DEVELOPMENT OF THE ESA EXOMARS ROVER

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ABSTRACT

ExoMars, the first mission of ESA’s Aurora Exploration Programme is currently under development. ExoMars has important technology demonstration objectives, such as the qualification of an entry, descent and landing system and the development of a rover with sample acquisition capabilities. The mission’s scientific research will concentrate on the search for signs of past and present life and on the characterization of the Martian environment. This paper gives an overview of the ExoMars rover development activities and the main proposed configurations. It also addresses aspects of particular relevance to the Automation and Robotics community, such as locomotion, autonomous navigation, surface and subsurface sample acquisition, and sample preparation and distribution.

1 INTRODUCTION

In the framework of its Aurora Exploration Programme, which focuses on the advancement of technologies for missions to Moon and Mars, the European Space Agency is currently developing the ExoMars mission, aiming at a launch in 2011. ExoMars will search for traces of past and present life on and under the Martian surface, characterise Martian geochemistry and water distribution at various locations, improve the knowledge of the Mars environment and geophysics, and identify possible hazards before landing other spacecraft or—in the longer term—humans.

The mission’s exploration strategy is:

a. Land on, and/or reach, a location of high exobiology interest for past and/or present life signatures, i.e. access an appropriate geological environment.

b. Collect scientific samples from different sites, using a rover equipped with a drill capable of reaching well into the subsurface soil and into surface rocks.

c. At each site, conduct a full set of measurements at multiple scales: beginning with a panoramic assessment of the geological environment, progressing to smaller-scale investigations on interesting surface rocks using a suite of contact instruments and culminating with the collection of well-selected subsurface samples to be studied by the rover’s analytical laboratory.

2 MISSION DESCRIPTION

The baseline mission configuration consists of a spacecraft composite with a Carrier and a Descent Module (DM), to be launched by a Soyuz 2b from the ESA launch site in Kourou (French Guiana). The Carrier will release the DM from the hyperbolic Mars-arrival trajectory. After the entry, descent and landing phase, the Descent Module will deploy a rover on the Martian surface. The landing platform will host a static package of geophysical and environmental instruments. Over its planned 6-month lifetime, the rover will ensure a regional mobility of several kilometres, using solar arrays to generate electrical power. The rover accommodates the Pasteur scientific payload. Pasteur includes panoramic cameras and a suite of analytical instruments for the characterisation of organic substances and minerals; a drill to access underground material (down to 2-m depth); and a Sample Preparation and Distribution System (SPDS) to ensure that the sample material is adequately processed and presented to each instrument for analysis. The drill system will also be capable to collect samples from exposed bedrock and boulders lying on the Martian surface. The combination of mobility with the capability to access locations where organic molecules might be well preserved is unique to this mission, offering the opportunity to answer the question of whether life ever arose on Mars.

At present, a latitudinal band between 15 ° South to 45° North can be targeted for landing, ensuring that the mission is flexible enough to accommodate interesting new sites, based on the latest available data from ongoing Mars orbital missions.

The ExoMars rover has an estimated mass of about 120 kg, of which about 10 kg could be allocated to scientific instruments. For navigation on the Martian surface, the rover will utilise the Autonomous Rover Navigation Software developed by the French National Space Agency CNES. An existing orbiter will be used for the data relay to Earth.

The Phase B1 work is planned to start in autumn 2005. Due to recent budgetary constraints, the overall mission architecture being considered relies on a Soyuz launcher. This paper, however, addresses results of the
Phase A work, carried out by industrial consortia in the period January 2004 to January 2005. For the Phase A some of the requirements and constraints were different; among them:

- Launch by either Ariane 5 ECA or Soyuz 2b;
- A dedicated ExoMars Orbiter for data relay, carrying a rendezvous experiment in preparation of a future Mars Sample Return mission;
- Landing latitude range -45° S to + 45° N;
- Higher number of scientific instruments to be accommodated in the Pasteur Payload.

3 INDUSTRIAL CONSORTIA AND ACTIVITIES

In parallel to the ExoMars Mission Phase A Studies carried out by three ESA-selected industrial teams, led respectively by Alcatel (France), Alenia Spazio (Italy), and EADS Astrium SAS (France); the design of the Rover and of its integrated Pasteur Payload has been the subject of two competitive Phase A Studies, conducted in competition by ESA-selected industrial teams:

a. EADS Astrium Ltd (UK), with Galileo Avionica (Italy), von Hoerner & Sulger (Germany), SciSys (UK), DLR (Germany), Surrey University (UK), LAAS (France), EPFL (Switzerland), and IPAC (Austria).

b. MacDonald Dettwiler Robotics (MDR, now MDA Space Missions) (Canada), with Kayser-Threde (Germany), Alcatel (France), Laben (Italy), and Carlo Gavazzi (Italy).

In addition, a support activity, focused on locomotion issues, with abbreviated name "ESROL-A," was performed for ESA by the Russian companies RCL and VNII Transmashto of St. Petersburg, known primarily for their Lunokhod chassis and Marsokhods development work. The results of this activity were provided to the aforementioned consortia.

4 OVERALL ROVER DESIGN

The Rover comprises the following subsystems:

a. Chassis and Structures;

b. Service Equipment; including booms, mechanisms, thermal control, power generation and distribution, data handling and telecommunications subsystems;

c. Pasteur Payload, comprising the drill, the sample preparation and distribution subsystem and all scientific instruments.

The vehicle is the combination of a and b.

The ambitious performance requirements, and the ESA decision (2004) to implement a large Pasteur Payload, forced both industrial teams to exceed the initially specified 200-kg mass limit —after application of maturity margins and a system margin. A revised limit of 240 kg, still compatible with the overall Descent Module design studied in the frame of the Mission Studies, was adopted in the later phases of the Rover Phase A Studies.

The mission operations on the Martian surface include the selection of sites of interests (with external instruments as Panoramic cameras, IR spectrometer, Ground Penetrating Radar), rover locomotion, acquisition of samples, preliminary analysis (Microscope, Raman, Close-up Imager, Moessbauer), data transmission, sample processing and finally analysis by the on-board Pasteur instruments (MOD/MOI, GC/MS, XRD). Each “Experiment Cycle” includes a complete set of measurements with all the instruments, plus the travelling required to arrive to the next sampling location, and processing and transmission of the collected scientific data.

In the frame of both Phase A rover studies, a number of technical solutions were considered:

The EADS Astrium rover [1], shown in Fig. 1, has a 6-wheel chassis, equipped with flexible wheels. It is powered by a 1.5 m² horizontal solar array (SA) with InGaGaAs/Ge cells and uses a low temperature Li-ion battery (1500 Wh storage capacity, 11.1 kg).

![Figure 1: EADS Astrium Rover Configuration](image-url)
network. The Rover has UHF Orbiter relay and X-band Direct-to-Earth communication capabilities. The Pasteur Payload is located at the front side, the service equipment in the middle and all late-fit items (RHUs), inertial measurement units and communications equipment at the rear. The external, panoramic instruments are mounted on a telescopic mast together with the stereo camera head. Surface and subsurface sampling capabilities are assured by two separate systems: a main drill, jettisonable in case of failure, and a surface rock corer. The latter is mounted on a robotic instrument arm, together with a set of contact instruments.

The MDR rover [2], shown in Fig. 2, is equipped with a 6-wheel chassis with rigid wheels. It is powered by an elevated (-3.5° to 55°) variable inclination and orientable sun-pointing SA (2 DOF, elevation and azimuth). RHUs have not been adopted, avoiding the technical and organizational complications associated with their use. The inclination angle of the SA can be adjusted to maximize solar power collection for different landing latitudes. This system also provides flexibility while driving on slopes and permits lowering the array in case of dust storm conditions. The array is asymmetrical with respect to its point of rotation. This is done to maximize the azimuth rotational range around the deployed mast. The SA is made up of 10 strings of solar cells mounted on four hinged, honeycomb panels, with a total area of 2.5 m². With the dust storm case expected to be critical power production case, dual junction GaAs/Ge cells were selected for their high efficiency at optical depth 2. In addition, a small extra horizontal array of 0.3 m² (hidden behind the inclined SA in Fig. 2) is proposed to increase power production under optical depth 2 conditions. When stowed, the outermost panel of the main array is exposed in order to provide survival power in the event of array deployment failure. New Li-ion batteries, currently under development, are envisaged to save mass (483 Wh, 3.8 kg).

An integrated box structure encloses both the internal payload units as well as the service equipment. For thermal control, super insulation material is used in combination with radiators to reject heat in hot conditions. Heat switches are utilised to control the heat flow. The panoramic instruments, as well as the UHF (orbital link) and X-band (direct-to-Earth) antennae and 2 sets of stereo cameras, are placed on a deployable mast equipped with a Pan & Tilt mechanism. All the surface and subsurface sampling elements are grouped on a single drill unit. Among the externally mounted instruments are the VHF dipole antennae of the Ground Penetrating Radar. A fully redundant Rover Management Unit includes the central processor and mass memory. These are used for the data handling of both the vehicle and the Pasteur Payload.

![Figure 2: MDR Rover Configuration](image)

The vehicle includes full electrical redundancy of all essential functions. The SPDS and Drill include electrical redundancy. Payload instruments are served by two independent power and data busses.

## 5 LOCOMOTION

The main locomotion requirements are:

1. Ability to operate in rough terrain, negotiate 0.3 m high step obstacles,
2. Longitudinal and lateral gradeability of 18° to 25°, depending on the soil type (cloddy to drift),
3. Static stability angle of at least 40°,
4. Average locomotion speed of 100 m per sol on a specified reference terrain,
5. Maximum locomotion speed 100 m/h for max. 20 minutes for contingencies,
6. Point Turning Capability.

When defining the chassis designs both Rover teams made use of the results of the ESROL-A activity. The main results of which are summarized here; further details can be found in [3] and [4].

The “chassis arrangement” is defined as (total nr. of wheels) x (nr. of powered wheels) x (nr. of steerable wheels); an addition +4W or +6W refers to the number of wheels equipped with walking capability.

Chassis concept C has as arrangement 6x6x4+4W and is shown in Fig. 3, where the combination of Service Equipment and Pasteur Payload is represented by a simple parallelepiped. The wheels of each board (i.e. lateral wheel-suspension assembly) are connected with each other and with the rover body by means of the suspension, formed by a hinge-lever mechanism. For each board the suspension kinematics distributes the weight over the three wheels.
In Concept E, the design of the module linkages is such that the wheel-soil contact points move up and down nearly vertically. The modules operate independently, i.e. there is no averaging linkage. Each of the wheels can be equipped with steering and wheel walking drives. The latter can be used for deploying the rover from its stowed configuration, and for longitudinal and lateral weight shifting on slopes.

The EADS Astrium team [1] selected for its rover chassis Concept C, with arrangement 6x6x4+4W, equipped with flexible wheels to save mass and volume and to reduce motion resistance. Accommodation of sensors in the wheels was proposed to enable advanced locomotion control.

Moreover, an averaging linkage constrains rotation of the central yoke of the boards to identical angles in opposite directions relative to the rover body. As indicated by the chassis arrangement formula the four corner wheels are provided with individual steering drives for turning, and with walking drives to enable “wheel walking” in combination with the traction actuators. When moving uphill, downhill or crosshill, the rover can redistribute the wheel loads by adjusting the position of the walking drives.

Concept D, with 6x6x4+4W arrangement, has improved weight distribution properties, especially in the case when the middle wheels are on top of a bump. This concept has been breadboarded at approx. 1:2 scale (“ExoMaDeR”, Fig. 4, platform and chassis only). Preliminary tests have confirmed its good gradeability and obstacle performance, albeit at the expense of some added mechanical complexity.

6 AUTONOMOUS NAVIGATION

Due to the time delay in Earth-Mars communications autonomous navigation is required for rover surface operations. A set of software algorithms constructs a 3D model of the terrain surrounding the rover. It then compares the model with respect to the rover’s locomotion capabilities to compute a compatible path. This capability has been developed by the French Space Agency CNES, taking into account limited onboard computer resources and safety requirements [5][6][7].

The following steps compose the iterative on-board loop:
A. Perception
   a1. Image Rectification, based on an optical bench calibration procedure;
   a2. Stereovision, selecting the best match for both images;
   a3. Disparity Filtering, to eliminate erroneous pixels;
B. Decision (Path Planning)
   b1. Digital Elevation Map Building, giving the altitude information of the terrain points;
   b2. Navigation Map Building, traversability analysis to discriminate navigable from non-navigable and unknown areas;
   b3. Map Merging, to merge the most recent Navigation Map with the previously established ones;
   b4. Path Planning, selecting a subgoal within the Navigation Map, identifying a short-term waypoint and calculating an optimal trajectory to reach it from the present position;
b5. Perception planning, to identify the line of sight for the next stereo image acquisition;

C. Action (Path Execution), execution of the locomotion towards the calculated short term goal (waypoint).

Figure 6: CNES Autonomous Rover Navigation; screen view of Navigation Map

7 DRILL

A key element in Pasteur is the drill system, in charge of acquiring soil samples both from surface targets and from the subsurface, from 0 to 2-m depth. The reason for this requirement is that organic molecules may only be preserved within low-porosity minerals and deposits—not exposed to sterilizing UV radiation or to reactive chemical species. These organic substances, if they indeed exist, may hold the answer to the question of whether life ever arose on Mars. The best targets for this type of research are well-compacted sedimentary and hydrothermal deposits; that is, minerals that were once associated with liquid water and warmer temperatures. Therefore the drill system must be able to penetrate into soil/rocks having an unconfined compressive strength range of up to 150 MPa; extract particulate samples and/or solid cylindrical samples of 4 cm length and 1 cm diameter; contain the sample material, and deliver it to the Sample Preparation and Distribution System (SPDS) for preparation and distribution to the instruments. Additionally, the drill must monitor/control torque, thrust, penetration depth and temperature at the drill bit. It must also have the ability to release a stuck drill element.

From a science point of view, another important constraint applies to the drill system. Grain to grain friction in a fast rotary drill generates a heat wave in the sample that can destroy the organic molecules that ExoMars seeks to detect. The drill system must therefore implement a variable cutting protocol to allow this unwanted heat to dissipate in a safe manner.

The EADS Astrium design uses a subsurface drill (designed by Galileo Avionica) and a surface rock corer, the latter serving also as redundant element for sample acquisition. The rock corer is mounted on a separate robotic arm (Fig. 7), together with the suite of contact instruments (close-up imager, APXS, and Mössbauer spectrometer).

Figure 7: EADS Rover with deployed drill and arm

Figure 8: EADS Astrium Team drill rod assembly (perspective view and top view)

The subsurface drill consists of:
1. A drill box containing a drill tool and extension rods to reach down to 2-m depth;
2. A positioning unit, to move the drill box from stowage to operational state;
3. A miniaturised IR spectrometer head integrated in the drill tip;
4. A close-up, monitoring camera.

A 2-m long drill pipe equipped with an auger is assembled from 4 rods (1 drill tool rod and 3 extension rods, 25 mm in diameter and each 575 mm long, Fig.
The first rod contains the drill tool with internal shutter and sample collection capabilities (Fig. 9).

The drill string is actuated by a mandrel with a drill motor and a motor for the translation. When the first rod penetrates completely into the soil, it is disconnected from the mandrel and an extension rod is inserted between it and the mandrel, after which the procedure can be repeated. The drill box weighs about 7.25 kg.

A 3 DOF (2 rotations, 1 translation) positioning mechanism is used to deploy and position the drill box. The translation degree of freedom (also used to press the drill onto the soil) is implemented exploiting one of the vertical sides of the drill box.

The MDR team has chosen a concept based on a segmented drill string, comprising 10 drill rods, each having a length of 20 cm, and a diameter of less than 20 mm. Also in this case, the drill string acts to stabilise the borehole and includes an auger to evacuate cuttings. The cutting face at the centre of the drill bit is as part of one of the rods; it can retract — thereby converting the bit into a kerf configuration — to collect a sample (Fig. 10, Fig. 11).

A spring-loaded ball valve (shutter door) detaches the core. For subsurface drilling a geotechnical cutting bit is used, which provides efficiency and penetration rate advantage in regolith. For surface rock drilling, a surface-set (natural diamond) bit or hybrid (surface set/impregnated matrix) is proposed, providing better performance and longer bit life in hard rock formations.

8 SAMPLE PREPARATION AND DISTRIBUTION

The samples acquired by the drill system are conditioned and distributed by the Sample Preparation & Distribution System (SPDS), which presents suitably prepared sample material to all analytical instruments in the rover’s laboratory. The SPDS must also store samples for further analyses and eventually discard them. It must be highly integrated and be compatible with the interfaces of the drill/rock corer on one side, and with the analytical instruments on the other.

In particular the following functions need to be performed:
• Receive the sample from the drill system and/or from the rock corer,
• Enable sample inspection with the Microscope and the Raman and LIBS spectrometers,
• Transfer the sample to the milling/grinding station,
• Mill/ grind the sample,
• Distribute the right amount of sample powder to the various analytical instruments,
• Collect and store any residual matter after the measurements,
• Clean the items in preparation of the following measurement cycle.

Again two design concepts have been studied:

The EADS Astrium / Galileo Avionica solution (Fig. 13) makes use of a 3 DOF manipulator arm (“articulation”) and a distribution carousel to perform all the sample handling operations.

It is characterised by the following key features:
• Utilisation of one tray sample holder to manage the sample, from the drill discharge point to the optical microscope and RAMAN/LIBS, for inspection up to discharge into the milling station;
• Implementation of two spoon-like containers to store two solid samples for further analysis;
• Use of disposable containers (ovens/ vessels), all fixed on a carousel rim for the “second part” of the sample processing (i.e. from the milling station to MOD/MOI, LMC, GC/MS, XRD);
• Utilisation of tablets of controlled composition for the cleaning of the milling station.

The facility operates as follows:
• The articulation moves the permanently attached tray sample holder in a place suited for sample discharge from the drill;
• The filled tray sample holder is moved by the articulation under the microscope and RAMAN/LIBS for inspection;
• The tray sample holder is moved to the milling station to transfer the sample into the milling station input port;
• The carousel places an empty sample container under the milling station and milling is performed, whereby the sample container is filled with powdered sample;
• The carousel subsequently presents the filled sample container to the other instruments (GC/MS, MOD/MOI, LMC, XRD);
• The carousel positions the dust-bin container below the milling station to support milling station cleaning;

• A cleaning tablet is put into the milling station port and ground; the debris falls into the dust-bin.
• The cycle is repeated with a new sample.

Figure 13: SPDS of EADS Astrium Team

The SPDS and associated instrument layout proposed by MDR / Kayser-Threde accommodates the optical instruments on two levels: the sample carousel is on the upper deck, and the sample consuming instruments on the lower deck (Fig. 14). The SPDS receives the sample (core) from the drill in a horizontal position on its upper deck. The cylindrical sample holders, mounted on the upper ring of the carousel, can be opened for presentation to the optical instruments.

After visual inspection the carousel positions the sample holder at the sample communication (powder preparation) station. The tool moves into the sample holder and grinds a small portion of the core to produce powder, which falls into the carrier funnel through a
sieveing channel in the sample holder. Only the required amount of powder (approximately 1 mm of the 40 mm length of the core) is obtained. The remainder of the sample is kept in the sample holder. A carrier funnel, located on the lower face of the carousel, brings the sample powder to the analytical instruments.

If a sample holder needs to be reused, i.e. refilled with another fresh sample, a mechanical discharge device is required to remove the waste from the holder. Reutilisation of sample holders is necessary if additional samples are to be processed (i.e. more experiment cycles are to be performed) than holders are available on the carousel. In the baseline design, 10 sample holders are installed on the carousel. For an extended mission, up to 20 samples would need to be processed.

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SPDS. Conceptual design of the rover ground control is part of this phase.

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11 REFERENCES

Figure 14: SPDS of MDR Team
The sample discharge device is a pushing mechanism that introduces a piston into the sample holder’s inner cylinder. It then pushes the sample out of the holder. The sample drops out via a sliding mechanism into a waste container. The holder must also be cleaned to fulfil the requirements of acceptable cross-contamination among samples (< 1 %). A metallic brush/sweeper can be foreseen for this operation. The brush can be combined with the discharge device and be operated by the same actuator. The brush/piston is moved back and forth inside the sample holder.

9 CONCLUSIONS
An overview has been provided of the design status of the ExoMars rover. The Phase B1 industrial work on the mission including all system elements is planned to begin in autumn 2005. This phase will be under the leadership of Alenia Spazio (I). In addition to the mission redesign due to the modified requirements, leading i.a. to a smaller rover with a more modest set of scientific instruments, particular attention will be devoted to the entry, descent and landing system of the DM, the rover locomotion and navigation, its drill and