

AUTONOMOUS OPERATIONS OF A MICRO-ROVER FOR GEO-SCIENCE ON MARS

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ABSTRACT. This paper describes the end-to-end control system used to program and supervise autonomous operations of a micro-rover placed on the Mars surface by a lander spacecraft. This rover, named Nanokhod, is characterised by an exceptionally high payload-mass/total-mass ratio. The Nanokhod weighs only about 3 kg but carries a payload of about 1.5 kg of scientific instruments. This is achieved by providing power to the rover from the lander through the tether rather than from energy sources on the rover. The tether also carries data and commands between the lander and the rover. To accomplish the required autonomy within the restrictions of the mission scenario, a novel end-to-end control system has been designed, featuring a control station to program high-level commands for the lander-rover pair. These commands are uplinked to the space segment to be executed autonomously. Data uploaded to the space segment during a communications window describes rover and lander operations for an entire day.

Keywords: Robotics, Interactive Autonomy, Command&Control.

1 OVERVIEW

This paper describes results of work performed in the ESA project Payload Support for Planetary Exploration, ESA contract no. 13501/99/NL/PA.

1.1 The end-to-end system

The primary scientific objective of the Nanokhod is to perform geo-science on Mars. Specifically, the rover must reach about 20 sites around the lander, where it applies its instruments in order to measure soil/rock characteristics.

For this mission, communication with Earth is only possible once per day, via a data-relay satellite. The satellite uses a store-and-forward communication mechanism, and has direct contact with Earth for less than 8 hours per day. Due to this restriction and the significant communication delays, a high degree of autonomy is required of the space segment (the rover and the lander), in order to achieve the mission objectives in a reasonable time.

To accomplish this goal a novel end-to-end control system has been designed. This features a ground control station to program high-level commands for the lander-rover pair. These commands are uplinked to the space segment to be executed autonomously. Data uploaded to the space segment during a communications window describes rover and lander operations for an entire day.

The ground system uses a digital terrain model of the environment in which the rover operates. The model is constructed automatically from images acquired by a stereoscopic camera system placed on the lander. The model includes the topography of the terrain surrounding the lander as well as estimated soil characteristics.

The ground system allows the mission scientists to select sites in the terrain where measurements must be performed. Subsequently, a rover operator interactively builds, explores and evaluates the possible paths connecting the selected sites. This exercise aims at minimising a weighted combination of power consumption, risk of entangling the tether, risk of slipping on slopes, etc., and is performed with the support of various automation tools, including an automatic path planner and a rover simulator.

The rover operator also selects which recovery action should be automatically undertaken in case of anomalies in the rover motion during the autonomous operations on Mars.

The set of commands programmed in this way implementing the daily mission of the rover are then uplinked to the space segment, and executed autonomously by the lander control computer. The rover is steered along the defined paths and driven to apply its instruments to the desired sites in a completely autonomous way. The lander computer tracks the position of the rover using a computer-vision localisation system that uses the stereoscopic cameras. Anomalies detected via this means are addressed using the pre-defined recovery methods. However, when the anomalies cannot be recovered autonomously, the rover is automatically put into a safe mode, allowing for ground-based operators to define the recovery action during the next communications window. In the nominal case, the rover completes its daily mission autonomously, and then goes into stand-by, ready for a new set of commands from the ground, describing the next day's operations.

This end-to-end system comprises three main components:

- the Nanokhod rover and its On-Rover Control System (ORCS);
- the On Lander Control System (OLCS) accommodated on a Lander deploy the rover and establish the communications with Earth, and control the Imaging Head used to make images of the Martian environment and provide localisation capabilities for the rover;
- the On Ground Control System (OGCS) is a specifically implemented to allow a non-robotics expert to plan the rover activities and consulting the results for previous operations.

The following picture represents all the elements of the end-to-end control system:

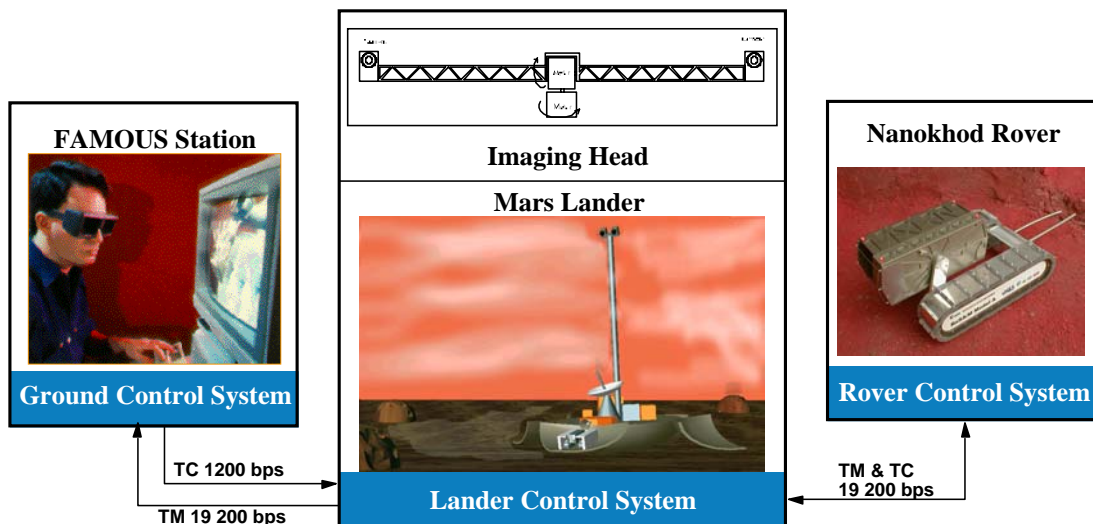


Figure 1. Elements of the End-To-End Control System.

1.2 The ground control station

The On-Ground Control System software is based on the FAMOUS robotics control station developed by Space Applications Services (Flexible Automation Monitoring and Operations User Station)¹.

This station allows the control of the rover six levels of abstraction. The six levels are (from the highest layer down): Compound Task level, Task level, Action level, Actuator level, Device level, and Physical level. The rover is normally controlled at the highest level, i.e. by Compound Tasks

¹ For more information on FAMOUS, please visit <http://www.sas.be/famous>

which typically include instructions to move the rover from a starting position to a desired final position and perform a series of measurements at that location. The operator defines the day's rover operations by selecting the corresponding Compound Tasks. The ground control station then prepares, verifies and validates the Compound Tasks and send them to the lander for execution. The operator may also choose commands at lower levels as required, typically down to level four only, i.e. at Task, Action and actuation level, as commanding at lower levels becomes impractical due to the long end-to-end delay times in the space-ground control loop.

1.3 The lander and the imaging head

For supporting the control and navigation of the Nanokhod rover, additional equipment is placed on the lander. This comprises:

- an Imaging Head placed on the lander top and fitted with optical means to allow the localisation of the Nanokhod and to generate images to be transmitted to the ground for generation of the model of the terrain around the lander;
- a computer that runs the navigation software and controls the rover through the tether.

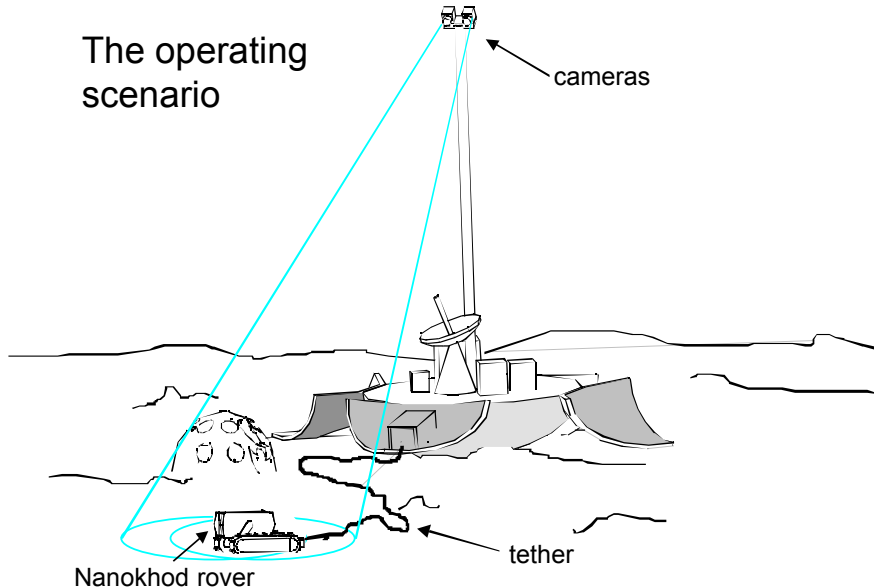


Figure 2. The rover moving around the lander. The rover position is tracked by the cameras mounted on the rod.

The Imaging Head enables the tracking of rover motion and supports the determination of its relative position and attitude of the rover with respect to the lander itself. It captures stereo images required for generating a map of the terrain around the lander. The Imaging Head is mounted on a rod of some 1.5m height on the lander.



Figure 3. The prototype Imaging Head.

The lander performs the rover localisation control: it moves the Imaging Head so its two cameras follow the rover position, it activates the LEDs and evaluates the rover position from the stereo views., and acquires images of the environment around the lander, to allow the Ground Station to reconstruct a Terrain Model.

The lander also establishes and maintains the communication to the OGCS:

- the up-link command channel contains the desired compound tasks, tasks or actuator commands, etc.;
- the down-link telemetry channel contains the environment data, the rover status as well as the sensor information as requested from the OGCS.

1.4 The Nanokhod Rover

The Nanokhod is a rugged, simple, reliable yet effective rover, to carry instruments in the immediate surroundings of a lander. In order to maximise locomotion efficiency, the Nanokhod carries only what is strictly needed for moving and deploying the instruments. No batteries or other power supply are on the rover, but it is equipped with a tether cable, providing the rover with power and data connection to the lander. This results in a very high instrument-mass/rover-mass ratio.

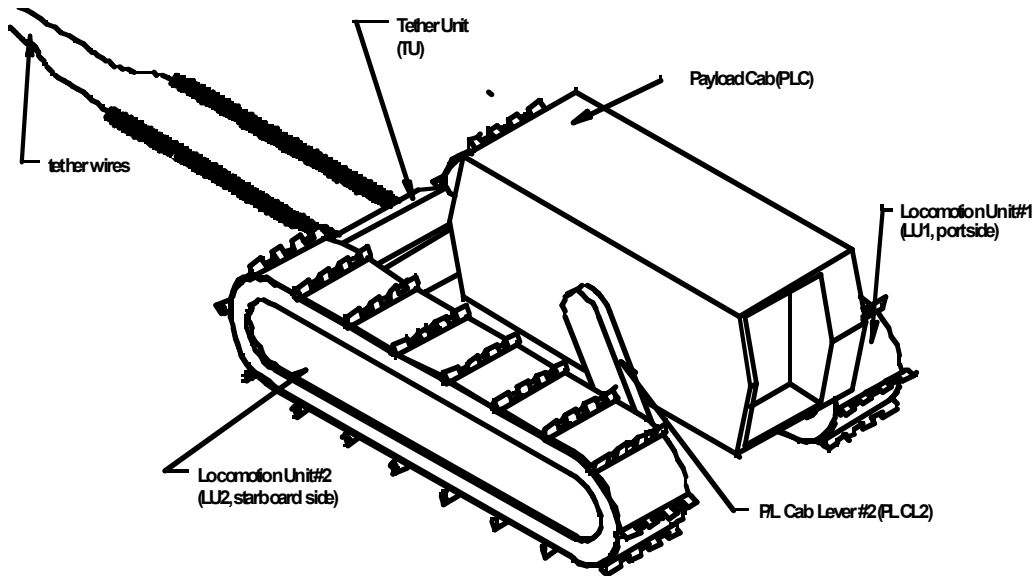


Figure 4. The Nanokhod rover.

The rover receives power and exchanges data with the lander via the tether.

The actuators of the Nanokhod breadboard comprise:

- the left track and right track locomotion motor, to allow the Nanokhod to move (track left-right forward-backward-stop);
- the payload cab (PLC) articulation motor (PLC up-down-stop);
- the lever articulation motor (lever up-down-stop);
- 4 LEDs that can be individually activated, used for localisation of the rover by the lander.

The sensors comprise:

- odometers (as 2 magnetic encoders) to measure the rover motion;
- angular encoders: one measuring the PLC angle, the other measuring the lever angle;
- 6 contact switches at the front of the PLC.

2 MISSION PREPARATION

This section describes the functions supporting the mission preparation phase, namely:

- the definition of the Initial Terrain Model;
- the definition of the pre-defined rover programs (Actuations, Actions, Tasks, Compound Tasks) and their pre-validation through simulation.

The corresponding Actuation, Actions, etc., are uploaded in the OLCS on a permanent basis, and are triggered by appropriate commands during the mission operations phase.

The OGCS is configured with an initial Digital Elevation Map obtained, for example, from a previous survey mission, or a Test Terrain Model representative of all the difficulties that may be encountered for traversing the kind of terrain anticipated: zones of non visibility or limited precision of localisation, obstacle that cannot be overcome, etc.

During the Preparation Phase, the Rover Operator successively defines and validate through simulation the Actuations, Actions, Tasks and Compound Tasks routines.

Because during the Preparation Phase, the actual Terrain Model is not known, the Routines of the Actuation and Action level can be checked on a Test Terrain Model only, using a series of "worst case" (most severe) utilisation scenarios.

3 MISSION OPERATIONS

3.1 Preparation of the Terrain Model

To build the Terrain Model, images of the site around the lander are expected to be acquired and transmitted to the OGCS.

The stereo vision cameras of the Lander Imaging Head produce raw images of the whole scene around the lander. These images are stored on the Lander mass memory device, typically in a compressed format. These images will be used later for terrain modelling

Since the cameras have a limited Field Of View, and since the minimum overlap between images of a stereo pair is 60%, the environment is recorded in a number of smaller segments. The environment is segmented into 4 circular rings according to the elevation FOV. Each ring is segmented in 30 sections of 12 degrees azimuth. For each of these segments, a stereo image pair is recorded. For higher accuracy, the environment can be segmented into more, overlapping segments, which of course also increases the needed mass memory space and downlink time.

The [compressed] stereo image files are transmitted to Earth with a communication protocol that takes into account the long end-to-end delay and the lack of reliability of the space links.

On the basis of images of the site, the OGCS can now build a **Digital Terrain Model (DTM)**. This model is comprised of a Digital Elevation Map (DEM), a Triangulated Mesh Model (TMM), a texture map and thematic maps:

DTM = DEM + TMM + texture map + thematic maps

3.2 Definition of the points of Reference

Once the Lander is on the planetary surface and the first imaging data are available to the scientists, a first rough planning of the overall mission is performed, identifying the sites which the scientists want to see at any rate during the 200 day mission. This is to avoid that the mission starts, expelling more and more tether, and at the end, there are some important sample sites left in a sector that has not yet been explored when the tether is used up.

The scientists must therefore define at the very beginning of the mission, the broad exploration concept: what is the overall rover exploration path around the lander, to which the actual site selection, will be "superimposed". This is done by defining Points Of Reference (PORs), which are "flags" to mark the most important science sites. The actual exploration path will jitter between PORs, depending on day by day science interests as they are developed from science results, and resource availability.

3.3 Path planning for the Rover

The primary scientific objective behind usage of the Nanokhod rover is to achieve a geo-science mission by determining the composition of a series of rocks in particular areas. As a consequence, the corresponding broad concept will most likely be a kind of circular movement in an annular segment around the planetary lander, with local radial excursions. The rover follows trajectories composed of many straight lines, which roughly will follow the chosen circular segment, with some local excursions.

Around this reference circular segment, the Nanokhod is expected to visit about 20 sites of scientific interest.

For the definition of the broad exploration path, the OGCS provides the Mission Interface. This is a graphical view in which the terrain is visualised but not necessarily with the highest fidelity. The texturing, however, should be as detailed as possible to allow for a good human-oriented presentation.

Upon request, a "Red-Orange-Green" (ROG) concept is applied to clearly indicate the safe zones (green), the risky zones (orange), and the forbidden zones (red). A Scientist chooses the sites he or she wishes the rover to visit, most preferably in a green zone, and by associated information to this point (e.g. a priority and a comment).

To execute the Rover movement on Mars, a Path Planner on the ground control station is used. The Path Planner is capable of finding paths which minimize: risk of tipping over, risk of entangling the tether, length of tether used, time to traverse, risk of sliding due to slopes and poor soil contact, and risk of getting stuck in loose soil.

The desired optimisation criteria can be selected by the OGCS operator. If more than one criterion is selected, the weighted sum of the corresponding cost functions is minimized. To minimize the risk of collision with obstacles, the Path Planner takes into account localisation errors and avoids areas that are invisible to the Imaging Head Cameras.

The Path Planner computes a route between the current position and the desired site. This route consists of a sequence of Path Segments. The Path Segments are identified by applying a two-step A* algorithm.

The general principle for the algorithm of the Path Planner is based on the construction of a corridor by using A* on a grid map covering the whole terrain but with reduced resolution, the cells being somewhat larger than the rover. Within this first corridor, a refinement of the path is performed with a higher resolution map.

The high-resolution path is not directly usable and needs to be decomposed into a collection of segments and associated waypoints. This leads to candidates for the Path Segments. These candidates are validated through simulation if it is possible to traverse them with single Piloting Action (i.e. the rover does not tip over, does not over-consume power, etc.).

In the case of the Nanokhod, the valid Piloting Actions are:

- move to a position (composed of a rotation on the spot and a move straight);
- climb an obstacle;
- overcome a trench.

Although a Path has been found, e.g. minimising the traverse time, it may not be suitable in terms of risks or resources consumed. Risk taken, resources requirements, etc.; along a Path Segment are modelled by Profile curves (i.e. the power consumption and the slope for the rover varying with the time). The maximum (or minimum) required values can also be modelled by such curves, and the feasibility of traverse finally assessed by comparing the simple / integrated Profile obtained with a "feasible" or "recommended" profile:

- the peak currents for the most demanding drive torques must stay within a power envelope,
- the slopes that the rover encounter must be kept within the capabilities of the rover:

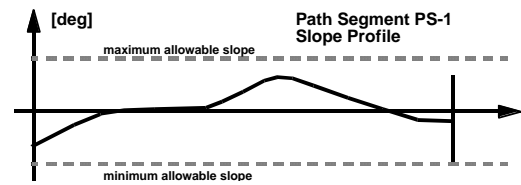
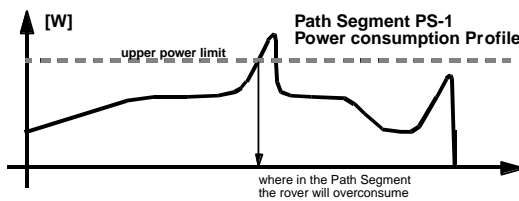


Figure 5. Estimation of the power consumption

Slope of the rover on a path segment

- the slopes that the rover encounter must be kept within the capabilities of the rover,
- The Nanokhod must remain sufficiently visible to the Imaging Head: this can be verified by comparing the achievable accuracy with a minimum recommended value:

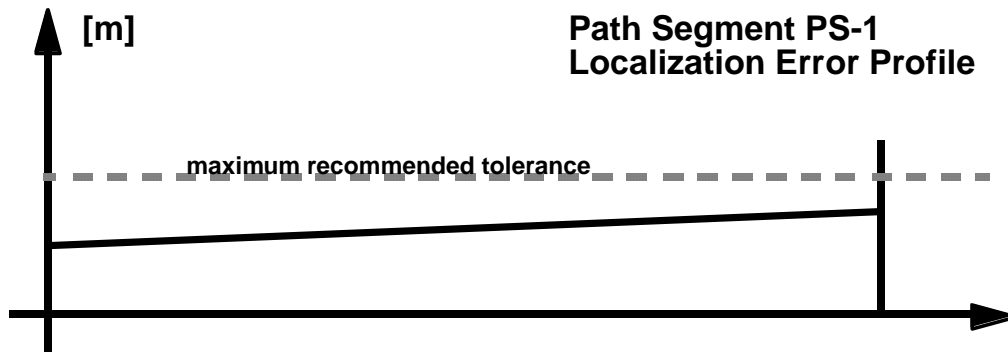


Figure 6. Estimation of the position error of the rover on a path segment.

The minimum and maximum limits are themselves Profile curves modelling the capabilities of the rover and its relevant parts (motors).

The suitability of the chosen Piloting Action with the characteristics of the terrain along the Path Segment to traverse can also be evaluated by such comparison. For example, climbing over a

small obstacle or moving to a point behind a 10 cm obstacle can be identified as questionable, at least for certain parts, and therefore suggest ways to further split the Path Segment.

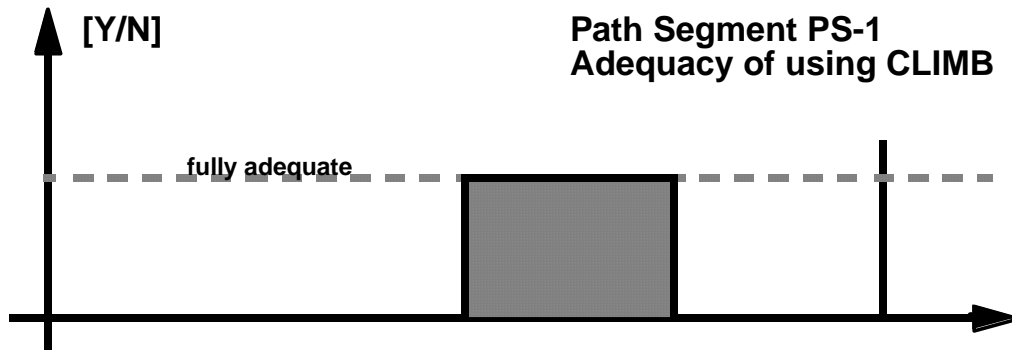


Figure 7. Decision map for the rover to check if it is possible to climb a given obstacle.

4 CONCLUSION

An end-to-end control system has been described to implement highly autonomous operations of a rover on a planetary surface.

The control system allows scientists and operators to select sites for exploration by the rover in a 3-D model of the terrain surrounding the lander. The ground control system then automatically determines the optimal rover path to visit these sites in a safe and efficient manner, and uplinks this information in the form of high-level commands (the so-called Compound Tasks).

The lander subsequently executes these Compound Tasks and ensures that the rover reaches its destination as planned.

The technology developed in the PSPE project has prepared Europe for enabling the control of the micro-rover which is included on the lander segment of the new ESA Cornerstone Mission PepiColombo, which will place a Nanokhod-type rover on Mercury, to collect geo-science data.

This technology has applications also on Earth, especially for control of mobile robots or vehicles in harsh environments. A practical application which is currently being implemented is to use the technology for the control of vehicles and machines in underground and surface mining in Canada. Other potential applications include control of robotics for clearance of anti-personnel mines, and control of remotely operated robots for sub-sea applications, arctic exploration, etc.