THE MICRO ROSA2 ACTIVITY – CONCLUSION AND FUTURE PLANS

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1. INTRODUCTION

European Space Agency (ESA) funded a GSTP activity "Micro Robots for Scientific Applications 2" (MRoSA2). 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 meters, on a planetary surface. Main work was done in concentrating to the Martian environment, although the concept is generic to any celestial body that is possible for landing and which offers adequate anchoring for drilling purposes.

The system consists of the Mars lander and the rover (Fig. 1). The rover carries the Drilling and Sampling Subsystem (*DSS*) module, which is able to penetrate and sample the Martian ground up to two meters, into unknown hardness up to number eight on the Mohs' scale. Rover is controlled by lander, which has a stereo camera system and image processing capabilities. Both the lander and the rover have their own computers to control their sub tasks. The lander was not implemented in this activity. It was only specified in required rover interface level and there was a control computer (ordinary PC), which acted as a lander and was controlled by a human operator. The main work in this activity was done in the RSS and DSS. The drilling technology was new and never before tested in this purpose.

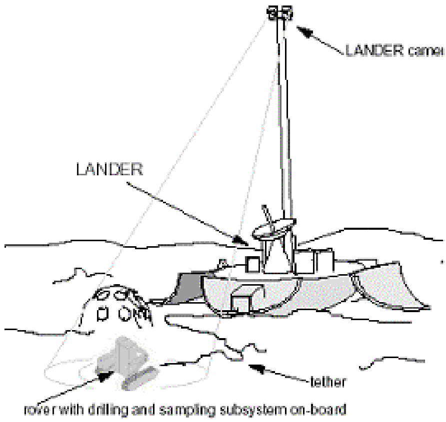

Fig. 1: Mars lander and the rover carrying the DSS module.

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.

This publication will explain the details of the project work: the requirements vs. the results and simultaneously analyse and plan how the work can be improved in the future projects. There were several details in the system, which were difficult to accomplish, mainly regarding the DSS module. The main emphasis of this document is in the DSS module.

2. MISSION OBJECTIVES AND REQUIREMENTS

The search for possible extinct or extant life is the goal of the exobiology investigations to be undertaken during future Mars missions. 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).

2.1 Operational Scenario

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 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 require extensive software design. Therefore emergency operations were included in mechanical design, but they were demonstrated only in manual control.

2.2 General Requirements for the System Performance

As mentioned above, the only sensible Martian exobiology investigation must be performed on pristine samples that have never been exposed to the surface environment [1]. Two types of samples have this characteristic:

- samples extracted from surface stones/rocks by coring at a depth of a few centimeters.
- deep soil samples acquired vertically from a depth of more than 1 meter.

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

- reach sampling locations in a 15m of radius around a lander spacecraft
- acquire samples and deliver them to the lander
- drill up to 2 meters into regolith
- drill up to several centimeters 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, which are defined later in this paper.

2.3 System Description

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

2.3.1 The Mars Surface Station

As mentioned in Chapter 1, 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 is, 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 is also possible to use low-level commands from the lander or from the ground control, if needed for example in emergency situations.

2.3.2 The Rover Functional Mock-Up (RFMU)

The requirements for the RFMU were that it should be a Nanokhod-like [8] 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 15m around the lander.

The rover has two tracks with the equipment and payload departments between the tracks. The whole middle part of the rover can be lifted, thus the clearance can be controlled between –20cm to 20cm. 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.

Fig. 2: Rover with drilling and sampling subsystem.

2.3.3 The 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-meter 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.

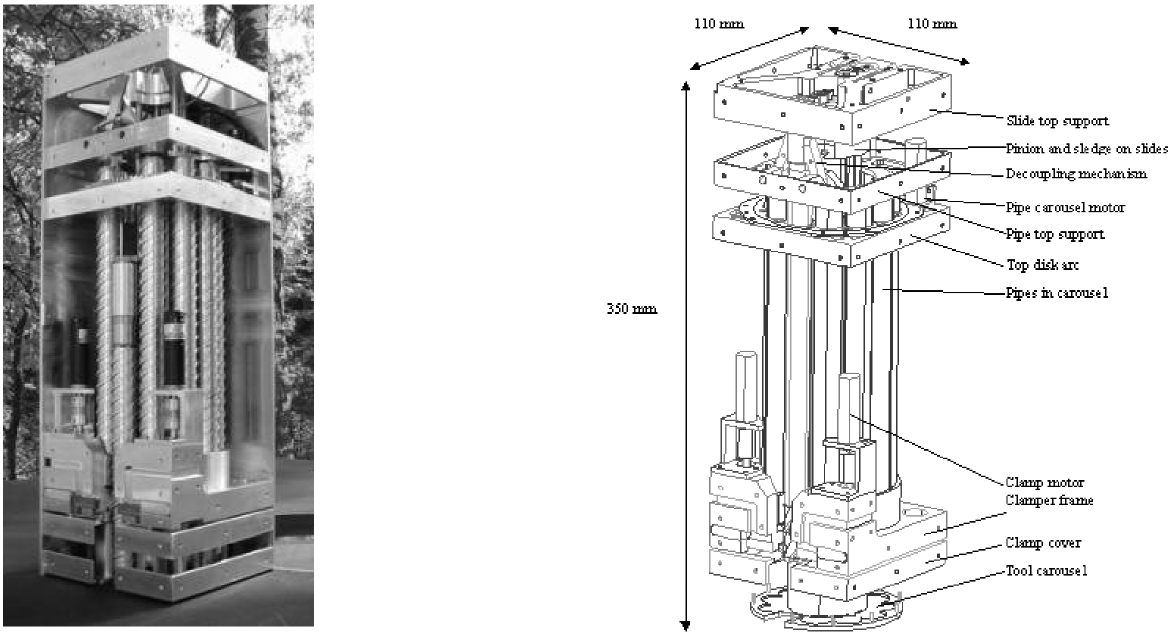

Fig. 3. The Drilling and Sampling Subsystem (DSS) module.

3. PROJECT RESULTS

The technical proposal [7] of the project was written in 1998, when the feasibility was evaluated within the project team and with technical consultants from other Finnish institutes. Matters discussed were mostly related to the sampling ability and the technical solutions.

3.1 Concept results

The project proved that a small sized robotic sampling and drilling vehicle is feasible. A 2-meter 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. Its much more easy to produce and store the electric power in the lander than in the rover. However, next 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 (Moh > 4). The mechanical structure of the DSS is good in principle but some small details like solenoid in the pipe gripper, positioning of the carousels and the design of pipe clampers need tuning. Anyway, the basic idea is functional and it will be developed further in two projects. First concentrating to the development of the drill system and another to the supporting rover.

3.2 Design bugs and lessons learned

The objective of the project was to study is the principle of a small-scaled drilling rover feasible. There was 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 the concept was functional there was some design matters, which have to reconsidered in the future. Most critical matters are listed below.

- *Carousels*: improved position accuracy needed
- *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 to be re-designed or improved, are:

- Drill power consumption
- Physical properties
- Drill system tests

3.2.1 Pipe and Tool Carousel Design

The pipe carousel (Fig. 4) 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 (Fig. 5) 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. More accurate sensors should be used, or then the stopping position of the carousels should be verified mechanically. One possible improvement idea is shown in Fig. 6.

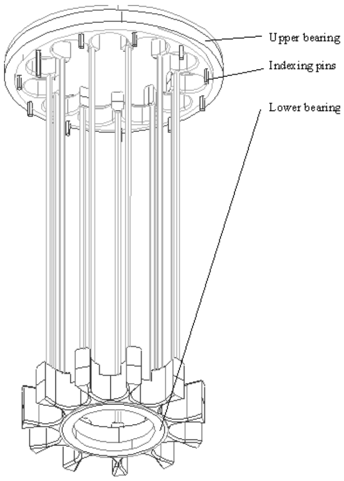

Fig. 4: Drill pipe carousel.

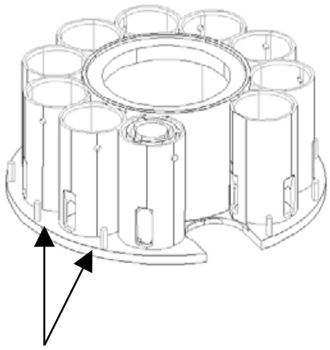

Fig. 5: Drill tool carousel.

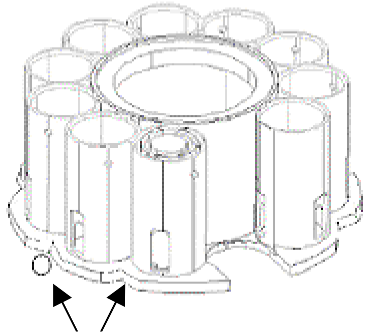

Fig. 6: Carousel positioning.

3.2.2 Pipe Clamping Mechanism

The string holding device (visible in Fig. 3), 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.

3.2.3 Pipe Gripper System

Spindle solenoid (Fig. 7) 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 using a permanent magnet core (Fig. 8) 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.

Fig. 7: Solenoid actuated pipe gripper.

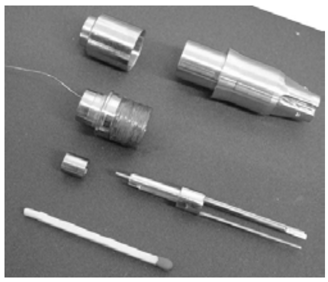

Fig. 8: Current solenoid configuration.

The solenoid caused a lot of problems while it jammed after collecting enough dust. 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 project team has 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 is illustrated in Fig. 9. Note that the figure doesn't include the spindle electrical connection rings, located in the exterior of the spindle.

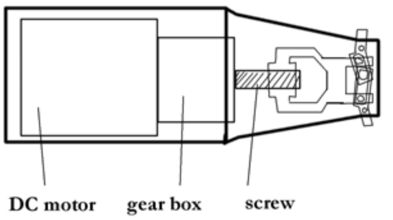

Fig. 9: DC Motor powered pipe gripper locking system.

3.2.4 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 material strength of the linear feed system. One possibility to solve these uncertainties would be screw coupling of pipes.

3.2.5 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, ie. 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.

3.2.6 Drill Tools and Sampling Mechanism

The tool is designed to drill a 17 mm diameter hole into rock material and to contain ~9 mm diameter and ~15 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 is broken with the aid of a core lifter (a ring shaped wedge) that grasp on the core when the tool is elevated. 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.

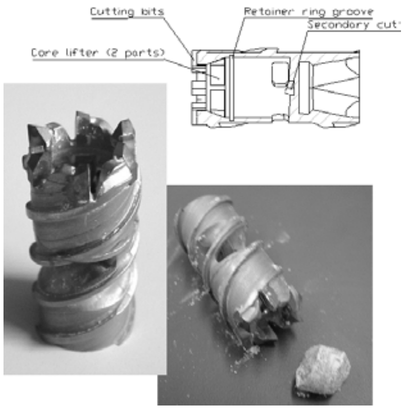

Fig. 10: The drill tool.

3.2.7 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 some percussion 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 that double thrust and 40 – 60 W power would be enough.

3.2.8 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, we have counterforce for the drilling 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.

3.2.9 Testing the drill system

The tool design was tested in test bench. Tests were done with a gear motor installed into vertical linear slide. The weight of the motor gave a 30 N thrust force and the motor speed was set to 30 RPM. The drilling was done into limestone. Tests show that penetration deep into limestone was 14 mm/hour (at 3 Watts 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 core inside the tool). Up to 8 cm deep was drilled in 24 hours. Dust exists the borehole properly and flow-through design of the tool is functional. The 20 mm core remains inside the tool during drilling as planned.

The thorough testing was done only for the drill tool and for the rover. However, there should also be more detailed tests simulating an actual operational scenario. 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.

4. CONCLUSION AND FUTURE PLANS

The acquisition of the deep soil sample is very demanding task, requiring a lot of study and different prototypes. Also the mechanical implementation of the DSS is quite demanding, since the available room is very limited and drilling dust may block the parts. The project goal was complicate to achieve, and there are numerous details, which were very beneficial to learn regarding possible future drilling projects. There are also other similar Mars exploration projects in the design board, including ESA and other international organisations.

4.1 ESA plans

According to the preliminary information ESA/ESTEC has planned to continue the MRoSA2 development in two separate projects: “Micro rover for mobile drill station” and “Highly integrated mobile drilling station”, possibly starting in 2003. These projects would be foundation for the Aurora program and future ESA’s Mars exobiology missions.

4.2 International plans

There are several ongoing projects to build different kind of drill or rover prototypes for future Mars missions. However, there are no exact plans for building a flight model of drilling capable system for any specific mission yet. NASA is sending two rovers to Mars in May and July 2003, which will arrive and land to the Red Planet in January and April 2004, respectively. These Mars Exploration Rovers (MER) are not capable to perform subsurface sampling, but they will survey the landing site and select the most scientifically intriguing rocks and surface soil samples for in-situ investigation [3]. Also ESA will send a Mars Orbiter next year, which will carry a small lander, the Beagle 2 [4].

First draft plans for possible deep drilling operations in Mars are designed to be done in the end of this decade. NASA has preliminary plans for sending a lander to Mars in the 2009 launch window. This project, Mars Science Laboratory (MSL), [2] is still under evaluation and it includes several options. If a rover platform for the drill module is selected, then the size of the rover will be substantially bigger than the MRoSA2 rover, offering more counter mass and power for drilling efforts, as well as more robust design.

5. REFERENCES

[1] ‘Exobiology in the Solar System and The Search for Life on Mars’, ESA SP-1231, ISBN 92-9092-520-5

[2] Dave Beaty, Mars Program Office, JPL, Dave Lavery, NASA HQ, Samad Hayati, Mars Technology Program, JPL, Sylvia Miller, Mars Advanced Studies Group, JPL, Jeff Simmonds, MSL Project, JPL Shallow Subsurface Access on Mars, RFI, v5, 6/5/2002, NASA.

[3] J. Erickson, M.Adler, J. Crisp, A. Mishkin, R. Welch, Mars Exploration Rover Surface Operations, IAC-02-Q.3.1.03,

[4] The Beagle 2 website, <URL: http://beagle2.open.ac.uk/>, date of reference, 24/10/2002.

[5] M Anttila, N Holsti, The Software Development for a Deep Drilling Micro Rover for Mars Exploration , DASIA 2002 Conference, Dublin, Ireland, May 2002.

[6] J Suomela, J Saarinen, A Halme, P Kaarmila, M Anttila, S Laitinen, G Vicentin, Micro Robots for Scientific Applications 2 – Development of a Robotic Sampling System, IFAC 2002 Conference, CA, USA, in press.

[7] N Holsti, T Ylikorpi, J Suomela, MRoSA2 Technical Proposal, OF-SSF-152, 1998.

[8] ‘Nanokhod Microrover Heading Towards Mars’ Fifth international Symposium on Artificial Intelligence and Automation in Space, I-Sairas ‘99, ESA SP-440 August 1999