AUTONOMOUS NAVIGATION ABILITY: FIDO TESTS RESULTS

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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 NASA/JPL FIDO Rover platform has been used to evaluate autonomous obstacle avoidance algorithms developed by JPL and CNES for autonomous long-range path planning and traversing. The algorithms have been tested in realistic conditions during 2 weeks in January 2000, in JPL's MarsYard. The ability of the rover to reach a distant goal in difficult terrain has been evaluated for several situations. Portability and computing resources evaluation for implementation on a Mars rover have been assessed as well as the maximum daily traverse allowed in an autonomous navigation mode. 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. Finally a combination of JPL and CNES navigation has been recommended.

Keywords: rover, stereovision, autonomous navigation, planetary exploration

1. INTRODUCTION

NASA's Mars exploration program includes several rover components that require long range mobility in order to fulfill the science objectives with a goal of a daily traverse of 100 meters per day. A pure ground operator based strategy is unable to reach this objective in rough terrain. Therefore, autonomous path generation is necessary to execute the daily traverse goal given by ground operators that received panoramic images from the last rover location. This is mainly due to the fact that, except in smooth areas with isolated and scarce obstacles, the ability to plan a safe path from the initial position is limited to about 10-30 meters maximum distance. In addition, trajectory drift during execution due to rover localization errors can lead the rover meters away from the desired path.

To overcome these problems, two navigation strategies have been studied by JPL and CNES and implemented on experimental rovers. Both are based on stereovision perception, with different implementations, but are quite different in the process leading to on-board path generation. The JPL algorithm uses waypoints provided by ground operators and tries to follow a direct path to the next waypoint. When an obstacle is detected by the rover's vision system and related on-board software, a local path is computed to find a way around the obstacle. The direct path to the next waypoint is then attempted again. The JPL waypoint navigation algorithm keeps track of a local obstacle map in the vicinity of the rover (approximately a 2 meter radius around the rover) and makes rover trajectory decisions based on an analysis of this local obstacle map. The algorithm represents a reactive obstacle avoidance capability that is always goal directed towards the waypoint once the rover determines that a clear local path towards the waypoint exists.

The CNES algorithm [1] constructs a Digital Terrain Model from the stereo images and then analyses it to determine the navigable areas and to score their difficulty. The result is a navigation map corresponding to a stereo pair, which is then merged with the previously computed ones to get a global navigation map.

Given a distant objective, the algorithm then generates the "best" waypoint inside this map and finds an optimal path to it. Only part of this path is executed and the whole process is restarted to update the path before its end. To evaluate the performances of JPL and CNES vision and navigation software, real tests have been implemented on a rover whose overall architecture is representative of the next generation of Mars rovers: FIDO. (Figure 1)

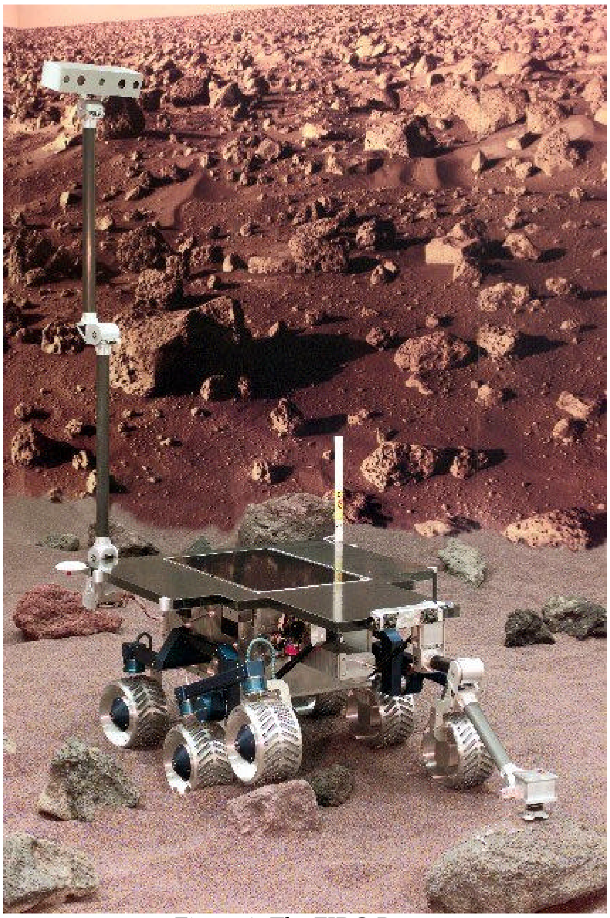

Figure 1: The FIDO Rover

The JPL FIDO team supplied the vehicle, managed the tests and the test site, and implemented the system software and the path execution control, as well as the localization sub-system. The JPL autonomous obstacle detection and avoidance was already implemented on the vehicle for the tests. CNES implemented the vision and navigation software on-board the rover and also provided a ground station that included the display and control software.

The ability of the rover to overcome obstacles and reach the goal that has been assigned with a minimal time and power consumption have been addressed by placing FIDO in the JPL MarsYard and comparing the behavior with the different algorithms. The comparison has been made on both vision and navigation algorithms and on the corresponding computation times and memory allocations. The analysis has been done both on single situation results and on complex long-range trajectories.

2. THE FIDO ROVER

The FIDO rover [2] is composed of a single body locomotion platform [3] mounted on a rocker-bogie suspension (see Figure 1) that connects to the body via a geared differential through two structural members (Jeff tubes). All 6 wheels are independently driven and steerable. FIDO is equipped with several sets of cameras including:

- The HAZCAM are used for hazard detection and avoidance and are stereo cameras with ultra-wide angle lenses (110° horizontal field-of-view). They are located on the front and rear end of the rover body and have limited resolution and range.
- The NAVCAMS are stereo cameras mounted on a four degree-of-freedom deployable mast that places the cameras at approximately 1.94 meter height above the ground when fully deployed. Their lenses produce a 43° horizontal field -of-view
- The PANCAMS are also located on top of the mast. They are are a stereo camera pair with a 10° field-of-view and are equipped with filters in the near-infrared for generating false color images of science targets.

The main body of the rover houses all of the rover's electronics including the central processor, motion controllers, science instrument electronics, video framegrabbers, power converters and batteries. The solar panel on top of the rover produces approximately 60 Watts of additional energy, however the solar array was not used during the tests.

The rover is equipped with odometry sensors along with a sun sensor and inertial sensors that are fused together to determine an overall understanding of the rover's position and orientation with respect to a fixed reference frame [4]. The on-board computer is a single board PC104-based CPU equipped with a Pentium processor running at 133 Mhz and its peripherals (among which a frame grabber to acquire the images). The communications with the control ground station are performed using a wireless Ethernet link.

The operating system is VxWorks 5.3 and the application software running on board is written in the ANSI C programming language. The ground stations used to control operations are a PC (for FIDO) and a Sun workstation (for the CNES software interface). The global software architecture is presented in Figure 2.

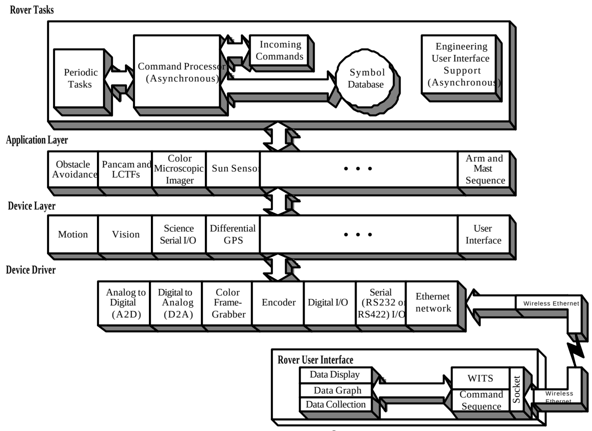

Figure 2: FIDO Rover software architecture

3. THE TEST SITE

The terrain used to perform the rover navigation tests was the JPL MarsYard. The obstacle density for the tests was rather high and the size of the rocks offered a good range of dimensions so that the classification into obstacles by the on-board software, regarding the mobility capability of the rover, was tested under varied conditions. The variety of slopes was however more limited on this field. This justified additional tests to be sure that dangerous slopes or combinations of rocks and slopes were correctly detected. A view of the terrain in the MarsYard is illustrated in Figure 3.

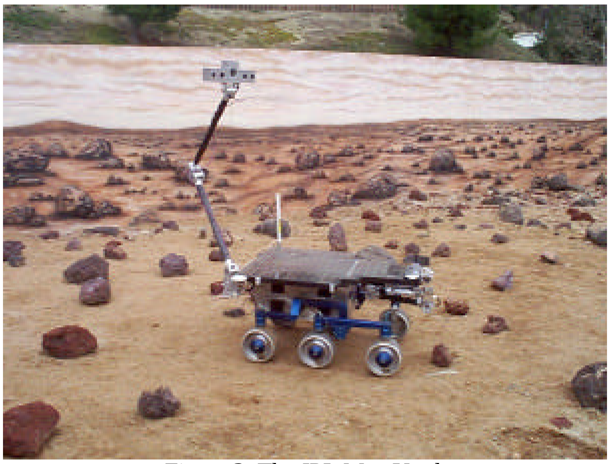

Figure 3: The JPL MarsYard

4. VISION TESTS

4.1. Tests objectives

The objectives of the tests were to evaluate the performances and robustness of the vision algorithms and also to measure the required CPU resources for different stereo and obstacle detection algorithms at various image resolutions.

4.2. Methodology

Vision tests have been performed on a FIDO NAVCAM stereo image pair in the MarsYard at half resolution and a stereo image pair taken with CNES stereo cameras at full resolution. Both images are represented by 8 bit (greyscale) pixels. The analysis consisted of a disparity maps analysis to compare density and evaluate accuracy of the computed values in some critical areas. It also included computing time measurement using the rover's on-board processor, and memory allocation for data and code. Several weaknesses of the analysis appeared during the tests:

- A valid comparison should be made from the same set of original images. However, the rectification process, which is an important step for the final data accuracy, could not be implemented for both algorithms. This made it impossible to compare the NAVCAMS processing at full resolution and the CNES images by the JPL algorithm.
- Precision analysis requires a reference model of the terrain which was not available during the tests, thus limiting the investigation to relative precision inside dedicated zones without attempting to measure the total absolute precision of the 3D model computed by the vision system.

A good preliminary evaluation could, however, be performed and the portability of the algorithms on a representative on-board computer was established.

4.3. Tests results

The filtered disparity maps obtained from FIDO NAVCAM images show that the CNES correlation algorithm produces a dense disparity maps (Figure 4). Although the tests were not sufficient to decide if this results from incorrect matching removal in rock-edges areas or not, it appears that in smother areas, the values computed by the CNES algorithm are correct (compared to neighboring cells) and give meaningful additional information.

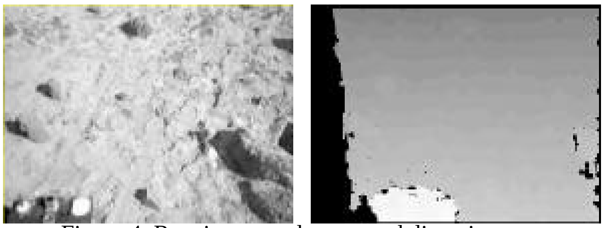

Figure 4: Raw image and computed disparity map

The corresponding Digital Elevation Model (DEM) is shown in Figure 5 and is computed with a high resolution compared to the robot wheel size, thus offering a very good navigability analysis of the terrain.

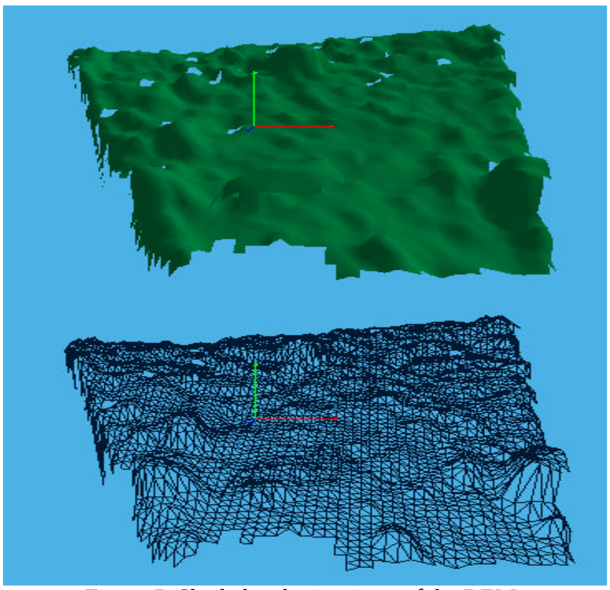

Figure 5: Shaded and wire views of the DEM

A further evaluation will require a reference model of the same area. This will be discussed in the future work section of the paper. Computing time measurements were also performed with several test sets of images and resolutions. For example, given a 512 x 486 pixel NAVCAM image whose resolution is degraded by a factor of 2, the disparity interval was chosen to be between 4 to 45 pixels and a DEM grid size of 50 mm with a total grid size of 251 x 251 cells. For this set of stereo processing parameters, the total processing time using the rover’s CPU was 2167 ms for the CNES stereo algorithm and 7400 ms for JPL stereo algorithm to reconstruct the DEM. As the total computation time represents less than 5% of the locomotion time, it can be considered that either stereo software can run on-board the rover without a significant impact on the time and power budgets.

5. OBSTACLE DETECTION

The classification of the terrain according to the mobility capability of the vehicle has been tested first on simple situations: isolated rocks, uniform slopes, and combinations of both. As a wide variety of slopes were not available in the MarsYard, this situation has been simulated by setting a bias in the accelerometer information so that the rover “feels” as if the whole terrain has been tilted. By varying this bias we could verify that a slope was classified dangerous by the image-based algorithm when the maximum allowed slope was reached. Figure 6 illustrates the behavior of the algorithm when the limit is reached. In this case, on an almost flat terrain with an average slope just below the maximum allowed, small stones or footprint on the terrain are detected as obstacles so that the attitude of the rover would reach excessive values if the rover was placed at that location.

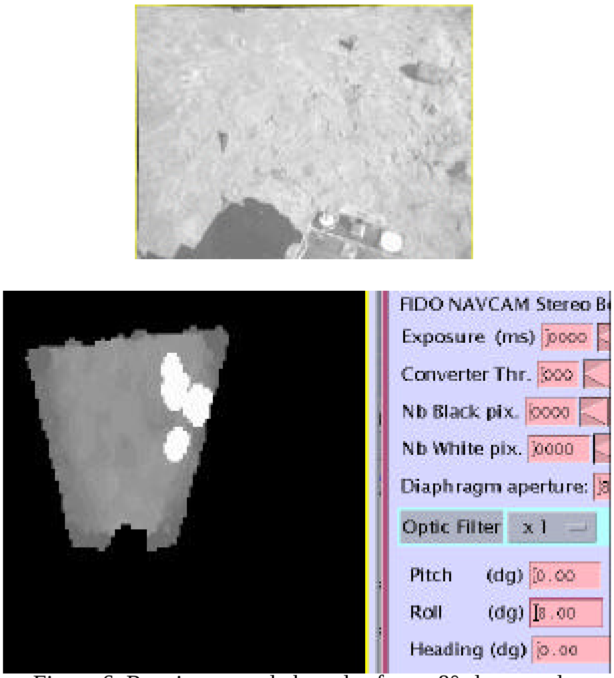

Figure 6: Raw image and obstacles for an 8° slope angle

Increasing the slope angle rapidly leads to the classification that the area is totally non-navigable. The same approach has been taken for mixed rocks and sloped areas. Figures 7 and 8 show the shape of the non-navigable areas around a rock when the terrain is tilted right or left.

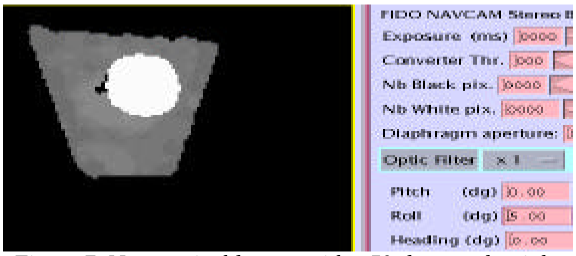

Figure 7: Non-navigable area with a 5° slope to the right

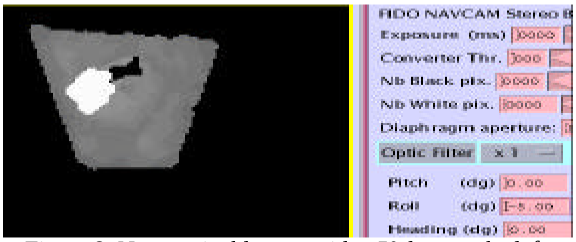

Figure 8: Non-navigable area with a 5°slope to the left

The resulting slopes were measured on the real terrain and the validity of the detection has been established.

5.1. Computing time and resources

For a 512 x 486 pixel NAVCAM 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 36 x 32 cells, the JPL obstacle detection algorithm had an on-board execution time of 216 ms. For the CNES algorithm using same images and DEM grid size, but with a grid size of 251 x 251 cells, the CNES obstacle detection software was executed in 1533 ms. The total execution time of both algorithms from image acquisition to path generated is, therefore, as follows:

- JPL software: 7616 ms
- CNES software: 3267 ms

In any case the maximum computing time was less than 5% of the locomotion time and is negligible along the mission.

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. This figure is compatible with an implementation on Mars rover on-board computer, as they are foreseen for the next flight opportunities.

6. LONG-RANGE NAVIGATION

6.1. Algorithm description

The results of the both JPL and CNES navigation algorithms used separately have been analyzed during long traverses across the MarsYard. In these tests, the rover was placed in difficult situations like a trap-shaped rocks arrangement. A short description of the JPL and CNES approaches to rover navigation are as follows:

- For the JPL navigation algorithm, the rover attempts to follow a direct path to the next waypoint given by the ground operator. During the movement, stereo pairs are acquired from the HAZCAMS in front of the rover and obstacle detection is performed from the corresponding DEM. When an obstacle is encountered, a path planner searches through the obstacle database for a clear path towards the waypoint. A low-resolution grid (36 x 32 cells) representing the navigability of the terrain around the rover is maintained to keep a short-term memory of the strategy used to find a path. When the direct path becomes possible again, the normal progression is restarted.
- For the CNES navigation software, only the final goal needs to be given by the ground operator. The rover then performs several acquisitions from the NAVCAMS at the start point. The different navigation maps computed from each stereo pair are merged together to obtain a global map (set to 12 x 12 m around the rover during these tests). This map represents not only the navigable, non-navigable and unknown areas but also the difficulty of the terrain. The algorithm then computes a path that optimizes the progression towards the goal using the easiest terrain. 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. Path planning is thus always using a 250 square meter knowledge around the rover.

6.2. Long range tests results

With relatively simple situations (isolated rocks on a smooth surface) and few meters trajectory, both algorithms correctly avoided obstacles and reached the objectives that have been assigned. The interest of a global planning strategy was demonstrated in more complex situations as the two described hereafter.

6.2.1. Multiple obstacles trajectory

The target was set at about 15 meters away in a region were several large rocks had to be avoided on the way. Figure 9 shows a view of the travel to the goal.


Figure 9: Multiple obstacles trajectory test

The rover is on the left side of the terrain and the goal at the extreme right. With the global planning algorithm, the goal has been reached in 6 steps (initial panorama and 6 additional perceptions). The rover used a path that was very near to the shortest way to the goal, using narrow gates between the rocks like in Step 3 (Figure 10) or in Step 5 (Figure 11).

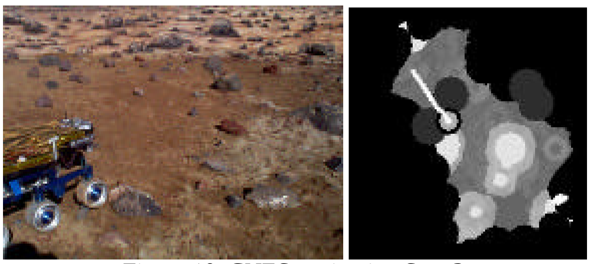
Figure 10: CNES navigation Step 3

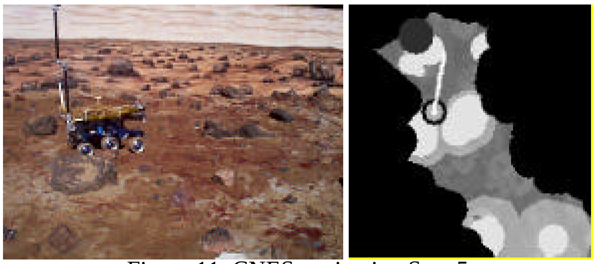

Figure 11: CNES navigation Step 5

With the JPL local obstacle avoidance algorithm, the first part of the traverse, where the rock density is lower, was rather similar to the CNES navigation traverse. However, when the rover arrived near the final target location that was surrounded by large obstacles, the local strategy avoided the big rock (Figure 12) and caused the rover to miss the shortest path to the goal, which was to the left of the rock.

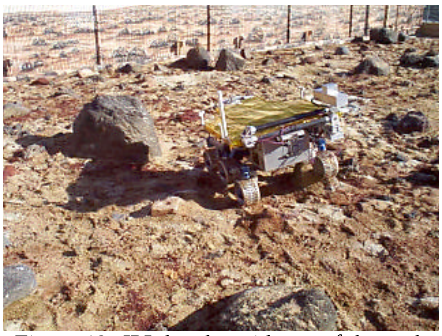

Figure 12: JPL local avoidance of the rock

The rover had then to follow a longer path before switching again to direct progression towards the goal as illustrated in the sequence shown in Figure 13.

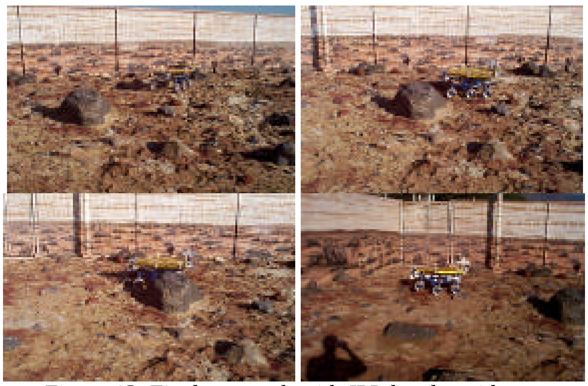

Figure 13: Final approach with JPL local avoidance

6.2.2: "Trap" situation

The "trap" was made up of large rocks configured in a semicircular pattern in front of the rover to create a dead-end as illustrated in Figure 14. The goal was set behind the stones line. The rover was positioned initially such that the distant rocks were outside of the range of the vision system so that the rover entered the trap.

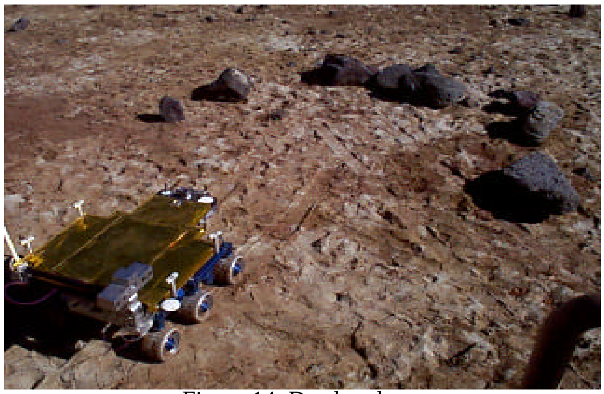

Figure 14: Dead-end test

With the JPL obstacle avoidance algorithm, the rocks were identified as hazards and a right escape strategy was initiated. Successive perceptions and obstacle avoidance on the right side led the rover back out to the entrance of the trap as depicted on Figure 15. At this time, however, the obstacles within the trap were outside of the local obstacle map maintained on the rover and the path planner considered this area free of obstacles. As a result, the rover re-entered the trap in an effort to reach the final waypoint. Although the obstacle detection and avoidance algorithm worked well and generated trajectories consistent with the position of the obstacles, the planing range was too short to successfully exit out of the trap.

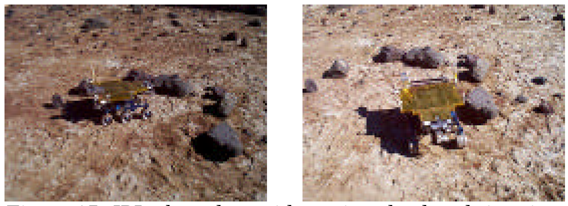

Figure 15: JPL obstacle avoidance in a dead-end situation

With the CNES global planning algorithm, starting with the initial panorama (5 images), 6 perception cycles were performed by the rover. The rover first attempted to escape the trap on the left side, however, after a new perception cycle, the navigation algorithm identified that the left side was closed and attempted to escape by the right side. As a result, the rover navigated around the rocks on the right of the rover and successfully exited the trap as shown in Figure 16.

Figure 16: CNES global planning in dead-end situation

It is interesting to note that, after the path was found that would allow the rover to exit the trap, the rover's progression was executed in several steps because the escape trajectory was found using already old perceptions. In this case, for safety reasons related to possible drifts during path execution, the navigation algorithm requires a new perception before executing the path in order to refresh the obstacle's position. The first image of Figure 17 shows that a navigable area around the rock has been identified (in gray) but a path is planned only on the next (right image) map.

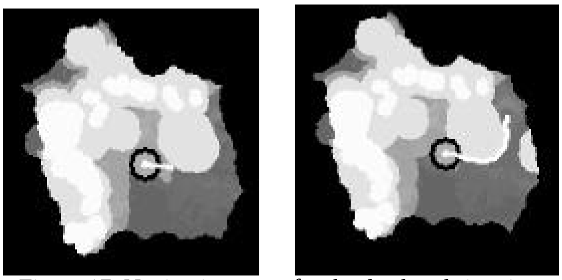

Figure 17: Navigation maps for the dead-end situation

7. CONCLUSIONS AND RECOMMENDATIONS

The tests have shown that global planning navigation algorithms give a significant improvement to the rover's daily traverse ability 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.

An efficient implementation of the navigation will be to have CNES navigation running at the higher level, using the NAVCAMS, and obstacle detection, using HAZCAMS running during path execution to guarantee an optimum safety with the 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 NAVCAMS (switch to obstacle avoidance strategy) or HAZCAMS (switch to unmonitored CNES navigation) without adding any hardware. This approach has been taken as the baseline for future work. A second test period is foreseen in 2001 with integrated on-board software and off-line monitoring on ground to reproduce a realistic situation for Martian surface exploration.

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