MARS ROVER AUTONOMOUS NAVIGATION

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ABSTRACT

Autonomous navigation of a rover on Mars surface can improve very significantly the daily traverse, particularly when driving away from the lander, in unknown areas. The autonomous navigation process developed at CNES for Mars exploration, the validation tools, experimental platforms and results of evaluation are presented. Portability and computing resources evaluation for implementation on a Mars rover are also addressed. The results show that only a very small amount of energy and computing time is used to implement autonomy and that the capabilities of the rover are fully used, allowing a much longer daily traverse than purely ground-planned strategies.

Keywords: rover, stereovision, autonomous navigation, planetary exploration

1- Introduction

The landing site for a planetary exploration mission is usually selected according to safety considerations and is thus a rather flat area which is not the most interesting area to perform scientific experiments. The total traverse that the rover can perform to reach more interesting areas from the landing site is of course limited by the daily available energy and the mission duration. However, for distant planets with restricted communications windows and low datalink bandwidth, the present limitation does not come from energetic considerations, but from the operation strategy : when the path is given by a ground operator to the rover through waypoints, the ability of this operator is limited , in rocky terrain, by the availability of a 3d model to perform the planning and by the precision of the planned execution by the rover [ref 1]. A reliable 3d model of the environment around the rover can hardly go beyond 10 meters around the rover ,or so, using a single telemetry window. If the data to compute the model are downloaded once a day, a maximum daily traverse around 10 meters is to be expected. This is much below what can be expected from energy limitations for a medium size rover (class 50 to 100 kg). Autonomous local obstacle avoidance can solve this problem when the obstacles are scarce along the rover path, but when the rocks size is such that they produce numerous and complex non navigable areas, on-board global planning strategy is the only solution to maintain an important daily traverse.
This paper summarizes the developments in autonomous navigation performed at CNES during the past decade and the on-going activities.

2- System requirements

Long range rover missions require daily traverses that can be 100 meters per day (Mars Sample Return program requirement) or even more. To plan the operations of the rover, the data transfer between the rover and the Earth ground segment can be performed either with direct communications or via a relay. Direct communications can be satisfactory solution on the moon but leads to antenna size and power consumption that are incompatible with small and medium size rovers. Data relay using the lander restricts the rover's exploration area to the region lying in direct visibility of the lander and thus is acceptable only for science tasks performed around the landing site. With a data relay satellite, the communication bandwidth can be reasonably higher, but the visibility periods restricts communications to one or two windows per day, when environmental data can be sent to the Earth to generate the mission plan during the following day or half day. These two iterations allow 20 or 30 meters traverse if the path execution deviates moderately from the desired trajectory. To control the execution, the rover should rely on an internal measurement of its position relatively to the daily start point.
Several localization procedures have been investigated : inertial unit, radio localization using the orbiter, odometry and vision. Inertial units that can produce an estimate of the movement with less than 10% error of the distance along the path are still heavy and power consuming.

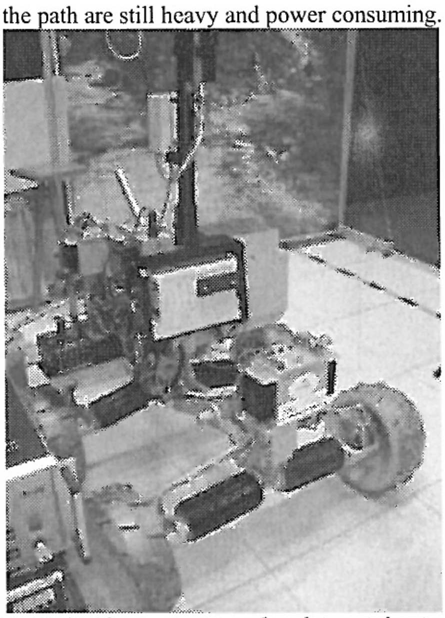

Figure 1 : IARES rover equipped with inertial unit

When both lander and rover are equipped with communications to an orbiter, this one can localize the rover relatively to the lander, during a single orbit processing, with a precision of a few tens meters. This can solve the problem of long term drift of the localization, but is not accurate enough to help executing the trajectory.
The operation of a planetary rover should then rely on a strategy using odometry and movement estimate by vision. These techniques will be addressed in the paragraph "trajectory control".

3- Control strategy :

The CNES control software has been designed to optimize long range locomotion between communications windows, and therefore without operator's generated waypoints. The role of the ground segment is to generate, from an initial daily panorama, the final objective, in terms of heading and distance or as a position relative to the initial one. This goal can be far away, as no path is given and thus no 3d model of the environment required at this step. The further phases are then performed by the rover autonomously. The figure 2 represents the main steps of the method used.

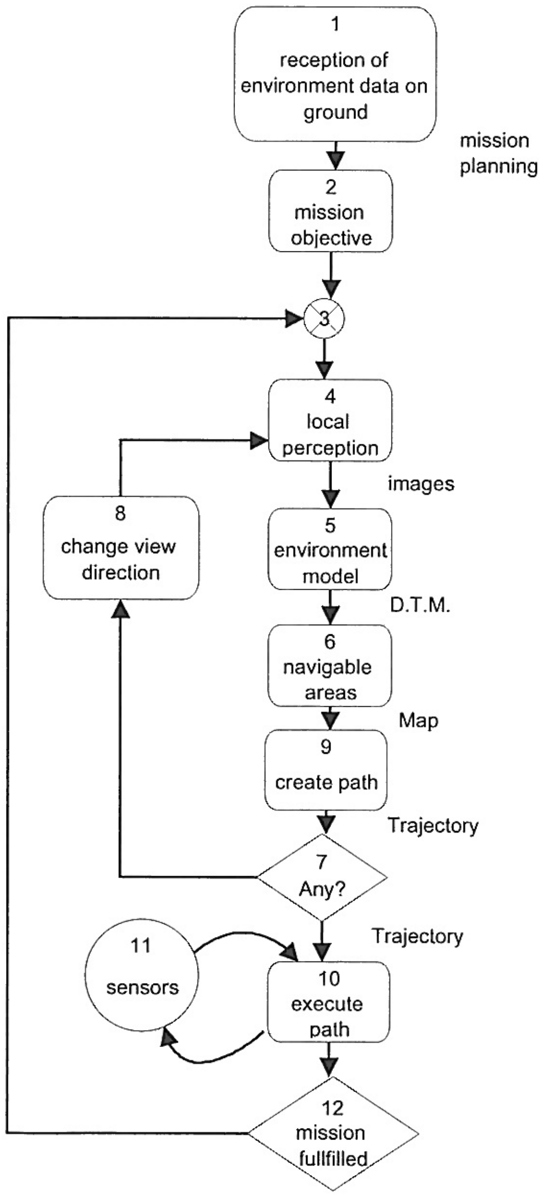

Figure 2 : autonomous navigation algorithm

The rover first performs several stereo images acquisitions at the starting point. For each stereo pair, a correlation algorithm is run to compute the distance to the terrain on every pixel image (disparity map).

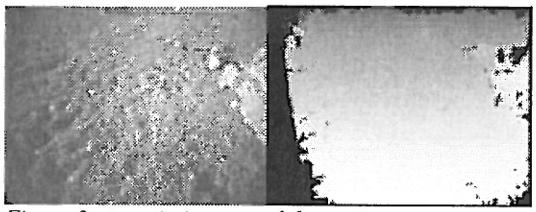

Figure 3 : terrain image and disparity map

The 3D points are then projected on a regular grid to get a Digital Elevation Model (DEM) of the environment of the rover corresponding to a single stereo pair.

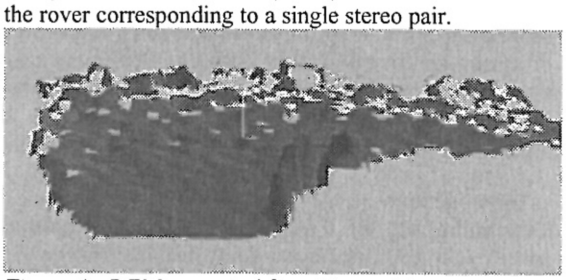

Figure 4 : DEM computed from Figure 3 image

This DEM is then analyzed, using the characteristics of the rover to select the navigable areas that are scored according to their difficulty. The result is a navigation map including unknown areas (represented in black) prohibited areas (in white) and navigable areas (coded in gray which level represents the difficulty of the terrain).

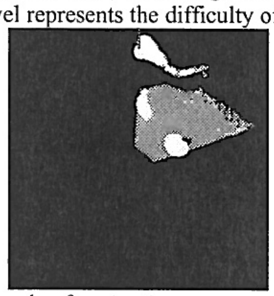

Figure 5 : example of navigation map

The different navigation maps computed from each stereo pair are merged together to obtain a global map that is maintained around the rover during the progression (usually from 10 x 10 m up to 20 x 20 m wide depending on the amount of available memory and on the localization accuracy).

A local goal inside this map is then selected, that optimizes the progression towards the final objective, and that can be linked to the initial position with contiguous navigable cells.

The algorithm then computes a path to this sub-goal using the easiest terrain and the shortest way. Margins corresponding to the localization errors and to inaccuracies in path execution are also included. Depending on the terrain characteristics, the path is usually around 5 meters long but only the first half is executed. A new perception is then planned to optimize the knowledge and the resulting navigation map is merged with the global navigation map.

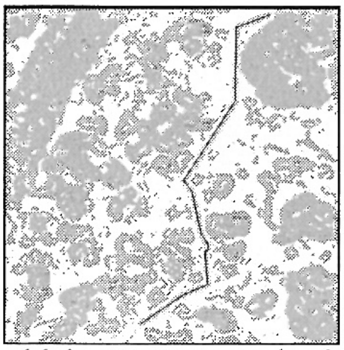

Figure 6 : global navigation map and path found in a very complex terrain

This step by step progression is executed in loop until the final goal is reached, or until the rover progression is stopped in every direction by non navigable areas.

4- Critical steps :

4.1- Stereovision :

Computing time is critical in stereovision processing with high resolution cameras (512 x 512 pixels) since it involves a high number of operations in a limited power computer. To limit the number of operations, two different ways have been studied :

- recursive organization of the elements computed for each pixel to minimize the total number of operations, and also approximation of the criteria and pre-processing filters by simpler but effective formulas
- reduction of the correlation search area with a high precision rectification of the images that allows correlation on a single pixel line (in fact a segment bounded by minimal and maximal distances).

To obtain this single line correlation, the rectification process should be accurate to much less than one pixel (typically 1/5 of a pixel) or a few microns. This is obtained on the calibration testbed depicted on figure 7. It operates as follows :

- a parallel light is emitted by a large collimator whose image is slightly out of focus to produce a dot covering several pixels on the stereo cameras placed in front of it.
- cameras are moved with precision two axis orientation tables and for each position, the center of the light dot is determined by image processing. The difference between this dot center and its expected position according to the table's sensors provides a correction that includes internal and external parameters deviation of the stereo device (and lenses distortion).
- These deviations are stored in the on-board computer as tables that are used by an interpolation algorithm to rectify the images.

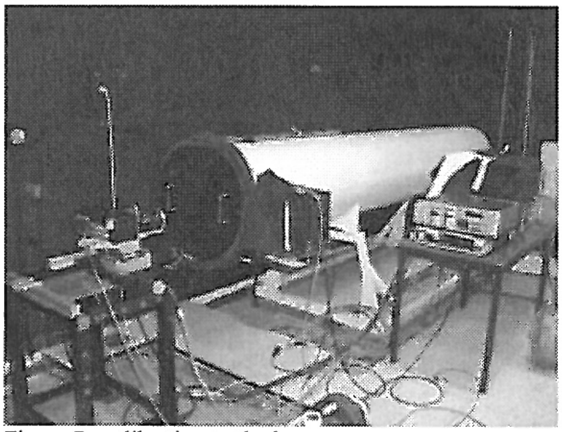

Figure 7 : calibration testbed

The computed rectification should remain stable during launch, travel and operations, as no in flight calibration is easy to implement with a satisfactory precision.

A specific hardware has been developed to get stable parameters. Figure 8 represent the last unit that has been tested for Ariane 5 launching vibrations and thermal cycling down to –100°c. It is made of 3D integrated ships mounted on a titanium structure. The CCD itself supports the lens that can be made with a very simple –and stable-design due to the fact that the rectification process is robust to high geometric and photometric distortions.

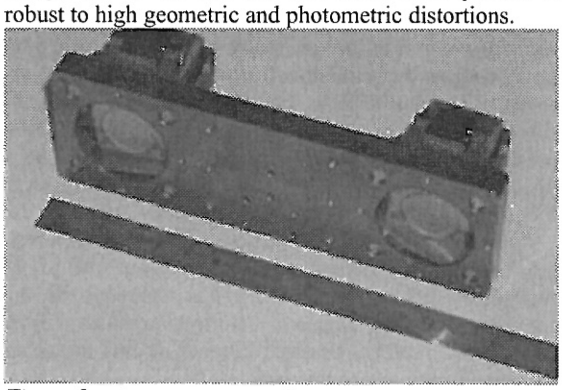

Figure 8 : stereo cameras unit

4.2- Navigation

The navigation algorithm [ref 2] must cope with two adverse constraints :

- include margins in the distance to obstacles, corresponding to the maximum expected path deviation
- avoid that the margins which are increasing with the distance prevent to plan trajectories between distant obstacles by clogging existing ways.

This problem has been solved by a separate processing of the information used for planning a path and those used to really execute it.

The planner has so the possibility to find a long range path in a complex environment. It will not be totally executed as the safety margins are no more sufficient at a certain distance, but the information on a possible way will not be lost. The planner will issue new perceptions commands to refresh the model and thus eliminate the errors coming from localization and trajectory control.

Figures 9 and 10 illustrate this behavior during tests performed in 2000 on the JPL FIDO rover : on fig.9 the way around the obstacle line has been found on the right side, but is not yet used for execution as the short trajectory shows. After a new perception decided by the planning algorithm, the path is confirmed for execution in fig.10. The tests have been presented in [ref 3]

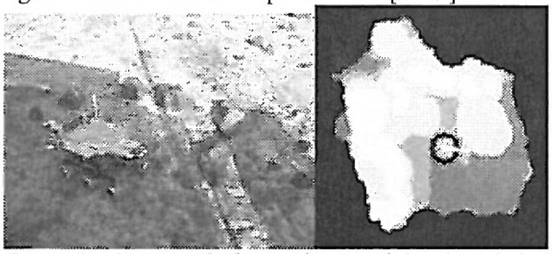

Figure 9 : the rover finds a path around the obstacle line

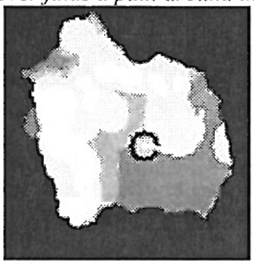

Figure 10 : after a new perception the path is executed

4.3- Trajectory control

To control the planned trajectory, the rover should rely on relative position information. As stated in the "system requirements" paragraph, odometry is used to get this information. The precision that can be expected from this technique is rather low on rocky terrain. To avoid very large margins that will slow down the progression of the rover, it is important to limit the odometry errors by filtering them with another source of information. CNES presently develops, in cooperation with CNRS/LAAS a vision-based algorithm that computes the movement of the rover from successive stereo pairs. Although this software is still under development, preliminary tests seem to indicate that a precision of about 1% of the movement can be achieved by this technique. If this figure is confirmed, longer trajectories and lower margins can be used safely. Updated outputs of this study are expected by the end of this year.

5- Experimental vehicles and test facilities

5.1- Vision evaluation testbed :

In order to evaluate the absolute precision of an on-board generated environment model, a 3D artificial landscape has been constructed. It is made of geometrical simple objects, whose model is well known, that have been coated with pouzzolane ground rocks to produce a texture similar to a natural landscape one. This texture allows the correlation algorithms to work in realistic conditions and to produce a dense model of this "landscape".
The model is then compared to a mathematical reference that represent the actual landscape with an absolute precision better than 5 mm. This allows an accurate estimation of the absolute precision of the terrain modelling performed by the rover. This in-door terrain is presented in figure 11.

Figure 11 : vision test facility

5.2- Test site :

To perform end to end tests with real rovers a 100m x 80m test site has been built [ref 4]. It features several difficulties a rover can meet like rocks, canyons, slopes ...and is coverd with pouzzolane rocks to represent both visual aspect and locomotion conditions with wheel-soil contact that is similar to the one that is expected on regolith soils under a lower gravity.
Infrastructure for tests is also present on the facility : trajectometer and differential GPS that allow real time monitoring of the position of the rover during its motion, lighting for night tests with high contrast illumination, optical facilities for equipment alignment ...
This facility is presently under reconstruction. The updated site will offer both internal (15m x 20m) and external terrain to allow continuous test availability during bad weather periods. Figure 12 represents the test site.

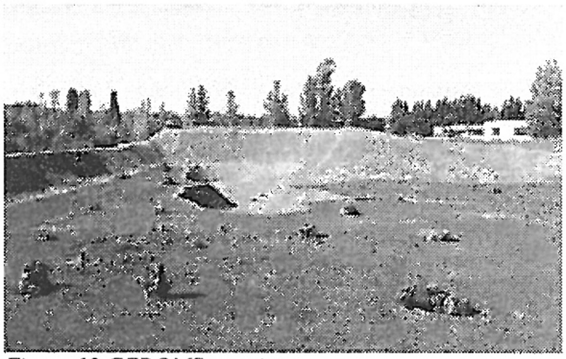

Figure 12 GEROMS test site

5.3- Experimental vehicles

Autonomous navigation has been implemented on several vehicles :

- EVE rover [ref 5], based on a Russian Marskhod platform, with powerPC on-board computer running under LynxOS operating system.
- IARES rover [ref 6], a dedicated platform designed by VNII Transmash (Russia) for a CNES-led project, with a similar computer.
- FIDO rover [ref 7] from NASA/JPL during tests performed in year 2000. For these tests the software was ported to VxWorks environment on a Pentium-like processor.

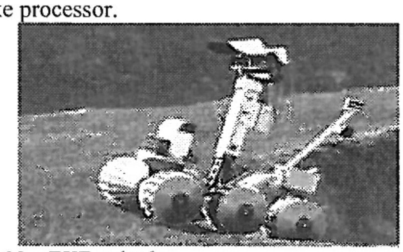

Figure 13 : EVE vehicle

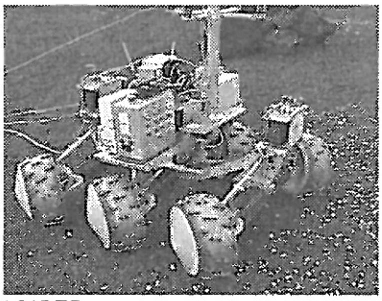

Figure 14 IARES rover

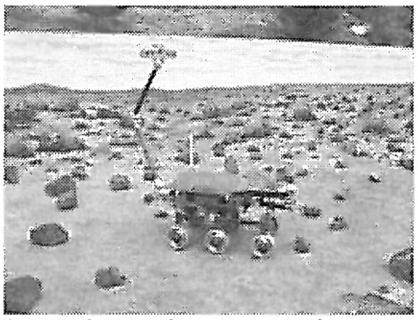

Figure 15 FIDO rover during tests on the JPL MarsYard

5.4- Simulator :

The software is developed on Sun workstations on which a real time simulator has also been implemented. The vision and navigation algorithms can connect, with exactly the same interface as a real rover, to this simulator. The simulator represents the terrain, the vehicle with all the degrees of freedom and the contact with the ground according to rover configuration and to the local terrain topology. It also provides simulation of the vision, localization and platform interfaces, allowing intensive tests of the on-board software for validation.

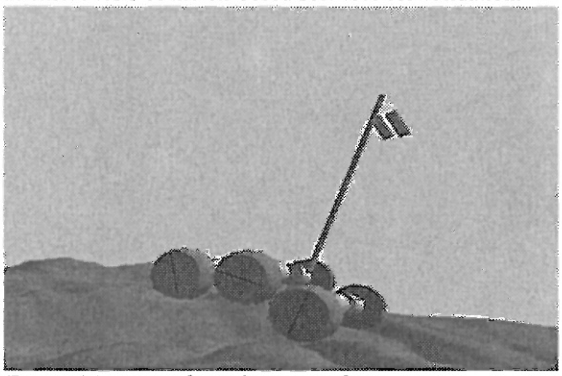

Figure 16 : view of simulator interface

6- Performances of the autonomous navigation

The algorithms have been tested and refined intensively during more than five years on real rovers and on simulator. They represent now an operational way to control the progression of a rover on a distant planet like Mars and provide a way to drastically increase its daily traverse, particularly in rocky environments with dense obstacles.

The tests performed on the FIDO rover at JPL included portability and computing performances evaluation that are summarized hereafter.

- For a 512 x 486 pixel stereo image pair whose resolution is degraded by a factor of 2 and a DEM grid size of 50 mm with a total grid size of 251 x 251 cells, the CNES complete software was run in 3267 ms
- A total memory allocation of 3.0 Mb including the input images is sufficient to run CNES stereovision and navigation software in the conditions of the FIDO tests.

In any case the maximum computing time was less than 5% of the locomotion time and is negligible along the mission as well as the energy wasted for computing the path is.

7- Possible implementation

An efficient implementation of the navigation that has been recommended after the FIDO tests is to have CNES navigation running at the higher level, using the cameras located on the deployable mast, and obstacle detection, using cameras located on the front of the rover, running during path execution to guarantee an optimum safety with two independent navigation subsystems contributing to autonomous rover navigation. This suggested approach also has the advantage of redundancy since the navigation of the rover remains possible in case of failure of either set of cameras without adding any hardware.

8- Conclusion :

Tests have shown that global planning navigation algorithms give a significant improvement to the rover's daily traverse ability particularly when crossing difficult areas. The required computing time and resources remain low compared to other computational and power budgets, and the portability of the software to an on-board rover computer has been established on several platforms.

9- References :

[ref 1] : J.Matijevic, D.Shirley The mission and operation of the Mars Pathfinder microrover. IFAC 13th Triennal world congress San Francisco USA 1996

[ref 2] : High rate autonomous navigation for a non stop traversing rover. M.Delpech, C. Proy, L.Rastel ISAIRAS 97

[ref 3] : M.Maurette E.T. Baumgartner Autonomous navigation ability : FIDO tests results 6th ESA workshop ASTRA 2000 ESTEC NL

[ref 4] : J.Runavot M.Delail A CNES facility to simulate CNES landscape 1992 IAF congress

[ref 5] : M.Maurette L.Boissier M.Delpech C.Proy C.Quere Autonomy and remote control experiment for lunar rover mission Control Eng. Practice vol5 N°6 Pergammon 1997

[ref 6] A.Balazs & al Locomotion system of the IARES demonstrator for planetary exploration Space technology vol 17 N° 3-4 Pergammon 1998

[ref 7] : R.Lindeman L.Reid C.Voorhees Mobility subsystem for the exploration technology rover 33rd aerospace mechanisms symposium Pasadena May 99