NANOKHOD MICROROVER HEADING TOWARDS MARS

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ABSTRACT

The European Space Agency has commissioned a number of development activities on micro-rovers for planetary surface missions, aiming primarily at geochemistry and exobiology science applications on Mars. This paper addresses first the background and development logic of these activities and recalls part of the results of the recently completed contract "Micro-Robots for Scientific Applications" which has produced a conceptual design of a flight model as well as an advanced breadboard model of a 'Nanokhod' tracked microrover. Furthermore it describes the complementary near-term development activities.

1. INTRODUCTION

There is growing interest in Europe and the world in exploration of celestial bodies by means of instruments deployed on their surface. An essential element of unmanned missions to the surface of planets such as Mars and Mercury will be robotic mobile devices to deploy instruments in a certain range around a lander spacecraft, to provide visual observation, to sample surface material, and to feed analysis instruments. Such robotic devices will have to function reliably and be versatile in poorly known and often difficult terrain, with very restricted means of intervention from Earth because of extreme remoteness.

To serve the current trend to do smaller, cheaper, more frequent missions, micro-rovers are considered a critical enabling technology. Here, the terms "micro-rovers" and "micro-robots" refer to roving vehicles of the class (significantly) below 10 kg, in keeping with an established terminology of large / mini / micro-rovers for space exploration. Since their primary purpose is to deploy scientific payloads, they have to be optimized to perform this task making as little use of resources as possible.

The European Space Agency (ESA) has funded the development of two micro-rover concepts, specifically designed to perform scientific analysis in-situ, in the frame of its Technology Research Programme activity "Micro Robots for Scientific Applications", abbreviated "Micro-Rosa", see [1],[2]. This work was performed by *Von Hoerner & Sulger GmbH* (vH&S, Schwetzingen, Germany) as prime contractor, with the *Max-Planck-Institut für Chemie* (MPICh, Mainz, Germany), the *DLR-Institut für Raumsimulation* (DLR, Köln, Germany), the *DLR-Institut für Robotik und Systemdynamik* (DLR, Oberpfaffenhofen, Germany), *Mecanex S.A.* (Nyon, Switzerland) and the *Ecole Polytechnique Fédérale de Lausanne* (EPFL, Switzerland). For the primary concept, named "Nanokhod", which is based on previous work performed at the Max-Planck Institute for Chemistry, a conceptual design of a flight model has been made which offers a very high instrument-mass/rover-mass ratio.

Furthermore ESA has initiated some complementary activities aiming at the delivery of a Nanokhod microrover system which is sufficiently ready to be used for a mission. These activities are related to the development of an end-to-end control system [3], the development of a robotic sampling system [4] and the rover design optimization and qualification of an Nanokhod engineering model.

2. NANOKHOD DESIGN SUMMARY

An overview of the requirements and the design are given in [1],[2]. The main features will briefly be recalled below.

Figure 1 shows the Micro-Rosa system architecture. The Nanokhod "rover segment", with a total mass of 2550 g, including 1100 g of payload, is shown in Figure 2. It is a rugged, simple, reliable yet effective microrover, to carry a set of instruments in the immediate surroundings of a lander (i.e. at least 20 m away from it). In order to maximize locomotion efficiency, it carries around only what is strictly needed for moving and deploying the instruments. Its scientific sensor instruments are accommodated in the central payload cab as shown in Figure 3. Two rotation axes at the ends of the payload cab levers provide 2 degrees of freedom for positioning one of its two viewing

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windows w.r.t. a rock or soil spot of interest. Locomotion is performed by means of tracks. As a consequence of the very limited mass and volume budgets no batteries or other power supply devices are on board of the rover. Instead it is equipped with a thin tether consisting of two wires, providing a power and data connection to the lander. Semi-autonomous control is performed using a 3D digital elevation model of the terrain acquired by means of a panoramic camera on the lander. Thermal control is entirely passive. All micro-rover components shall withstand, under non-operating conditions, temperatures of -140°C to +70°C. Operation will be limited to time slots during which drives and electronics are within their operating range of -80°C to +50°C.

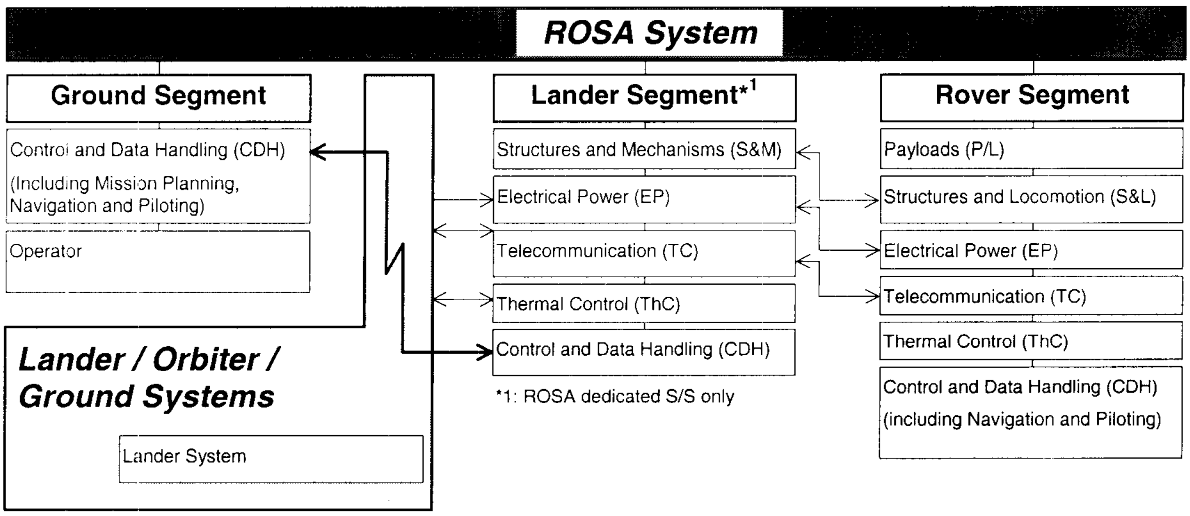

Figure 1: Micro-ROSA System Breakdown

3. BREADBOARD MODEL DEVELOPMENT AND TESTING

As part of the Micro-RoSA activity an advanced breadboard model of the Nanokhod micro-rover has been developed and produced [1]. The main objectives for this breadboarding activity had been to demonstrate locomotion and payload positioning performance in a configuration that is representative in mass and size of the actual rover flight model. Dry lubrication, wear and friction performance, track guidance as well as dust sealing were addressed in detail. The Power and Telecommunication subsystem was designed following the conceptual design baseline for the flight model with respect to the integration of power conversion and telecommunication on the tether wire.

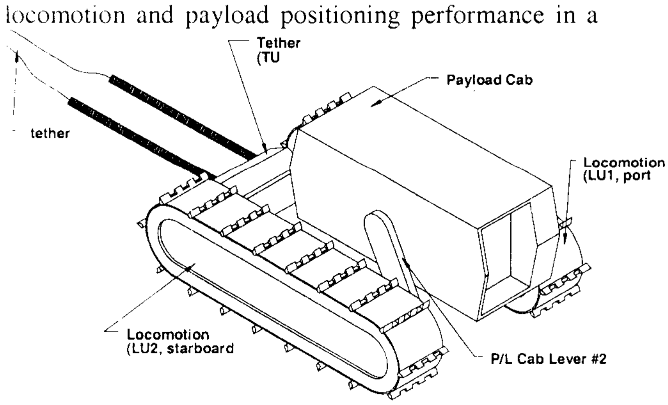

Figure 2: Isometric Sketch of the Nanokhod Rover Segment

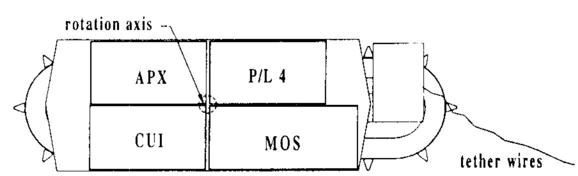

Figure 3: Typical Payload Accommodation (Stowage Configuration)

Figure 4 shows the hardware items of the laboratory model.The rover is controlled with a standard notebook computer which communicates with the on-rover microprocessor. The rover can be operated by manual piloting using joysticks, or it can execute automated motion sequences in a macro mode including simple sensor feedback.

With 1376.5 g, the breadboard model in its current state is already within the mass specification of the flight model (1450 g), confirming the feasibility of the concept within the given mass requirements.

A variety of tests have been undertaken not only to verify the performance of the Nanokhod laboratory model with respect to the specified requirements, but also to show that the key design concepts chosen in the conceptual design baseline can actually be realised for a flight mission.

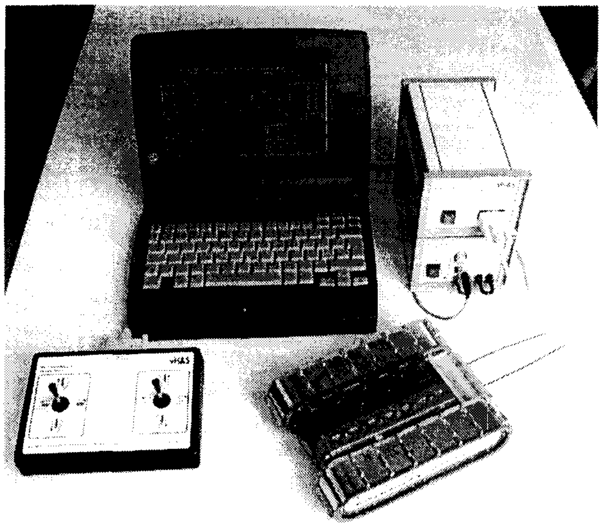

Figure 4: Model A Breadboard Model Hardware

Proof of Concept Testing

Considering the extreme mass restrictions and the resulting passive thermal control approach, environmental compatibility of components and subsystems is a critical point. Therefore, a number of assessment tests have been carried out in order to verify the feasibility of the chosen technical solutions. These tests included:

Deep temperature behaviour of commercial off-the-shelf DC-brush-motors: After removing the lubricant from the motor, it was possible to operate it down to temperatures of -170°C. A careful analysis and adaptation of the motor needs to be carried out prior to flight model development, but the early tests confirmed the feasibility in principle.

Deep temperature behaviour of the track sealing: In order to protect subsystems accommodated in the locomotion units, sealing of the track bodies is a critical issue. With a special brush sealing, this problem has been solved. The mechanical characteristics of the sealing were tested well under -120°C

Tether Mechanical and Electrical Behaviour at Deep Temperatures: Multiple deployment tests of the tether cable including thermal cycling between ambient temperatures and −195°C have been carried out, confirming mechanical and electrical robustness of the chosen tether under worst case mechanical loads.

Tether Low Pressure Glow Discharge Test: This test was conceived to check the electrical behaviour of a pair of tether wires under simulated Martian atmospheric conditions. In a vacuum tank with a CO_2-atmosphere between 0,15 and 14,2 hPa, no plasma phenomena could be triggered assessing different tether configurations (parallel, divergent, twisted) and voltage levels up to 500 V.

Operation of electronic subsystems at low temperatures is also an important issue. However, earlier studies [5] have shown that the operating temperatures targeted are inside the actually attainable limits of space-qualified components.

The tests allowed to confirm the feasibility of technical concepts and component issues, thus supporting the conceptual baseline definition by verification of key design issues. A more detailed and complete verification will be performed in the frame of complementary technology studies and the detailed design and development of the rover flight model.

Breadboard Verification Tests

Within the Micro-RoSA activity, the Nanokhod breadboard model has been submitted to overall system tests in order to verify traction capabilities, tether unrolling on flat terrain, overcoming of obstacles, slope climbing, tip-over recovery, payload cab positioning, as well as use of control and sensors. In particular the locomotion tests have proven the outstanding performance of the tracked micro-rover concept.

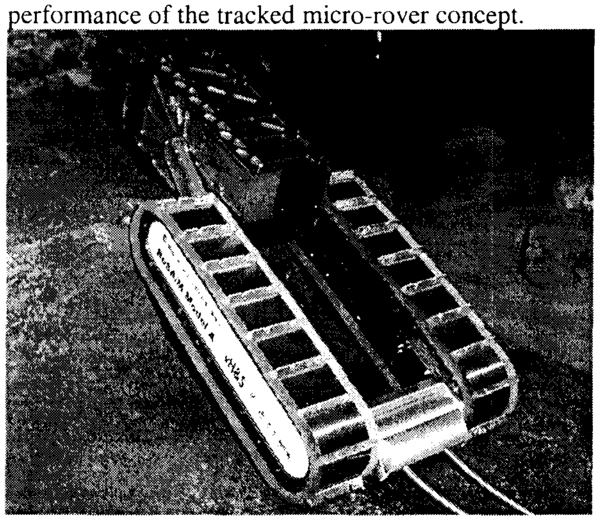

Figure 5: Obstacle Climbing

Although having a total height of only 60 mm in stowed configuration, the Nanokhod was able to overcome 0.1 m step-shaped obstacle.

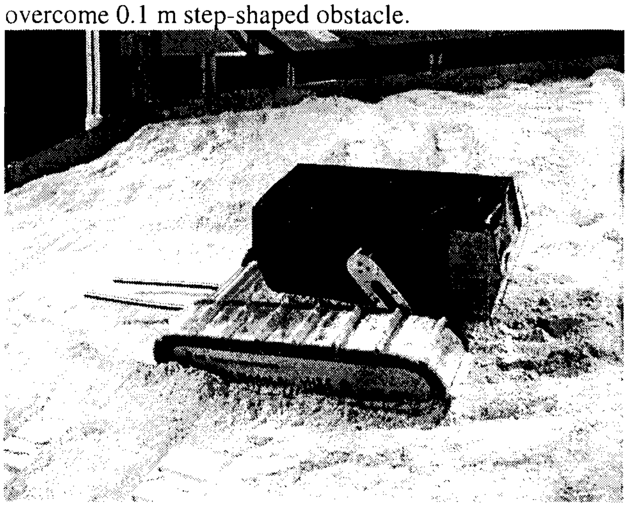

Figure 6: Slope Climbing

Climbing obstacles is facilitated by adjusting the center of mass by movements of the payload cab (Fig. 5). A similar procedure can be applied for trench shaped obstacles. In Fig. 6, Nanokhod climbs a slope on Mars soil simulant (particles with sub-micron size) at a slope angle of 24 °. On the slope, the vehicle was also able to turn on the spot and to drive sideways.

Another test addressed the tether mechanical behaviour while driving on flat terrain. 50 m of tether cable had been accommodated in the tether unit on the rover. In this test, the tether was deployed while driving forward over a distance of 20 m. The deployment was successful and had no impact of the operational behaviour of the mechanical, electrical and telecommunication subsystems.

The Micro-RoSA test campaign confirmed that all breadboard requirements as specified in the test plan have been met. Nanokhod in particular showed a very robust and reliable performance with respect to overcoming of obstacles and recovery from tip-over.

4. END-TO-END CONTROL

To support the control and navigation the following items are planned to be used:

- an imaging head placed on top of the lander and fitted with optical means to allow modelling of the environment and the localisation of the Nanokhod (part of 'Lander System' in Figure 1)
- a lander-mounted computer that runs the navigation software and controls the rover through the tether (also part of 'Lander system')
- a ground control station (as part of 'Ground Segment').

ESA has recently initiated an industrial activity with Space Applications Services (B) as prime Contractor, together with DLR-Oberpfaffenhofen (D), KU Leuven (B), and von Hoerner & Sulger (D), the overall objective of which is to produce all the remaining elements of the end-to-end control system, to enable quick completion of the Nanokhod in an upcoming mission. In particular, this activity shall study, define, design and produce:

- the ground control station (GCS)
- the on-lander control system (LCS)
- the imaging head of the localisation subsystem (optics, cameras, and pointing)
- the on-rover control system (RCS)

This activity will not produce flight-ready hardware, however it shall use standards, processes, components and materials, which enable a relatively low cost qualification for the Martian environment. The development of all the control system will be based on the MORCA architecture [6], following the 'Interactive Autonomy' concept originally applied for robot arms working in a structured environment.

The end-to-end elements will be designed to support three phases of operation:

- *Pre-preparation*: this phase starts immediately after the lander settles on the planet surface. The relevant elements of the control system are used to acquire the characteristics of the environment in which the rover will operate.
- *Preparation*: in this phase rover operations are programmed. The rover motion and interaction with the environment is planned, programmed in form of rover programs and verified.
- *Utilisation*: In this phase the rover programs are downloaded to the LCS and executed. This phase includes also the analysis of the telemetry produced during the execution.

The principle on which the control of the Nanokhod is based is that everything is as much as possible rigidly programmed. Therefore the pre-preparation and preparation phases features enable the creation of robot programs the execution results of which can be predicted with high accuracy. In Pre-preparation, great care is taken to create an extremely precise model of the environment. The geometry of the terrain is acquired with the use of the imaging head and high precision computer vision algorithms. Computer vision is also used for interpreting the soil characteristics.

In Preparation, the rover motion is planned using a high performance path planner which produces paths that optimise rover motion and minimise risk of deviation. In Utilisation, the rover motion is continuously measured by the imaging head, together with the localisation software. The control system is therefore able to correct deviations before they become significant.

5. ROBOTIC SAMPLE ACQUISITION

Functions and Requirements

A clear extension of the capabilities of the Nanokhod is in the direction of acquiring samples and not just analyzing them in-situ.

The task of collecting samples for scientific analysis presents several aspects with related requirements. The first aspect is related to accessing the samples. Specifically scientists demand two types of samples:

- Surface samples: these are extracted from surface stones/rocks by coring at the depth of few centimetres
- Deep soil samples: these are extracted vertically from a depth of >1 meters

Beside its use in Earth crust investigations, drilling has been already addressed for space exploration missions and seems to be the most acceptable technical means for accessing both surface and deep samples.

The requirements related to drilling can be resolved into the tasks to:

- penetrate deep (>1 or even 2 meters)
- penetrate non-homogeneous soil of unknown hardness (soft to very hard)
- allow multiple drilling (the research nature of the deep sampling does not guarantee anything interesting is found in the first drill hole)

- operate in unmanned and automatic mode (deployment, drilling and sampling)
- operate in low gravity: the system cannot rely on weight to generate drill thrust

The second step of sample acquisition is sampling. The requirements relative to sampling are:

- acquire a pristine sample of unknown hardness (soft to very hard) and consistency (loose to compact)
- sample at a certain depth, material of that specific layer (not material carried through from upper layers)
- allow investigation of several layers
- preserve morphology of the sample

The third step consists of delivering the collected material. Some analysis instruments, due to their large dimensions, cannot be transported by the rover. They are mounted on the lander and the collected soil/rock material needs to be brought there. The requirements for delivering are:

- transport the sample to the instrument
- do not alter sample morphology
- do not pollute sample with surface material

In view of these requirements, ESA has initiated a first technology research activity (see [4]) to analyse, design and develop a Robotic Sampling System based on the Nanokhod micro-rover (RSS/N). The RSS/N shall be capable of deep drilling, sampling and delivering samples to a lander.

This activity has been recently started by an industrial team composed by Space Systems Finland Ltd. (FIN) with VTT Automation (FIN) and Helsinki University of Technology (FIN). The following description shows only the preliminary concept of such system.

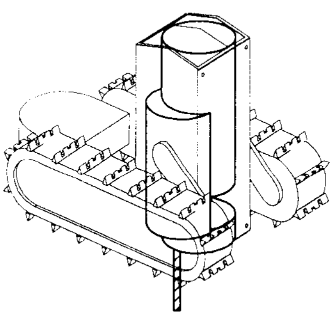

Figure 7: The Drilling and Sampling Subsystem inside the Payload Cab

The RSS/N will be composed of two main items:

- the Drilling and Sampling Subsystem: this element is housed inside the Nanokhod Payload Cab (see Figure 7) and allows the coring of surface rocks as well as sampling in depth.
- the Docking and Sample Delivery Port: this element is accommodated on the lander (see Figure 8) and allows the handing over of samples from the rover to a Sample Processing and Distribution System.

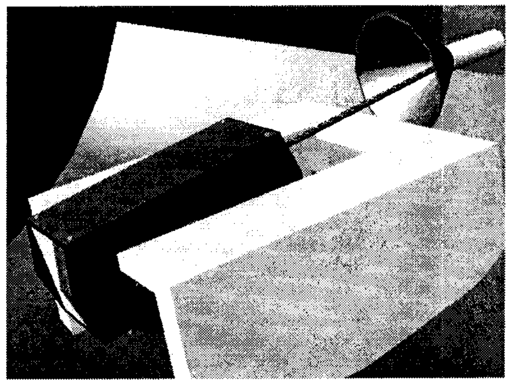

Figure 8: Concept of the Docking and Sample Delivery Port

The Drilling and Sampling Subsystem

This subsystem implements the functions of drilling and coring. For achieving different drilling inclinations the articulation of the payload cab is used. The requirement of drilling at different depths is accommodated by the capability of the subsystem of assembling a *drilling string* of variable length. The *drilling string* is composed by one *tool bit* and up to ten *drill pipes*. A typical assembly sequence is shown in Figure 10.

The *drill pipes* and *tool bits* are connected via socket-plug joints. The coupling and de-coupling is performed by a *drill string assembly unit*. The joints provide a stiff connection thanks to the use of an elastic o-ring, to the matching tetrahedral shape of the socket and plug and to magnetic/thermally actuated clips (see Figure 11).

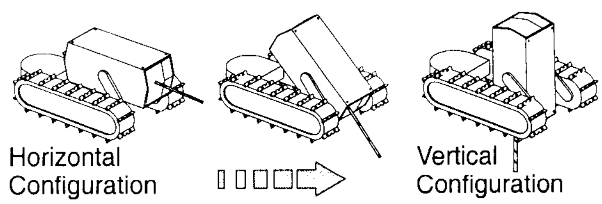

Figure 9: Different Possible Drilling Configurations

The requirement to be able to sample at different depths is accommodated by a simple drill operating procedure and by an innovative tool bit design. Basically the tool bit performs three functions at the same time: drill bit, coring tool and sample storage. The switch between different functions is achieved through different combinations of thrust and rotation. The combined action of drilling and coring (see Figure 13) is achieved when the drill string is pushed downwards and rotates in clockwise direction. Once the desired depth of sampling is reached, the core, which has been developed into the tool bit, can be cut by operating at zero thrust speed and anticlockwise rotation. This combination of thrust/rotation activates the core cutter, which slowly separates the core from its originating material. At this point the drill string

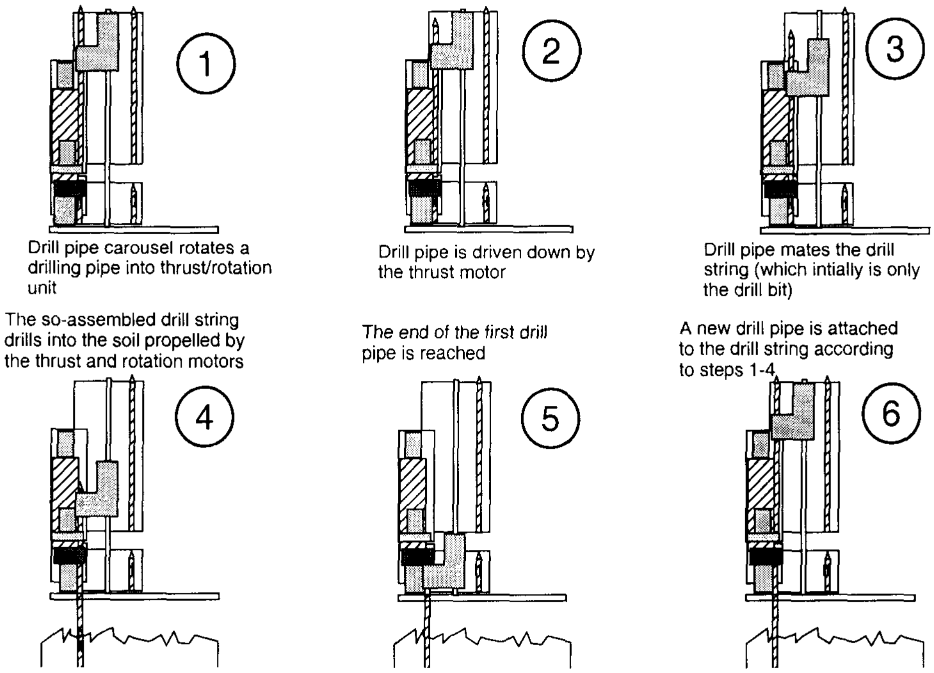

Figure 10: ***Drill String Assembly Sequence***

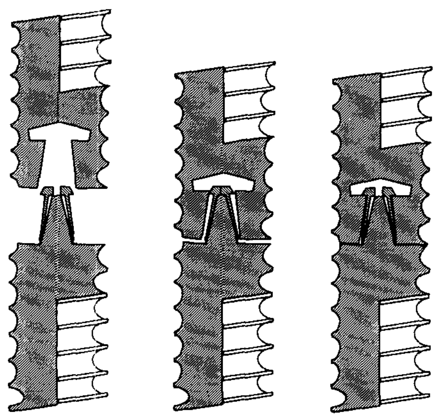

Figure 11: Sequence showing the Connection between two Drill String Elements

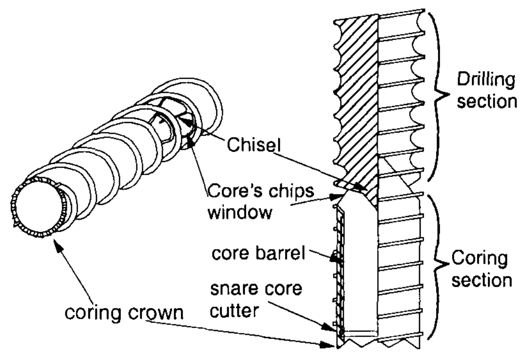

Figure 12: The Tool Bit

may be pulled out of the hole by imposing an upward thrust and an anticlockwise rotation.
When the drill string is disassembled, the tool bit holds the core. It is therefore used as sample storage until it is transferred to the Sample Delivery Port. Since the Drilling and Sampling Subsystem holds up to 10 tool-bits, the Nanokhod can collect a total of 10 samples before getting back to the lander.

The Docking and Sample Delivery Port

This subsystem implements the interface between the rover, its Drilling and Sampling Subsystem and the lander. Its is conceived to enable:

- an easy deployment of the rover on the planet surface
- some passive guidance of the rover when it returns to deliver samples
- easy delivery of samples (held into *tool bits)* to a Sample Processing and Distribution System

The first two functions may be realised with rather conventional means (foldable ramps with suitable shapes).
For the last function a first simplistic implementation has been already shown in Figure 8.
The delivery operation uses the Nanokhod payload cab and the Drilling and Sampling Subsystem as a 3 degrees of freedom robot. First, the two tilt-axis of the payload cab point the Drilling and Sampling Subsystem towards the Sample Delivery port. The tool bit is then inserted into the latter by the thrust action of former. The tool bit is then detached from the drill string and its content passed to a Sample Processing and Distribution System.

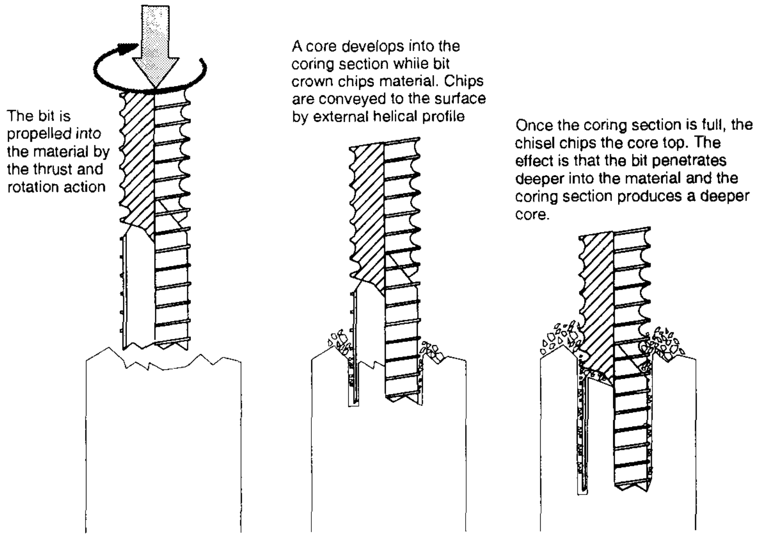

Figure 13: *Combined Drilling and Coring*

6. TOWARDS AN ENGINEERING MODEL

Complementary to the development steps mentioned in section 4 (End-to-End Control) and section 5 (Robotic Sample Acquisition), the further development of the micro-rover can now address overall system aspects of environmental compatibility including system testing. Within Micro-RoSA, technical concepts for all subsystems have been established and basic technical and operational principles have been verified. While the breadboarding activities have been focussed on locomotion and payload accommodation, the rover as an integrated system now needs to be further advanced in order to resist the environmental conditions on Mars. These activities must include in particular the detailed definition of:

- the low temperature concepts for motors, gears and bearings
- sealing concepts for bearings, tracks, payload cab and tether unit

These can then be implemented in an engineering model which allows for testing of the complete rover in thermal vacuum and dust chambers. The objectives of these tests are to verify the overall system behaviour under realistic environmental conditions, thus establishing the basis for flight model development.

Another issue to be addressed is the system integration of electrical, control and data handling subsystems, as well as payloads. This would include a detailed analysis and design for distribution and optimisation of subsystem and payload elements (P/L sensor parts, analogue and digital electronics, power conversion and distribution, interfaces for power, data, and control), as well as reliability, redundancy, and risk considerations on a subsystem and overall system level.

Applicability on possible other target planets is being considered too, e.g. for a Mercury Sample Return Mission.

7. CONCLUSIONS

Feasibility of a micro-rover for scientific applications with a system mass below 3.3 kg, a peak power need of less than 3 W and a payload to total rover mass fraction between 40 and 50 % has been demonstrated.

Complementary development work has started and has been planned to produce all elements needed for a flight model development for a Mars mission, although there is no confirmed mission opportunity so far.

8. ABBREVIATIONS

APX	Alpha-Proton-X-ray-Spectrometer
C&DH	Control and Data Handling
CUI	Close-Up Imager
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ESA	European Space Agency
I/F	Interface
LU	Locomotion Unit
Micro-ROSA	Micro-Robots for Scientific Applications
MOS	Moessbauer-Spectrometer
MPICH	Max-Planck-Institut für Chemie
P/L	Payload
PLC	Payload Cab
PLCL	Payload Cab Lever
vH&S	Von Hoerner & Sulger GmbH

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