AUTOMATION AND ROBOTICS FOR HUMAN MARS EXPLORATION

R. Gelmi*, D. Otto*, P. Putz**, D. Vennemann*

* System Integration & Operation Division, Manned Spaceflight Programme Department, ESA / ESTEC
** Mechanical System Division, Mechanical Engineering Department, ESA / ESTEC

ABSTRACT:

Around the world, there is revived interest in the human exploration of Mars. A Reference Mission for a potential international enterprise in the 2010 – 2015 timeframe has been generated by NASA, and ESA is investigating a possible European participation.

After ESA-internal assessments of potential European roles in such an international co-operation, a number of key technology areas have been identified as crucial for such missions and at the same time of strategic significance for Europe. Automation and Robotics (A&R) is one of these key technology areas.

Consequently, the first systematic studies on European contributions to human Mars missions and the associated A&R needs and opportunities have been started. This paper will summarise the status of these studies as far as relevant for A&R systems.

1. INTRODUCTION

1.1. SCOPE

The mission scenarios, architectures and system level requirements will be presented first. From this, the required functions and performance of A&R systems in the different phases of Mars exploration will be extracted.

A priori, A&R systems under consideration will include the following classes:

- automated instrument packages for in-situ analysis and documentation
- automatic mechanisms (such as booms, deployable masts or shelters) on landers, on rovers or in the field
- specialised automation systems for (deep) drilling and sample distribution
- penetrators (moles) for underground investigations
- micro rovers (less than 10 kg mass), possibly with very small arms / tools for scientific instrument deployment and inspection
- unmanned mini rovers (about 100 kg mass), typically with a small robot arm, for inspection, regional exploration / prospecting, scientific and lighter logistics field tasks
- unmanned larger rovers (up to 1000 kg mass) with exchangeable tools for larger-scale mining / in-situ resource utilisation and the routine civil engineering works in base building
- larger robot arms (gantry or cylindrical crane types) for heavy hauling, construction, erection of structures
- manned pressurised larger rovers with attached dextrous arms / tools for longer-distance crew transportation and scientific field trips in shirt sleeve environment
- flying robots (aerobots) for regional to global mobility.

The outcome of the studies will not only be the proposed architecture and preliminary design of candidate elements of a European A&R participation (after judicious tradeoffs concerning the areas where Europe can indeed establish a strategic leadership position) with their development plan, but also an inventory of required innovative A&R technologies to be injected into ESA's next technology development programmes.

1.2. BACKGROUND

During the last decade many countries have taken initiatives to define scenarios to prepare and support human exploration of Mars. Particularly NASA has generated a Reference Mission for a potential international enterprise to be realised in the 2010 – 2015 timeframe (Fig. 1).

As a consequence, an ESA-internal "Groupe de Réflexion" has assessed the NASA Reference Mission in order to prepare a position concerning an eventual

European involvement. One of its conclusions has been that, beside a number of crucial technologies on which Europe could take a leading position in the Reference Mission as currently outlined by NASA, scope exists for potential European missions which would be self-contained, but contributing to the international human Mars exploration. Particularly, NASA and ESA agree about the need of an extensive preparation and a phased approach, reaching sequential milestones of achievement.

One such milestone would be the establishment of a permanent robotic outpost on Mars, which could become a critical, enabling link to human exploration. A candidate for this role could be a robotic mission based on existing European technologies, infrastructures and capabilities, and their realistic potential evolution in the time frame of interest. Robots can indeed expand human capabilities in hazardous and extreme environments, and could be sent to Mars in both pioneering and supporting roles.

In this context, Automation and Robotics (A&R) is one of the most attractive areas in space technology. It allows for experiment handling, material processing, sample collection and servicing. Over the past 15 years Europe has built up a substantial capability in space A&R, not only by the earliest application in Low Earth Orbit (e.g. the European Robotic Arm for the International Space Station), but also by developing systems and technologies for planetary exploration.

2. SCENARIOS, ARCHITECTURES

The ESA assessment identifies advanced A&R as a key mission-enabling technology area, and especially declares the concept of a "robotic colony" of particular strategic interest in Europe. Top levels objectives of this robotic outpost are then to prepare or support the human Mars exploration, which can be divided into 3 main phases as suggested in the Mars Reference Scenario:

1. Explore/pioneer the planet by many unmanned missions ;
2. Prepare the arrival of humans by teleoperations both from Earth and from Mars orbit;
3. Support human activities on Mars.

The first phase has been already started by many past missions. Recently Mars Global Surveyor allowed us to better understand the Mars environment, and also Mars Climate Orbiter and Mars Polar Lander would have contributed to this effort, if only a bad fate would not have put them out of this phase. Actual plans envisage Mars orbiting satellites to perform global mapping and weather monitoring. Also a navigation satellites fleet may be deployed, function of the selected navigation system.

One of the suggested ideas is that such satellite infrastructure could operate together with a network of automatic stations. Those would constitute a robotic outpost providing multi-dimensional (orbital, airborne, surface and sub-surface) coverage capabilities over wide areas of Mars, and exploiting a robust infrastructure for communication, computing, data storage, navigation, surveillance and weather assessment. Flying robots, aerostatic balloons or airship could be used, some of them perhaps deployed in the Martian atmosphere after re-entry, so that a landing site wouldn't be needed. Automatic stations would be used to perform in-situ measurements, and data rates in the order of Mbit/s would be achieved by means of a mini-/microsatellite relay network. Goal of this phase is to improve our knowledge of the Martian environment, and to select the best landing site while enhancing our database for precision guidance.

Mobile robotic devices would instead perform better in the second phase, during which they would support the preparation of the landing site for human arrival. The NASA Reference Mission envisages many human landings in the same site. The consequence is that radio beacons and communication relay stations must be used and well positioned to allow future human landings each near the other. Mobility is the key issue for such work.

Figure 1: NASA concept of future Mars Exploration Scenario (Courtesy of NASA)

Those robots would help also after the arrival of the cargo and power modules for the manned mission by deploying and connecting them just to have a well established infrastructure ready to host humans. In this phase they would be remotely controlled from Earth. Then, when astronauts are in Low Mars Orbit, robots could be also controlled from the orbiter, taking so advantage from the absence of a long time delay.

In the third phase, when humans are landed on Mars, mobile robots could help them during their exploration and investigation by positioning scientific payloads or by substituting men in hazardous activities.

3. SYSTEM LEVEL REQUIREMENTS

Considering the above-described scenario, a set of requirements can be produced taking into account some aspect like:

- Robotic functions (missions, tasks, actions) during the different phases of the scenario;
- environmental constraints during the mission;
- interface constraints with other elements of the spacecraft or of the launcher, and constraints given by their limitation;
- resources availability (mass, communication, power);
- lifetime, safety, reliability.

Of those constraints, the most stringent are the ones coming from Martian environment features. Mars is a harsh environment for many aspects, among which storm can be considered as the greatest. Storms of fairly long duration can drastically reduce the correct functional performance and lifetime of mechanism's bearings and gears.

Other Mars features can instead be profitably handled. Thermal control for example can be easily made by combining proven space technologies with low air temperature and heat convection. By this way we can properly use Martian atmosphere as an in-situ resource. The consequence of this is that cooling problems are not design drivers.

Other requirements came from the activity scientists want to do both before and after human arrival. Collection of samples from different locations and in-situ analysis require mobile robots and automatic procedures. Furthermore, surface sampling can be easily performed by scooping devices with low power requirements, while subsurface sampling needs more resources and solutions can be very different depending on sample size.

Mobility is required not only to explore the planetary surface, but also simply to avoid that samples could be observed by using a video system, but could not be reached to be collected and analysed (like what happened during the Viking lander mission). Thus rovers become key technologies for many activities like for example research on chemical and mineralogical composition of rocks and soil, research on the vertical structure and composition of the planet subsurface, search for traces of life (also as extinct life) in the subsurface material, and search for subsurface presence of water as a factor for planet formation, erosion, and life. However we can generally distinguish among:

- small rovers for local science investigations;
- medium-size rovers for regional exploration and infrastructure deployment;
- large rovers for long-distance exploration (scouting for safe locations), heavier safe construction, crew transport, etc.

To those requirements, typical of an unmanned mission, others must added due to the presence (or preparation of the presence) of humans. They are:

- construction of facilities for the crew and for crew support, and facilities maintenance;
- support in human exploration tasks which would be too risky, too complex, or too time-consuming;
- exploration under crew supervision.

Also other robotic devices can be useful for the mission, like a robotic arm to move load on the surface and for support activities.

Furthermore, due to the deep space remoteness of the planet such as Mars, with significant signal delay in the order of tens of minutes during communications with Earth, the performance of all robotics operations may only contemplate limited, not real-time, ground commands. This increases the required grade of autonomy, and leads engineers to consider autonomous rovers as more promising than others.

Those constraints influence the entire set-up of the mission, and can drive decisions not only about robotic devices themselves, but also on power generation, telecommunications, Data Handling and Control, structure design, etc… as systems servicing the robotic one. Thus design of rovers and automatic devices has a key role in the entire mission analysis and design, and must be considered since early phases.

4. FUNCTIONS AND TECHNOLOGIES

To exploit all functions required by a planetary exploration many technologies are required, each dealing with a possible field of use of advanced Automation and Robotics.

4.1. AUTOMATED INSTRUMENT PACKAGES

Many instruments are required for a proper scientific and technical analysis of a planetary surface. Europe, United States and Russia used already some of them on

Mars in the past missions. However, investigations made are not enough for a proper understanding of the Martian environment to be able to plan a manned mission. Thus is therefore essential to develop instrument packages that would address many of the scientific and engineering issues that we haven't already clarified. They could be both used on Mars surface by a lander or in Mars orbit on an orbiter. For the first case some possibilities are radio and radar systems for atmospheric analysis, wind sensors, seismometers, and biological experiment for search for life, even if someone believes that the last should be delayed to the human exploration phase. In orbit spectrometers, radars, magnetometers and photometers can be envisaged. However there is not a clear division between systems to be used on ground and systems to be used in orbit. Their use shall depend on the specific goal assigned.

4.2. AUTOMATIC MECHANISMS

This category includes booms, shelters, deployable masts, and more generally all mechanisms used on landers, on rovers or in the field to move and/or position scientific instruments, samples, or also other devices.

Design of a boom is a compromise between many requirements on deployment, stiffness, mass, and strength. Also the requirement of the object that the boom is servicing must be taken into account.

4.3. ROBOT ARM SYSTEMS

Robot Arm System is one of the most flexible automatic mechanisms. The robot arm is the key but not the exclusive element of the system, because it can operate only as a subsystem (s/s) embedded into a scheme which envisages also other subsystems (like a payload interface s/s, an on-board control s/s, a ground control s/s, and a ground support equipment).

Operations made by a robot arm system must be well studied and planned concerning the level of automation and autonomy that is required. Any serious space robotic professional should first of all answer to key questions like how much the operation control must be delegate to the on-board control system instead of using a tele-operation mode. Even the set of simple operations to achieve the final goal must be assessed, because it can be possible that the best strategy would require to use not a single powerful device, but two smaller and simpler devices properly co-ordinated.

Past experiences on Robot Arm Systems were gained during design, development, and use of many systems, some of them simply tested in simulation mode, other instead used in the reality of the space environment, like the Canadian Remote Manipulator System on board of the US Space Shuttle. Europeans are making a great effort in this field, not only because they are developing the European Robotic Arm for the International Space Station, but also because the future european mission to Mars, Mars Express, will bring to the red planed a lander which uses a small robot arm to position a package of tools and scientific instruments on the martian surface (Fig. 2).

Important are also sensor and actuators, whose technology has made many progresses in the last years, especially on the integration between electronic and mechanical structure.

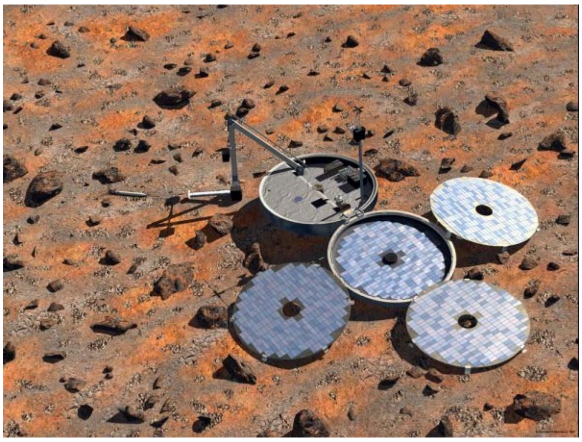

Figure 2: Beagle 2 lander planned for the ESA Mars Express Mission (Courtesy of ESA)

4.4. SPECIALISED AUTOMATION SYSTEMS FOR DRILLING AND SAMPLE DISTRIBUTION

Drilling and sampling device technology was improved in the past years, and now also new technologies enter in the group of ones used for this purpose. Connected with sample distribution are also sample preparation and handling. Some instruments indeed require the sample to have certain features (e.g. a flat surface) to be properly analysed. Handling techniques can use robotic arms or carousel devices, the last particularly useful when the same sample must be analysed by different instruments. However in this case also contamination issues must be taken into account, because it could happen that removing of residual background effects of an experiment are required to proper conduct the next one.

In the last years many prototypes of drilling devices have been developed in Europe. A great experience was acquired within developing the drilling and sample distribution system for the ESA Rosetta mission. Studies are furthermore continuing on new solutions also for Mars missions. Particularly interesting it is one of the recent studies made by the European Space Agency on a robotic deep driller mounted on a small rover. A brief introduction on it can be found on Ref. [13].

4.5. PENETRATORS

A new way to explore the subsurface world has been recently opened by the use of penetrators (moles). They can be used in two ways: as retrievable or no-retrievable devices. In the first type of use their key mechanism is a penetrometer of cylindrical shape. It crawls along the surface by an internal hammering mechanism, dives beneath an overhanging rock, and penetrates the regolith up to 1.5m. On its front end it carries an actuated tool for collecting a soil sample to bring within the mole when this is retrieved by wiring its power and signal cable.

In the non-retrievable version a mole brings all required instruments within its body. The advantage of this solution is that no return path is envisaged, and the mole can penetrate the surface up to hundreds of meters.

However, whichever is the solution chosen, the advantage of a penetrator, compared with the classical drilling solution, is that it doesn't need any external mounting support and can move independently in the soil. For this particular feature, moles are very useful for planetary research, in particular for automated lander missions.

On the other hand some risks must be taken into account as counterpart for this independence. First of all it is possible that, for some reasons, the tether could no more be deployed, or more generally the penetrator cannot more proceed in its exploration. For penetrators whose goal is simply to collect samples and bring them back to the scientific equipment on the lander, a collapse of the drill hole could lead the mission to a failure. Also the mechanical complexity of the equipment is a great challenge for designers.

4.6. UNMANNED MICRO AND MINI ROVERS

During Mars exploration, investigations cannot be limited to a single site, but a certain grade of mobility is required. Thus rovers become a key part of the future planetary missions. Generally they are divided into 3 categories:

1. Micro rovers: less than 10 kg mass, generally without arms or with a small arms;
2. Mini rovers: less than 100 kg mass, typically with a small or medium sized robot arm, used not only for inspection and regional exploration, but also for light logistic tasks;
3. Large rovers: up to 1000 kg mass, used for many hard activities like mining, in-situ resource utilisation, and civil engineering tasks in the base. Generally they can also host large robotic arms.

The main classical goal of micro and mini rovers is positioning scientific instruments in the field or collecting samples in different areas to analyse them. Analysis can be done by instruments carried on the rover or by instruments on the lander. In the first case a sort of in-situ analysis is made, while in the second one the rover must return to the base once concluded its mission. In the most sophisticated case samples are returned to Earth for a complete in-depth analysis. However, for sample selection, the rover must always carry a minimum of basic instruments.

Micro and mini rovers could be used also to transport and properly leave on the surface instruments that require a certain disposition to work, like for example small stations for geochemistry and geophysical measurements. In this case the rover would be used as a mean to transport those items far away from the landing site. More rarely they can also be used for other uses like transporting equipment or assembling antennas. However, such uses envisage a small robotic arm on the rover.

Concerning system design, as for Earth application, also in planetary exploration the most common locomotion solutions are wheels, mechanical legs, tracks or a combination of them. Generally they are selected depending on the type of terrain on which the rover is required to operate. For small vehicles the simplest solution is a rigid body with two or three couples of wheels. This must not lead to think that such rovers are very easy to design, because the complexity and uncertainty of the planetary landscape compels engineers to consider several different solutions among which to trade off.

Concerning the mobility of the rover tasks to be considered in system design are:

- Path finding: obstacles could be avoided by using scanning and obstacle-detection devices. Unfortunately such an operation requires a large computing capability, and is generally substituted by the execution of a fixed sequence of preplanned manoeuvres.
- Route planning: this is the evolution of path finding, and refers to the capability of the rover to find the path from one point to another one. On the other hand this requires a more advanced sensing capability, making the system more complex.
- Autonomous navigation: this is the reasoning aspect of a global route planning. A digital representation of the landscape must be stowed in the rover computer, together with a good and efficient sensors system to acquire the real world data and compare them with the model.

Unfortunately those tasks, typical of Automation and Robotics, are not the only one space robotics must deal with. Furthermore other issues like power control, structural design, communication, tracking, or data handling generally drive the design of a rover. Designers are thus constrained to solutions that have poor requirements on mass, power, and bit rate. Nowadays great help is coming from the miniaturisation and integration process which is involving electrical and mechanical equipment, by which is now possible to foreseen lighter but more capable rovers than years ago.

4.7. LARGE ROVERS

The main purpose for use of large unmanned rovers is civil engineering to prepare the outpost for human arrival. Indeed, even if inspection on a regional basis can be envisaged during the first two phases of the mission (the unmanned ones), this would be done by micro and mini rovers. However the use of large unmanned rovers is not widely planned, and someone even thought that they could be avoided.

Instead large manned rovers are present in every mission plan made either by Americans or Europeans. Numerous concepts were developed in the past, especially for lunar exploration. They would be used to expand the radius of exploration, to help in constructing the human outpost, to deliver crew between different installations, and to increase the crew safety. The only manned planetary rover even used was the Apollo Lunar Roving Vehicle during Apollo 15, 16, and 17 missions.

Nowadays many solutions and configurations are proposed, generally grouped into three categories:

1. Light Reconnaissance Rovers: they are similar to the Apollo Rover, and should be used to move around the base within a range of several km. Their would be used for sample collection, scientific instrument positioning, and would travel only in daylight.
2. Heavy Construction Rovers: these are unpressurised vehicles used to move heavy payloads, especially in supporting the construction of the human base. In the most complete configuration they can also have a robotic arm used for loading, unloading, and moving masses. A cunning solution would be to make these rovers also remotely controllable, so that they could be used not only by astronauts during extra-vehicular activity, but also without leaving the pressurised environment or even from Earth.
3. Mobile Laboratory Rovers: these rovers would be used to expand exploration beyond the limit imposed by the requirement to return at the base during night-time. Hosting astronauts in a pressurised shit-sleeve environment, they would allow reach places up to 500 km from the base and to conduct in-situ scientific attended activities during excursions that can take up to 10 days. We could even affirm that they are one of the key parts for exploiting the flexibility concept that is at the base of the planetary manned exploration in spite of a simple unmanned one.

A well-established design phase should create a synergy between the three categories of rovers. For example a modular design could lead to produce not only specific segments (like cabins for the third type of rovers), but also common parts which could be used on all rovers. This would be also an issue for safety against mechanical failures, because in case of emergency a broken piece could be substituted with one taken from another rover.

Figure 3: MANTA free-flyer breadboard model (Courtesy of DASA)

4.8. FLYING ROBOTS

Since now only satellites, landers, and rovers have conducted Mars exploration. This architecture has had the great disadvantage to give detailed information only within a maximum of 10m around the landing site, or global but undetailed information by satellite observations. Now, as above described, rover capabilities are planned to be expanded, so to explore a wider area. But the best way to extend Mars exploration on a regional basis is to use flying robots. Airships, balloons, fixed-wing aircraft, helicopters and autogyros were studied for this role, but only balloons, fixed-wing aircraft and autogyros were found very interesting. Particularly NASA suggests to use a fixed-wing aircraft, ESA made a detailed study on the MANTA autogyro (Fig. 3), while aerostatics balloons were proposed from both of them as complement to Mars exploration.

Automation and Robotics disciplines have a great role in this field, particularly because micro system technologies are required to build low mass vehicles. Obviously the Mars environment deeply influences design of such systems, particularly if we consider that Mars atmosphere is not-combustible (95% carbon dioxide), that atmospheric density is low (1/100 of Earth), and that huge dust storm can occur. As consequences, for example, a small aeroplane would require large wingspan and electro-motor or hydrazine turbine.

Flying robots would be used both during unmanned and manned phases, and during manned operation they could operate not only autonomously, but also remotely controlled. Their purpose would be surface reconnaissance, atmospheric measurements, and IR/visible video imaging. If high landing capability would be provided, they could be also used to land in remote areas, collect samples, and return to the base.

5. INNOVATIVE A&R TECHNOLOGIES AND CONCLUSIONS

Such mission architecture as described above requires developing and improving innovative automation and robotics technologies. European effort in this sense are co-ordinated by ESA, by which the first systematic studies on European contributions to human Mars mission and the associated A&R needs and opportunities were started. These studies (still in progress) will review the entire mission architecture, trying to identify areas where Europe can establish a strategic leadership position, and producing a preliminary design of candidate elements of an European participation.

However, it is already possible to identify some technologies that are of main interest for Europe and more generally for developing a Mars mission. They are:

- Micro sensors and actuators, and more generally micromechanical devices;
- Harsh environment devices and electronics, especially for low temperature, looking also for thermal control systems with high mass efficiency.
- Innovative actuator elements (piezo, shape memory alloys, …) with high reliability in harsh environment;
- Vision-based control systems, to be used by autonomous navigation and control or by telerobotics with remote control;
- Drilling and sampling devices, and more generally promoting research and development on small (miniaturised scientific instruments, cameras, …);
- Innovative power systems, which include ultra low-temperature lithium battery and improved high-efficiency solar cells.

Together these technologies typical of automatic systems, also Closed Life Support Systems must be considered to sustain crew when manned phase has started.

6. REFERENCES

1. Hoffman S. J. & Kaplan D. I., "Human Exploration of Mars: The Reference Missions of the NASA Mars Exploration Study Team", NASA Doc. n. SP 6107, NASA-JSC, Huston, Texas (USA), July 1997
2. Hoffman S. J. & Kaplan D. I., "Addendum to Human Exploration of Mars: The Reference Missions of the NASA Mars Exploration Study Team", NASA-JSC, Huston, Texas (USA), June 1998
3. "ESA and the Mars Initiative: Final Report of the Interdirectorate Groupe de Réflexion", ESA Doc. n. D/MSM/98-248, 15 September 1998
4. Seboldt W. & Reichert M., "System Concepts, Architectures and Technologies for Space Exploration and Utilisation (SE&U Study), ESA Doc. n. 12756/98/NL/JG(SC), ESA, July 1999
5. "Space Exploration and Resources Exploitation (ExploSpace) Workshop", ESA Doc. n. WPP-151, ESA, 20-22 October 1998
6. "European Mission Architectures and Technologies in the Mars Exploration Scenario - Statement of Work", ESA Doc. n. IMT-TS/4337/MN/mn, issue 1, revision 4, ESA, February 2000
7. "Automation and Robotics for Human Mars Exploration (AROMA) - Statement of Work", ESA Doc. n. TOS-MMA/1999/14, issue 1.2,ESA, 11 October 1999
8. "MANTA: Mars nano/micro-technology aircraft", presentation by DaimlerChrysler Aerospace AG - Space Infrastructure, Technology Workshop, ESA ESTEC, Noordwijk (The Netherlands), 15 May 2000
9. Putz P., "Space Robotics", chapter at pages 547-596 of Ehrenfreund P. et al (eds), "Laboratory Astrophysics and Space Research", Kluwer Academic Publishers, The Netherlands, 1999
10. Novara M., Putz P. Marechal L. Losito S., "Robotics for lunar surface exploration", paper inside "Robotics and Autonomous Systems", Issue 23 pagg. 53-63, Elsevier Science, The Netherlands, 1998
11. Chicarro A., Scoon G., Putz P., "Scientific applications of robotic systems on planetary missions", paper inside "Robotics and Autonomous Systems", Issue 23 pagg. 65-71, Elsevier Science, The Netherlands, 1998
12. Putz P., Didot F., Van Winnendael M., Visentin G., "Recent ESA Activities in Space Robotics", paper presented at the 31st International

Synposium on Robotics - ISR 2000, Montreal (Canada), 14-17 May 2000

13. Suomela J., Visentin G., Ylikorpi T., Zelikman M., "A Robotic Deep Driller for Mars Exploration", paper presented at the IFAC Conference on Mechatronic Systems, Darmstadt (Germany), 18-20 September 2000

14. Bertrand R., Van Winnendael M., "Mechatronic Aspects of the Nanokhod Micro-Rover for the Planetary Surface Exploration", paper presented at the IFAC Conference on Mechatronic Systems, Darmstadt (Germany), 18-20 September 2000