associated sensors.

It is expected that the Drill System's overall mass shall not exceed 11 kg, including margin.

It is expected that the Drill System's power consumption during operations shall not exceed the following values: ≤ 10 W average, ≤ 40 W peak, with an extra capability ≥ 70 W to be used solely in case of emergency, if the drill gets stuck and needs to be dislodged.

RM-1-4210 The Drill System shall support Pasteur payload science operations:

a) By collecting scientific samples and delivering them to the Sample Preparation and Distribution System (SPDS).
b) By allowing the precise positioning of the collection devices to obtain the sample from the right spot.

RM-1-4220 The Drill System shall be capable to collect and deliver samples to the SPDS for further preparation and distribution to other Pasteur instruments.
C: The sample shall be in a suitable condition to undergo the following analysis: optical/morphological, chemical, mineralogical, isotopic, and search for signs of present and extinct life.

RM-1-4230 The Drill System shall support the search for water in all forms (ice, permafrost, liquid water, water mixtures and solutions [brines], adsorption water, and possibly vapour) in the Martian subsurface.

RM-1-4235 The Drill System shall preserve the possible water fraction in the sample in its original condition.
C: e.g. ice, permafrost.

RM-1-4240 The Drill System shall support the search for organic compounds in the Martian subsurface.

RM-1-4240 The Drill System shall preserve the possible organic fraction in the sample.

RM-1-4250 The Drill System shall support the search for oxidising agents in the Martian subsurface.

RM-1-4260 In the process of obtaining and delivering a sample, the Drill System shall not induce physico-chemical degradation or alterations in the sample.
C: This implies, for example, that the sample collection and delivery operation must be completed in a short time to minimise the sample's exposure to reactive substances, present either on the Martian surface or atmosphere. Of particular concern is the possible degradation of organics due to the action of putative oxidants.

RM-1-4270 Through the monitoring of its various sensors' information as a function of penetration progress, the Drill System shall support the determination/estimation of the soil's mechanical properties: density, porosity/compaction, hardness/cohesion, cementation, etc.

RM-1-4280 The Drill System shall be capable to collect subsurface samples down to ≥ 2-m depth.
C: It is recognised that the maximum depth attainable at a given location may depend on a number of factors, such as soil stratigraphy, cohesion/hardness of the various layers to be perforated, available energy, time to operate, etc.

RM-1-4290 The Drill System shall be capable to collect samples from within surface rocks.

RM-1-4300 When collecting samples from within surface rocks, the Drill System shall be capable of penetrating beyond the weathering rind (estimated to be less than 10 mm) to retrieve the sample.

RM-1-4310 The Drill System shall be capable to penetrate into the subsurface with physical characteristics as modelled in Annex 4.

RM-1-4320 A Drill sample shall consist of a small cylindrical core (if allowed by the soil material), plus powder material from the same location where the core is obtained.
C: Most instruments require a dust or powder sample. The process of drilling already produces particulate material. This dust/powder, however, may still require further processing before it can be distributed to other instruments.

RM-1-4330 The average dimensions of the cylindrical core sample shall be: 4 cm (TBC) in length by 1 cm (TBC) in diameter.
C: It is recognised that the ability to retrieve a small core depends on the hardness of the material; and that in some cases the resulting core may be brittle or fragmented.

RM-1-4350 The Drill System shall include redundant temperature sensors capable to estimate the temperature of the sample at the bit contact point.

RM-1-4360 The Drill System shall be capable to monitor and control its torque.

RM-1-4370 The Drill System shall be capable to monitor and control its thrust.

RM-1-4380 The Drill System's operations shall not cause the melting of possible ice inclusions in the sample.

RM-1-4390 The Drill System shall be capable to monitor and control its penetration depth.

RM-1-4400 In case a Drill gets stuck and repeated attempts to execute the emergency dislodge manoeuvre are unsuccessful, it shall be possible to release the blocked Drill unit.

RM-1-4410 The Drill System shall include a close-proximity camera at its base to help position the bit in the right place to start drilling.

RM-1-4420 The Drill System's close-proximity camera shall also be capable to monitor the soil mound formed around the drill shaft at regular intervals.
C: This will permit having a look at the material being excavated by the drill as it progresses into the soil. It provides visual information of the material encountered by the drill bit, and complements the data provided by the other sensors.

RM-1-4430 Based on information from one or more PanCam images, from the navigation cameras, and with the assistance of the Drill System's close-proximity camera, from a distance of 3 m from the desired target, the rover/ Drill System shall be able to position the drill bit with an accuracy of 1 cm in all directions in a single operation (this means without requiring a further iteration cycle with mission Ground Control).

RM-1-4440 The Drill System, in its stowed position, shall fit within the rover/descent module's available envelope.

RM-1-4450 Under no circumstances shall any of the Drill System's deployable elements interfere with the rover's progress on the Martian terrain when executing a traverse.

Sample Preparation & Distribution System (SPDS) Requirements

C: The objective of the SPDS is to receive samples from the Drill System, to prepare them, and to present them to the various Pasteur analytical instruments for study. The SPDS is a fundamental device, as the quality of the scientific results that can be derived from the various instruments depends first and foremost on the sample being adequately prepared for each of them. After the measurements are completed, the SPDS must be able to store the solid part (core) of two samples for possible subsequent analysis. The other samples will be discarded after analysis.

The expected SPDS overall mass, including all devices, associated mechanisms, sensors, and their related internal harness, shall not exceed 5 kg, including margin.

The expected SPDS power consumption during operations shall not exceed an average value of 10 W.

RM-1-4510 The SPDS shall be able to (repeatedly) receive, prepare, distribute and store/discard a sample from the Drill System (either the drill itself or from the redundant collection device).

RM-1-4520 In the process of collecting/receiving a sample from the Drill System, the SPDS shall not induce undesired physical-chemical degradation or alterations in the sample.

RM-1-4530 In the process of preparing, distributing and storing a sample, the SPDS shall not induce undesired physical-chemical degradation or alterations in the sample.

RM-1-4540 The SPDS control loop shall ensure that the sample preparation is conducted in a manner that does not induce the melting of any possible ice inclusions.

RM-1-4550 The SPDS design shall be optimised for the sequence of preparation activities required by each instrument, and for the sequence of diagnostics to be used for each sample.

RM-1-4555 The SPDS design approach shall follow high reliability criterias, avoiding to the maximum extent technical solutions with single point failure items; in particular, the failure of one of the Pasteur instruments shall not endanger or block the measurement sequence.

Automatic Analysis Sequence (non destructive)

C: This part of the analysis is pre-programmed and will proceed automatically, without Ground Control intervention. It will provide results to define a possible more detailed analysis sequence (the one requiring human intervention). During the execution of the Automatic Analysis Sequence, the rover shall not move/traverse. A likely Automatic Analysis Sequence consists of taking a few multi-spectral colour images of sample with the microscope at low magnification measure some points with the Raman spectrometer. All this information is transmitted to Earth. Based on these data, the science team in Ground Control may decide to further examine parts/sections of the sample, e.g. at high magnification, or to proceed with the destructive analysis (crush the sample). While this “response” arrives from Ground Control (which could take up to 24 hr), the rover may be allowed to move/traverse; it is therefore very important that the sample be held firmly in place. *[See example in Annex 5 of this SRD in reference [63].]*

RM-1-4570 The SPDS shall be able to present the acquired sample material to the microscope /Raman/LIBS assembly for inspection.

RM-1-4580 The sample material must be presented to the instruments in a manner that ensures images are “in focus.”

RM-1-4590 Provided that the sample’s hardness allows a cylindrical solid core to be obtained, the SPDS shall present the core’s complete cylindrical surface to the microscope/Raman/LIBS for imaging.

RM-1-4640 The SPDS shall be capable to establish if it was not possible to obtain a solid core (i.e. because the sample was too fragile).

<u>*Detailed Analysis Sequence (includes destructive analysis)*</u>

C: It requires information from the Earth science team. Based on the results from the Automatic Analysis Sequence, Ground Control may define a list of "sample space" coordinates to be analysed in detail. The SPDS system will then be capable to position the sample for a series of more detailed measurements, e.g. microscope/Raman/LIBS observations at high magnification. Once Ground Control is satisfied with the non-destructive analysis results, then the sample will be crushed to obtain particulate material for additional investigation (e.g. search for organic compounds with the GC/MS and Life Marker Chip instruments). During the execution of the Detailed Analysis Sequence, the rover shall not move/traverse.
[See example in Annex 5 of this SRD in reference [63].]

RM-1-4650 The SPDS shall be able to physically present the sample to the microscope/Raman/LIBS optical assembly for <u>detailed</u> optical/spectroscopic inspection.

RM-1-4660 The SPDS control loop shall be able to position the sample in the microscope's optimal field of view for <u>high-magnification</u> imaging.

RM-1-4670 The SPDS control loop shall position the required portion of the sample in the field of view of the microscope/Raman/LIBS optical assembly with a precision of 5 μm in all directions.
C: The high-magnification measurements on this sample location are then performed.

RM-1-4680 The SPDS control loop shall be capable to repeat this procedure for various points/locations in "sample space."

RM-1-4690 The SPDS shall be able to crush the sample to produce particulate material of suitable size for all instruments requiring a dust sample.

RM-1-4700 The SPDS shall be able to dispense particulate material to the MOI (oxidants) and XRD (mineralogy); to the MOD; to the GC-MS and Life Marker Chip (organics) instruments for analysis.
C: MOD, being the most sensitive instrument to search for aminoacids, should perform the first screening for organic compound; in case of positive detection, then the GC-MS and Life Marker Chip instruments would also be used.

RM-1-4710 Until instructed otherwise, the SPDS shall save unused sample/dust particulate material for possible subsequent experiment runs.

RM-1-4720 When instructed, the SPDS shall be able to discard the remaining sample material according to the Planetary Protection directives.

RM-1-4730 The SPDS shall avoid as much as possible any contamination/cross contamination among the samples and between the samples and all instrument receiving stages.

Appendix V: Reference physical characteristics of the subsurface environment

This document (Appendix V) is the **Annex 4** for the ExoMars/Pasteur SRD [63], presented in Appendix IV.

A4-1 Reference Rocks Distribution

Surface rocks distribution: as in Annex 1.
Subsurface rocks distribution assumed similar to surface rocks distribution.

A4-2 Reference Subsurface Physical Characteristics for the upper 3 meters

Model: Homogeneous soil matrix with embedded fractured basaltic rock material of different sizes (pebbles, cobbles, boulders).

Homogeneous Soil:

Poorly consolidated dust/sand (“Duricrust”), formed by surface-atmosphere interaction leading to cementation in presence of solutes and water (e.g. Viking-1 Blocky soil).

Assumed bulk density:
- 2000 kg/m^3 at the surface,
- raising to 2850 kg/m^3 at 1 m depth,
- 2925 kg/m^3 at 2 m depth,
- 2950 kg/m^3 at 3 m depth.

Assumed cohesion:
- 8 kPa at the surface,
- raising to 11.6 kPa at 1 m depth,
- 12.2 kPa at 2 m depth and
- 12.4 kPa at 3 m depth.

Assumed angle of internal friction:
- 34 deg at the surface,
- raising to 48 deg at 1 m depth,
- 49 deg at 2 m depth and
- 49.5 deg at 3 m depth.

Embedded Rocks:

Assumed unconfined compressive fracture strength: up to 150 MPa,
bulk density 2700 to 3100 kg/m^3

Notes:

1. Locally occurring drift deposits of very fine-grained material are not considered in this model since this type of soil is much weaker.
2. At high latitudes the presence of a frost layer needs to be considered too.

This annex may have to be updated in the future.

Appendix VI: Reference Soil Cases and Related Parameters for Locomotion

This document (Appendix VI) is the **Annex 2** for the ExoMars/Pasteur SRD [63], presented in Appendix IV.

A2-1 Reference Soil Types and Soil Parameters

Soil type	Bulk Density (kg/m3)	Exponent of sinkage n	Frictional modulus Kphi (N/m^{n+2})	Cohesive modulus Kc (N/m^{n+1})	Cohesion (Pa)	Internal Friction Angle (deg)
Type A: MPF All Cloddy	1550	1 [2]	820000 [2]	1400 [2]	170 [1]	37 [1]
Type B: MPF Mixed Drift-Cloddy	1350	1 [2]	820000 [2]	1400 [2]	220 [1]	33.1 [1]
Type C: MPF All Drift	1150	1 [2]	820000 [2]	1400 [2]	530 [1]	26.4 [1]

A2-1 Wheel-Soil Interaction Parameters

Adhesion Coefficient μ for Rocks-Metallic Wheels contact	assume 0.3 to 0.5
Shear Deformation Modulus K	0.8 to 2.5 cm [1], [3]

Comments

1. The values with reference [1] originate from the Mars Pathfinder (MPF) mission.
2. Since there are no experimental Mars data for n, k_Φ and k_c Lunar values have been adopted, which happen to have a simple value for n and therefore simple units for k_Φ and k_c.
3. For the rock-wheel adhesion coefficient μ it is assumed that the Coulomb friction model applies and that there is no hooking of the wheel on to rock surface roughness features, which in reality may occur for short instances.
4. The shear deformation modulus depends on the normal stress and on the wheel-soil contact patch area [3], therefore a range is given.
5. Additional soil types based on Mars Exploration Rover mission observations in 2004 are planned to be added after these data are published (planned Aug-Sept 2004).

References for Annex 2

[1] Moore, H.J. et al., Soil-like deposits observed by Sojourner, the Pathfinder rover, J. Geophys Res. 104, no E4, pp. 8729-8746 (April 15, 1999)

[2] Lunar Sourcebook, G. H. Heiken et al, Cambridge University Press, Cambridge, New York, USA 1991)

[3] R. Godbole, R. Alcock, D. Hettiaratchi (1994). The prediction of tractive performance on soil surfaces. *Jnl. of Terramechanics* 30[6], pp. 443-459, 1993.

Appendix VII: Mass Breakdown for the MASA Drill Unit

This table is an approximated mass breakdown for the MASA Drill Unit, not including the lever arm or Drill Positioning Unit. Total mass estimate of the MASA DU is 9.2 kg including estimated margins.

Component	Subsystem	Mass g	Margin %	Quantity pcs	Total mass, g	Material
Clamper mechanism structural frame	Clampers	700.0	15 %	1	805.0	Al
Clamper mechanism	Clampers	425.0	10 %	1	467.5	SS, Ti
Clamper motor: Maxon RE d13 118430 DC motor and Maxon 110 316 gear	Clampers	35.0	5 %	2	73.5	
Linear slides: 4 x 80 g (295 mm)	Feed	80.0	5 %	4	336.0	SS
Pipe detachment fork system	Feed	100.0	10 %	1	110.0	SS, Ti
Ball screw: 'SKF SH 6x2', 6 mm x 300 mm	Feed	54.0	5 %	1	56.7	SS
Feed motor: Maxon RE d10mm 118392 DC	Feed	36.0	5 %	1	37.8	
Feed gear: Maxon 110308 gear	Feed	20.0	5 %	1	21.0	
Misc. accessories: nuts, pinions, screws etc.	Miscellaneous	200.0	15 %	1	230.0	Misc.
Internal wires, electrical accessories.	Miscellaneous	100.0	15 %	1	115.0	
Pipe + pipe internal accessories + plugs	Pipe carousel	90.0	5 %	10	945.0	Al+misc.
Pipe, including the push-rod DC-motor	Pipe carousel	115.0	10 %	2	253.0	Al+misc.
Pipe carousel structure	Pipe carousel	220.0	10 %	1	242.0	Al, Ti
Maxon RE d10' DC motor with gear in the pipe carousel (MRoSA2) + gear	Pipe carousel	35.0	5 %	1	36.8	
Brushless Maxon EC-Max 40, gearhead Planet. GP 42 C, dig. encoder Maxon MR. [144-146]	Sledge	650.0	5 %	1	682.5	
Sledge structure	Sledge	200.0	20 %	1	240.0	Al
Spindle components	Sledge	150.0	20 %	1	180.0	SS, Ti
Sledge asseccories	Sledge	100.0	20 %	1	120.0	SS, Ti
Linear piezo motor: PI line M-661.4P0	Sledge	30.0	5 %	1	31.5	
Spring, based on AS R C0420-063-0500*S[142]	Sledge	25.0	5 %	1	26.3	
Slide top support	Structural	330.0	10 %	1	363.0	Ti
Right wall, part of the supporting frame	Structural	345.0	10 %	1	379.5	Al
Left wall, part of the supporting frame	Structural	345.0	10 %	1	379.5	Al
Back wall, part of the supporting frame	Structural	345.0	10 %	1	379.5	Al
Front wall, 2mm	Structural	345.0	10 %	1	379.5	Al
Base plate structure	Structural	330.0	10 %	1	363.0	Al
Central strut / skeleton	Structural	350.0	10 %	1	385.0	Ti
Roof structure	Structural	325.0	10 %	1	357.5	Ti
Shaft top end support	Structural	160.0	15 %	1	184.0	Ti
Top wall	Structural	110.0	10 %	1	121.0	Al
Bottom wall	Structural	110.0	10 %	1	121.0	Al
Drill tool (bit)	Tool carousel	45.0	5 %	11	519.8	SS, BN
Sample container (tubes on the carousel)	Tool carousel	20.0	10 %	11	242.0	SS
Tool car. motor: Maxon 118383 DC + gear	Tool carousel	35.0	5 %	1	36.8	

Total mass including estimated margin:	**9220.5**	**g**
Total mass without margin:	8410.0	g

Notes:

Left, right and back wall: 2 mm Al plate, 140 mm x 444 mm, part of structural supporting system.

Material acronyms: Al = aluminium, SS = stainless steel, Ti = titanium, BN = boron nitride, misc. = miscellanous.

Appendix VIII: MIRANDA-2 test results

MIRANDA-2: Diopside drilling
September 09, 2004

t/s	T/°C	R/Ω	T/NTC °C	F/N	U/V	I/A	P/W	D/mm	rpm	MRR/ml	Note
0	19.7	12500	19.99	100	0	0	0.0	0	0	0	
100	21.5	12180	20.56	100	10.1	0.65	6.6		75		
200	21.7	11850	21.17	100	10.1	0.61	6.2		77		
300	21.9	11700	21.46								
400	22.1	11580	21.69	100	10.1	0.63	6.4		76		
500	22.0	11450	21.94								
600	22.0	11370	22.10	100	10.1	0.63	6.4		77		
700	22.1	11300	22.24								
800	22.1	11250	22.34	100	10.1	0.63	6.4		77		
900	22.1	11210	22.42	100	10.1	0.63	6.4		77		
1000	22.2	11100	22.64								
1100	22.2	11060	22.72								
1200	22.2	11050	22.74	100	10.1	0.63	6.4	1.04	77	0.3	
0	19.8	12200	20.53	100	20.0	0.87	17.3	0	151	0	
100	20.6	11060	22.72	100	20.0	0.80	16.0		153		
200	24.5	10570	23.74	100	20.0	0.77	15.4		153		
300	26.6	10470	23.96	100	20.0	0.76	15.1		152		
400	29.0	10440	24.02	100	20.0	0.72	14.4		153		
500	29.1	10290	24.35	100	20.0	0.74	14.7		153		
600	33.3	10250	24.44	100	20.0	0.74	14.7	1.67	153	?	crown T=39.5C
0	19.6	12060	20.78	100	25.1	0.77	19.2	0	248	0	
100	24.5	10270	24.39	100	25.1				248		
170		9880	25.25	100	25.1				248		
220	25.3	10000	25.00	100	25.1	0.80	20.1		248		
250	26	9790	25.48	100	25.1	0.79	19.8		248		
300		9890	25.25	100	25.1	0.75	18.8		248		
400		9900	25.23	150	25.1	0.88	22.1		245		Increase thrust
500	30.5	9780	25.51	200	25.1	0.90	22.6	0.35	240	?	Increase thrust

MIRANDA-2: Mafurite drilling
October 10, 2004

t/s	T/NTC1 °C	R/NTC1 Ω	T/NTC2 °C	R/NTC2 Ω	F/N	U/V	I/A	P/W	D/mm	rpm
0	18.6	13300	18.3	13500	100	10.1	0.7	7.1	0	72
20	20.7	12100	20.0	12510	100	10.0	0.7	7.0		72
100	28.7	8500	20.5	12210	100	10.0	0.7	7.0		72
150	32.3	7300	20.8	12040	100	9.9	0.7	6.9		72

180	34.0	6800	21.1	11870	100	9.9	0.7	6.9		72
210	35.1	6500	21.4	11740	100	9.9	0.7	6.9		72
240	36.3	6200	21.5	11690	100	9.9	0.7	6.9		72
250	36.7	6100	21.6	11630	100	9.9	0.7	6.9		72
270	37.5	5900	21.7	11580	100	9.9	0.7	6.9		72
280	37.6	5860	21.7	11550	100	9.9	0.7	6.9		72
290	38.0	5770	21.8	11510	100	9.9	0.7	6.9		72
300	38.1	5740	22.0	11410	100	9.9	0.7	6.9		72
330	38.8	5580	22.1	11390	100	9.9	0.7	6.9		72
350	39.2	5510	22.2	11340	100	9.9	0.7	6.9		72
360	39.4	5460	22.3	11290	100	9.9	0.7	6.9		72
370	39.5	5430	22.4	11230	100	9.9	0.7	6.9		72
390	39.7	5400	22.4	11220	100	9.9	0.7	6.9		72
410	39.8	5360	22.5	11160	100	9.9	0.7	6.9		72
420	39.9	5340	22.7	11090	100	9.9	0.7	6.9		72
450	40.4	5250	22.8	11030	100	9.9	0.7	6.9		72
480	40.5	5220	22.8	11000	100	9.9	0.7	6.9		72
510	40.6	5190	23.0	10900	100	9.9	0.7	6.9		72
540	40.8	5150	23.2	10850	100	9.9	0.7	6.9		72
570	41.1	5100	23.2	10810	100	9.9	0.7	6.9		72
600	41.3	5060	23.2	10810	100	9.9	0.7	6.9		72

0	19.5	12790	19.4	12810	100	20.0	0.82	16.4	0	156
10	22.8	11010	19.6	12700	100	20.0	0.82	16.4		156
30	27.4	9010	20.0	12470	100	20.0	0.82	16.4		156
40	29.6	8200	20.3	12300	100	20.0	0.82	16.4		156
50	31.4	7600	20.5	12200	100	20.0	0.82	16.4		156
60	33.3	7010	20.7	12080	100	20.0	0.8	16.0		156
75	36.7	6090	21.1	11900	100	20.0	0.8	16.0		156
90	38.7	5610	21.6	11640	100	20.0	0.8	16.0		156
100	41.3	5060	21.8	11510	100	19.9	0.8	15.9		156
120	43.8	4570	22.3	11250	100	20.2	0.8	16.2		156
130	44.7	4410	22.5	11150	100	20.2	0.8	16.2		156
150	46.6	4100	22.9	10960	100	20.2	0.8	16.2		156
170	48.8	3770	23.3	10800	100	20.2	0.8	16.2		156
180	49.0	3740	23.5	10660	100	20.2	0.8	16.2		156
200	51.8	3360	23.8	10540	100	20.2	0.8	16.2		156
210	51.8	3360	24.1	10400	100	20.2	0.8	16.2		156
220	52.5	3280	24.3	10300	100	20.2	0.8	16.2		156
230	53.6	3150	24.5	10240	100	20.2	0.8	16.2		156
240	53.7	3130	24.6	10190	100	20.2	0.8	16.2		156
270	54.4	3050	24.8	10100	100	20.2	0.8	16.2		156
285	55.0	2990	25.0	10000	100	20.2	0.8	16.2		156
300	55.9	2890	25.3	9890	100	20.2	0.8	16.2		156
330	57.6	2710	25.7	9690	100	20.2	0.8	16.2		156
360	58.1	2660	25.5	9780	100	20.2	0.8	16.2		156
390	58.6	2620	26.2	9500	100	20.2	0.8	16.2		156
420	59.4	2540	26.9	9210	100	20.2	0.8	16.2		156
450	59.6	2520	26.9	9200	100	20.2	0.8	16.2		156
480	60.1	2480	27.4	9010	100	20.2	0.8	16.2		156
500	59.9	2500	27.5	8970	100	20.2	0.8	16.2		156
540	59.6	2520	27.7	8910	100	20.2	0.8	16.2		156

600	59.4	2540	27.6	8920	100	20.2	0.8	16.2		156

0	20.7	12100	20.5	12200	100	25.0	0.9	22.5	0	228
25	23.9	10500	20.5	12200	100	25.0	0.9	22.5		228
40	28.0	8780	20.5	12200	100	25.0	0.9	22.5		228
60	32.7	7200	20.8	12050	100	25.0	0.9	22.5		228
80	38.3	5700	20.9	12000	100	25.0	0.9	22.5		228
100	44.0	4540	21.1	11900	100	25.0	0.9	22.5		228
140	54.8	3010	21.0	11950	100	25.0	0.9	22.5		228
150	56.4	2840	21.3	11800	100	25.0	0.9	22.5		228
160	58.1	2660	22.3	11260	100	25.0	0.9	22.5		228
180	59.6	2520	21.2	11820	100	25.0	0.9	22.5		228
200	61.8	2330	21.6	11600	100	25.0	0.9	22.5		228
210	63.1	2230	22.2	11300	100	25.0	0.9	22.5		228
220	64.5	2120	22.8	11000	100	25.0	0.9	22.5		228
240	65.6	2040	23.9	10500	100	25.0	0.9	22.5		228
250	66.3	1990	25.0	10000	100	25.0	0.9	22.5		228
270	66.7	1960	26.4	9400	100	25.0	0.9	22.5		228
285	66.3	1990	26.7	9300	100	25.0	0.9	22.5		228
300	67.5	1910	26.9	9200	100	25.0	0.9	22.5		228
320	68.4	1850	27.3	9040	100	25.0	0.9	22.5		228
360	69.2	1800	27.8	8860	100	25.0	0.9	22.5		228
390	69.5	1780	28.1	8750	100	25.0	0.9	22.5		228
420	69.4	1790	28.1	8730	100	25.0	0.9	22.5		228
450	69.4	1790	28.2	8710	100	25.0	0.9	22.5		228

540	70.5	1720	29.0	8400	200	25.0	0.93	23.3		225
570	73.0	1580	29.6	8200	200	25.0	0.93	23.3		225
600	75.2	1470	30.2	8000	200	25.0	0.93	23.3		225
660	81.4	1200	30.7	7810	200	25.0	0.93	23.3		225
800	82.0	1150	33.0	7410		25.0	0.93	23.3		225
1000	81.9	1155	33.4	7310		25.0	0.93	23.3		225

MIRANDA-2: Calcite drilling
October 10, 2004

t/s	T/NTC1 °C	R/NTC1 Ω	T/NTC2 °C	R/NTC2 Ω	F/N	U/V	I/A	P/W	Notes
0	23.9	10490	20.9	12000	50	10.0	0.53	5.3	
60	24.1	10400			50	10.0	0.53	5.3	
90	25.5	9800			50	10.0	0.53	5.3	
120	26.9	9200			50	10.0	0.53	5.3	
150	27.7	8900			50	10.0	0.53	5.3	
180	28.7	8500			50	10.0	0.53	5.3	
210	29.0	8400			50	10.0	0.53	5.3	
240	29.6	8200			50	10.0	0.53	5.3	
270	29.9	8100			50	10.0	0.53	5.3	
300	30.0	8050			50	10.0	0.53	5.3	
360	30.8	7800	22.8	11000	50	10.0	0.53	5.3	
420	31.1	7700	22.8	11000	50	10.0	0.53	5.3	
540	31.7	7500	22.6	11100	50	10.0	0.53	5.3	

550	33.0	7100			100	10.0	0.7	7.0	
570	33.7	6900			100	10.0	0.7	7.0	
600	34.9	6550			100	10.0	0.7	7.0	
630	35.9	6300			100	10.0	0.7	7.0	
660	36.3	6200			100	10.0	0.7	7.0	
670	37.5	5900			200	10.0	0.75	7.5	
680	38.1	5750			200	10.0	0.75	7.5	
690	38.8	5590			200	10.0	0.75	7.5	
700	39.2	5500			200	10.0	0.75	7.5	
750	40.1	5300			50	20.0	0.58	11.6	
760	40.1	5300			50	20.0	0.58	11.6	
780	40.6	5200			50	20.0	0.58	11.6	
800	42.4	4840			100	20.0	0.8	16.0	
820	44.2	4500			100	20.0	0.8	16.0	
840	45.0	4360			100	20.0	0.8	16.0	
850	45.0	4370			100	20.0	0.8	16.0	
870	45.3	4320			100	20.0	0.8	16.0	
880	48.3	3840			100	20.0	0.8	16.0	
900	51.5	3400			100	20.0	0.8	16.0	
960	56.7	2800			100	20.0	0.8	16.0	
1100	84.1	1100			400	25.0	0.87	21.8	
1200	91.7	870			400	25.0	0.87	21.8	

MIRANDA-2: Calcite drilling
October 10, 2004

#	t/s	T/NTC1 °C	R/NTC1 Ω	T/NTC2 °C	R/NTC2 Ω	F/N	U/V	I/A	P/W	Notes
1	0	20.5	12200	N/A	N/A	50	10.0	0.53	5.3	
	60	21.8	11500			50	10.0	0.53	5.3	
	90	24.3	10300			50	10.0	0.53	5.3	
	120	26.9	9200			50	10.0	0.53	5.3	
	150	27.7	8900			50	10.0	0.53	5.3	
	180	28.7	8500			50	10.0	0.53	5.3	
	210	29.0	8400			50	10.0	0.53	5.3	
	240	29.6	8200			50	10.0	0.53	5.3	
	270	29.9	8100			50	10.0	0.53	5.3	
	300	30.0	8050			50	10.0	0.53	5.3	
	360	30.8	7800			50	10.0	0.53	5.3	
	420	31.1	7700			50	10.0	0.53	5.3	
	540	31.7	7500			50	10.0	0.53	5.3	
	550	31.7	7500			50	10.0	0.53	5.3	
	570	32.0	7400			50	10.0	0.53	5.3	
	600	31.7	7500			50	10.0	0.53	5.3	
	670	32.3	7300			50	10.0	0.53	5.3	
	680	32.3	7300			50	10.0	0.53	5.3	
	690	32.5	7250			50	10.0	0.53	5.3	
	700	32.5	7250			50	10.0	0.53	5.3	
	750	32.5	7250			50	10.0	0.53	5.3	
	800	32.8	7150			50	10.0	0.53	5.3	

	820	32.7	7200			50	10.0	0.53	5.3	
	870	31.7	7500			50	10.0	0.53	5.3	
	880	32.0	7400			50	10.0	0.53	5.3	
	900	31.7	7500			50	10.0	0.53	5.3	
	960	32.0	7400			50	10.0	0.53	5.3	
	1100	31.7	7500			50	10.0	0.53	5.3	
	1200	32.0	7400			50	10.0	0.53	5.3	
2	0	20.5	12200			100	10.0	0.7	7.0	
	60	23.3	10800			100	10.0	0.7	7.0	
	90	26.4	9400			100	10.0	0.7	7.0	
	120	28.5	8600			100	10.0	0.7	7.0	
	150	30.2	8000			100	10.0	0.7	7.0	
	180	31.4	7600			100	10.0	0.7	7.0	
	210	32.7	7200			100	10.0	0.7	7.0	
	300	34.0	6800			100	10.0	0.7	7.0	
	360	34.6	6650			100	10.0	0.7	7.0	
	420	34.9	6550			100	10.0	0.7	7.0	
	540	35.3	6450			100	10.0	0.7	7.0	
	600	36.1	6250			100	10.0	0.7	7.0	
	630	36.3	6200			100	10.0	0.7	7.0	
	660	36.5	6150			100	10.0	0.7	7.0	
	670	36.7	6100			100	10.0	0.7	7.0	
	700	37.1	6000			100	10.0	0.7	7.0	
	750	37.1	6000			100	10.0	0.7	7.0	
	760	37.3	5950			100	10.0	0.7	7.0	
	780	37.3	5950			100	10.0	0.7	7.0	
	800	37.3	5950			100	10.0	0.7	7.0	
	820	37.3	5950			100	10.0	0.7	7.0	
	840	37.4	5920			100	10.0	0.7	7.0	
	850	37.4	5920			100	10.0	0.7	7.0	
	870	37.3	5935			100	10.0	0.7	7.0	
	880	37.5	5900			100	10.0	0.7	7.0	
	900	37.5	5900			100	10.0	0.7	7.0	
	960	37.5	5890			100	10.0	0.7	7.0	
	1100	37.5	5900			100	10.0	0.7	7.0	
	1200	37.4	5910			100	10.0	0.7	7.0	
3	0	20.5	12200			200	10.0	0.75	7.5	
	60	23.7	10600			200	10.0	0.75	7.5	
	90	26.4	9400			200	10.0	0.75	7.5	
	120	29.0	8400			200	10.0	0.75	7.5	
	150	31.1	7700			200	10.0	0.75	7.5	
	180	32.5	7250			200	10.0	0.75	7.5	
	210	34.4	6700			200	10.0	0.75	7.5	
	240	35.9	6300			200	10.0	0.75	7.5	
	270	36.3	6200			200	10.0	0.75	7.5	
	300	36.5	6150			200	10.0	0.75	7.5	
	420	37.3	5950			200	10.0	0.75	7.5	
	540	37.5	5900			200	10.0	0.75	7.5	
	550	30.2	8000			200	10.0	0.75	7.5	
	570	33.3	7000			200	10.0	0.75	7.5	

	600	38.3	5700			200	10.0	0.75	7.5	
	670	38.8	5600			200	10.0	0.75	7.5	
	680	38.8	5590			200	10.0	0.75	7.5	
	690	38.8	5580			200	10.0	0.75	7.5	
	700	39.2	5500			200	10.0	0.75	7.5	
	800	39.9	5340			200	10.0	0.75	7.5	
	820	40.0	5330			200	10.0	0.75	7.5	
	840	40.0	5320			200	10.0	0.75	7.5	
	850	40.1	5310			200	10.0	0.75	7.5	
	870	40.0	5315			200	10.0	0.75	7.5	
	880	40.1	5305			200	10.0	0.75	7.5	
	900	40.1	5300			200	10.0	0.75	7.5	
	960	40.0	5315			200	10.0	0.75	7.5	
	1100	40.1	5300			200	10.0	0.75	7.5	
	1200	40.1	5300			200	10.0	0.75	7.5	
4	0	20.9	12000			50	20.0	0.58	11.6	
	60	24.3	10300			50	20.0	0.58	11.6	
	90	26.4	9400			50	20.0	0.58	11.6	
	120	29.2	8350			50	20.0	0.58	11.6	
	150	31.5	7550			50	20.0	0.58	11.6	
	180	33.0	7100			50	20.0	0.58	11.6	
	210	34.9	6550			50	20.0	0.58	11.6	
	240	36.7	6100			50	20.0	0.58	11.6	
	270	37.5	5900			50	20.0	0.58	11.6	
	300	37.9	5800			50	20.0	0.58	11.6	
	360	38.1	5750			50	20.0	0.58	11.6	
	420	38.3	5700			50	20.0	0.58	11.6	
	540	38.8	5600			50	20.0	0.58	11.6	
	550	38.8	5590			50	20.0	0.58	11.6	
	570	39.1	5520			50	20.0	0.58	11.6	
	600	39.4	5450			50	20.0	0.58	11.6	
	630	39.7	5400			50	20.0	0.58	11.6	
	660	39.9	5350			50	20.0	0.58	11.6	
	670	40.0	5330			50	20.0	0.58	11.6	
	680	40.1	5300			50	20.0	0.58	11.6	
	690	40.4	5250			50	20.0	0.58	11.6	
	700	40.6	5200			50	20.0	0.58	11.6	
	750	40.7	5180			50	20.0	0.58	11.6	
	760	41.1	5100			50	20.0	0.58	11.6	
	780	41.3	5050			50	20.0	0.58	11.6	
	800	41.4	5040			50	20.0	0.58	11.6	
	820	41.4	5040			50	20.0	0.58	11.6	
	840	41.3	5060			50	20.0	0.58	11.6	
	850	41.2	5070			50	20.0	0.58	11.6	
	870	41.4	5030			50	20.0	0.58	11.6	
	880	41.5	5010			50	20.0	0.58	11.6	
	900	41.4	5035			50	20.0	0.58	11.6	
	960	41.5	5010			50	20.0	0.58	11.6	
	1100	41.1	5090			50	20.0	0.58	11.6	
	1200	41.3	5050			50	20.0	0.58	11.6	

5	0	21.0	11950			100	20.0	0.8	16.0	
	60	26.2	9500			100	20.0	0.8	16.0	
	90	27.9	8800			100	20.0	0.8	16.0	
	120	30.2	8000			100	20.0	0.8	16.0	
	150	32.3	7300			100	20.0	0.8	16.0	
	180	33.3	7000			100	20.0	0.8	16.0	
	210	35.9	6300			100	20.0	0.8	16.0	
	240	37.5	5900			100	20.0	0.8	16.0	
	270	40.4	5250			100	20.0	0.8	16.0	
	300	42.1	4890			100	20.0	0.8	16.0	
	360	30.5	7900			100	20.0	0.8	16.0	
	420	44.2	4500			100	20.0	0.8	16.0	
	540	55.0	2990			100	20.0	0.8	16.0	
	550	55.1	2970			100	20.0	0.8	16.0	
	570	55.4	2945			100	20.0	0.8	16.0	
	600	55.2	2960			100	20.0	0.8	16.0	
	630	55.6	2920			100	20.0	0.8	16.0	
	660	55.9	2890			100	20.0	0.8	16.0	
	670	55.9	2890			100	20.0	0.8	16.0	
	680	55.9	2890			100	20.0	0.8	16.0	
	690	56.1	2870			100	20.0	0.8	16.0	
	700	56.3	2850			100	20.0	0.8	16.0	
	750	44.8	4400			100	20.0	0.8	16.0	
	840	56.0	2880			100	20.0	0.8	16.0	
	850	56.2	2860			100	20.0	0.8	16.0	
	870	56.3	2850			100	20.0	0.8	16.0	
	880	56.4	2840			100	20.0	0.8	16.0	
	900	56.4	2830			100	20.0	0.8	16.0	
	960	56.7	2800			100	20.0	0.8	16.0	
	1100	56.6	2810			100	20.0	0.8	16.0	
	1200	56.3	2850			100	20.0	0.8	16.0	

6	0	21.3	11800			400	25.0	0.87	21.8	
	60	28.2	8700			400	25.0	0.87	21.8	
	90	30.2	8000			400	25.0	0.87	21.8	
	120	32.7	7200			400	25.0	0.87	21.8	
	150	37.5	5900			400	25.0	0.87	21.8	
	180	46.6	4100			400	25.0	0.87	21.8	
	210	55.8	2900			400	25.0	0.87	21.8	
	240	61.0	2400			400	25.0	0.87	21.8	
	270	66.9	1950			400	25.0	0.87	21.8	
	300	72.7	1600			400	25.0	0.87	21.8	
	360	78.9	1300			400	25.0	0.87	21.8	
	420	84.4	1090			400	25.0	0.87	21.8	
	540	64.8	2100			400	25.0	0.87	21.8	
	550	84.7	1080			400	25.0	0.87	21.8	
	570	85.0	1070			400	25.0	0.87	21.8	
	600	87.2	1000			400	25.0	0.87	21.8	
	630	87.2	1000			400	25.0	0.87	21.8	
	660	87.5	990			400	25.0	0.87	21.8	
	800	90.9	890			400	25.0	0.87	21.8	
	820	89.2	940			400	25.0	0.87	21.8	

840	70.9	1700			400	25.0	0.87	21.8	
850	84.1	1100			400	25.0	0.87	21.8	
870	89.5	930			400	25.0	0.87	21.8	
880	90.2	910			400	25.0	0.87	21.8	
900	89.2	940			400	25.0	0.87	21.8	
960	77.8	1350			400	25.0	0.87	21.8	
1000	87.2	1000							
1100	89.9	920			400	25.0	0.87	21.8	
1200	90.6	900			400	25.0	0.87	21.8	

MIRANDA-2: Granite drilling
October 10, 2004

#	t/s	t/s	T/NTC1 °C	R/NTC1 Ω	T/NTC2 °C	R/NTC2 Ω	F/N	U/V	I/A	P/W
1	0	0	20.8	12050	23.5	10700	50	10	0.52	5.2
	30	30	25.2	9900			50	10	0.52	5.2
	60	60	26.2	9500			50	10	0.52	5.2
	90	90	26.9	9200			50	10	0.52	5.2
	120	120	28.1	8750			50	10	0.52	5.2
	150	150	29.0	8400			50	10	0.52	5.2
	180	180	29.6	8200			50	10	0.52	5.2
	210	210	29.9	8100			50	10	0.52	5.2
	240	240	30.2	8000			50	10	0.52	5.2
	300	300	30.5	7900			50	10	0.52	5.2
	420		30.5	7870						
	540		30.5	7875						
	660		30.6	7860						
	780		30.8	7800						
	900		30.7	7825						
2	910	310	30.8	7800			100	20	0.54	10.8
	960	360	33.0	7100			100	20	0.54	10.8
	1020	420	40.1	5300			100	20	0.54	10.8
	1080	480	43.7	4600			100	20	0.54	10.8
	1140	540	44.2	4500			100	20	0.54	10.8
	1260		45.1	4350						
	1380		44.5	4450						
	1500		44.8	4400						
	1620		44.5	4450						
	1740		44.8	4400						
2B	1800	600	44.8	4400			100	25.0	0.65	16.3
	1830	630	46.6	4100			100	25.0	0.65	16.3
	1860	660	49.3	3700			100	25.0	0.65	16.3
	1920	720	49.6	3650			100	25.0	0.65	16.3
	1980	780	50.0	3600			100	25.0	0.65	16.3
	2040	840	50.7	3500			100	25.0	0.65	16.3
	2160		51.9	3350						
	2280		51.0	3470						
	2400		51.0	3465						
	2520		50.7	3500						
	2640		51.1	3450						

3	2700	900	50.7	3500			200	25.1	0.7	17.6
	2730	930	63.4	2200			200	25.1	0.7	17.6
	2760	960	70.9	1700			200	25.1	0.7	17.6
	2820	1020	78.9	1300			200	25.1	0.7	17.6
	2880	1080	88.1	970			200	25.1	0.7	17.6
	2940	1140	92.4	850			200	25.1	0.7	17.6
	2970	1170	93.2	830			200	25.1	0.7	17.6
	3000	1200	94.4	800			200	25.1	0.7	17.6
	3120		93.4	825						
	3240		93.4	825						
	3360		94.0	810						
	3480		93.2	830						
	3600		93.8	815						
4	3630	1230	97.1	740			400	25.1	0.94	23.6
	3660	1260	103.7	610			400	25.1	0.94	23.6
	3720	1320	104.8	590			400	25.1	0.94	23.6
	3780	1380	104.2	600			400	25.1	0.94	23.6
	3840	1440	105.4	580			400	25.1	0.94	23.6
	3870	1470	106.0	570			400	25.1	0.94	23.6
	3900	1500	106.0	570			400	25.1	0.94	23.6
	4020		105.4	580						
	4140		106.0	570						
	4260		105.7	575						
	4380		104.8	590						
	4500		105.4	580						
5	4530	1530	103.7	610			100	25.1	0.66	16.6
	4560	1560	100.9	660			100	25.1	0.66	16.6
	4590	1590	96.6	750			100	25.1	0.66	16.6
	4620	1620	94.4	800			100	25.1	0.66	16.6
	4680	1680	93.8	815			100	25.1	0.66	16.6
	4800	1800	93.6	820			100	25.1	0.66	16.6
	4920		94.0	810						
	5040		93.0	835						
	5160		92.8	840						
	5280		92.4	850						
	5400		92.8	840						

NOTE:

The temperature values from the NTC resistance values were calculated by using the Steinhart-Hart equation (Equation 14 below):

$$\frac{1}{T} = A + B \cdot (Ln \quad R) + C \cdot (Ln \quad R)^3 \qquad (14)$$

where constants A = 0.001129148 K^{-1}, B = 0.000234125 K^{-1} and C = $8.76741 \cdot 10^{-8}$ K^{-1} (as calibrated by the NTC manufacturer). R is the measured resistance / 1 Ohm. Nominal resistance of the NTC in 25 °C is 10 kΩ with negative temperature coefficient.