ADVANCED ROBOTICS TECHNOLOGY INFUSION TO THE NASA MARS EXPLORATION ROVER (MER) PROJECT

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Abstract: This paper presents four new technology developments and their infusion into the Mars Exploration Rover (MER) mission. These technologies were not ready for infusion prior to the launch of this mission. Three of these new capabilities are designed to increase the level of autonomy for the operations, i.e., fewer ground-in-the-loop steps for executing commands. One of the new capabilities is designed to intelligently filter rover obtained images and return only those that are very likely to contain useful information. These new capabilities will be used for this and future NASA planetary missions.

Keywords: Rover, Autonomy, Autonomous Science, Mars, Space Robotics, Instrument placement, Planetary Rovers

1. INTRODUCTION

The NASA Mars Program is science driven program that develops and launches missions to Mars every couple of years. These missions are discovery driven. They are designed based on science obtained from pervious missions and planned based on science hypothesis. The successful development and landing of the Mars Pathfinder mission in July of 1997 with an experimental rover, Sojourner, demonstrated the value of mobility for exploration. This led to the development and launch of the Mars Exploration Rovers in 2003. The Mars Technology Program [1], an element of the Mars Program, developed and enabled many of the mobility capabilities that are used in this mission. The MER mission was planned for 90 sols, but fortunately, the rovers have lasted much longer. The extended mission has provided many more opportunities for scientists to explore and a rare opportunity for the technologists to further develop and infuse technologies to this mission. Since many of the future Mars missions will use rovers, this effort is seen as technology feed forward for future missions in addition to increased capabilities for the MER mission.

This paper will discuss new capabilities that have been developed for Opportunity and Spirit rovers. New capabilities include: 1- More sophisticated path planning that expands the planning horizon, thus eliminating local traps that the MER rovers have experienced in the past 2- Visual target tracking to reach targets of interest in a closed-loop sense, thus eliminating stopping and communicating to the operators on Earth for verification before proceeding, 3- Automated instrument placement, which includes safety checks for deploying the manipulator arm, and finally 4- Automated detection of dust devils and clouds, thus eliminating the transmission of large data files to Earth that only occasionally contain scientific data.

This paper will also present the difficulty involved in "flight qualifying" autonomy capabilities for space missions and discuss the steps taken to satisfy stringent mission requirements.

2. GLOBAL PATH PLANNING

Up until now, autonomous navigation with hazard avoidance (AutoNav) on MER has been performed using a local path planner called Grid-Based Estimation of Surface Traversability (GESTALT) [2]. During each GESTALT cycle, stereo images are acquired from the rover's on-board hazard cameras (HazCam) or navigation cameras (NavCam), stereo ranging and terrain assessment is performed, a safe drive arc is selected, and the rover is driven along the safe arc a short distance (normally 50cm). Then new stereo images are acquired and the process is repeated. During the terrain assessment step, the stereo range data are used to generate a local goodness grid map. Once terrain assessment is

completed, a set of candidate drive arcs are considered.

Each arc is evaluated based on three criteria: avoiding hazards, minimizing steering changes, and reaching the goal. For each candidate drive arc, the hazard avoidance, steering bias, and waypoint arc votes are weighted and merged. The arc with the highest merged vote is selected.

GESTALT has worked well to guide the rovers around narrow and isolated obstacles, however, it is susceptible to failure when there is a wide obstacle or a cluster of closely spaced obstacles blocking the path of a rover to a selected the goal. In such cases, the hazard avoidance and waypoint arc votes severely conflict. The hazard avoidance votes will not allow the rover to go through the unsafe area and the waypoint votes will not allow the rover to deviate enough from the straight line path to the goal to get around the unsafe area. Figure 1 illustrates a cluttered scene on Mars where such a failure occurred.

In 2005, a new technology task was initiated at JPL to address this limitation by simultaneously performing GESTALT local path planning and global path planning. A version of the Carnegie Mellon University (CMU) Field D* global path planner was integrated into the MER flight software. Field D* is capable of planning an optimal path from any location in a map to a selected goal position in real time, even when changes occur to the map [3].

Field D* operates on cost values, where low cost corresponds to highly traversable terrain, and AutoNav uses goodness maps, where high goodness corresponds to highly traversable terrain. Combined GESTALT local hazard avoidance and Field D* global path planning enables the rovers to autonomously navigate around much more complex obstacle arrangements than has previously been possible.

2.1 Results from Field D Checkout Tests on Mars*

Thus far, three of five planned D* checkout tests have been performed on Mars using Opportunity. All three have been successful. The first and second tests verified the software. In the third checkout (sol 1160), Opportunity performed D* assisted hazard avoidance around not only keepout zones placed at a small crater named Granada, but also successfully avoided 10-15cm high rocks next to the crater (and outside the keep out zones). See Figure 2.

The fourth checkout involves performing D* assisted hazard avoidance on a long traverse (>25 meters). Once the checkout phase is complete and mission personnel gain confidence in the technology, Field D* assisted hazard avoidance will likely be used in the majority of future MER AutoNav drive sequences.

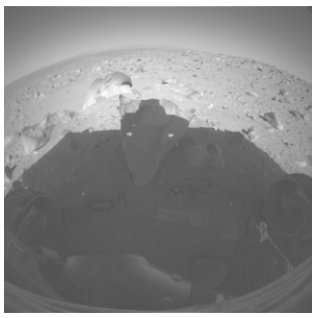

Figure 1. During sol 108, Spirit tried in vain for 105 minutes (47 drive steps) to circumnavigate to a goal on the other side of this cluster of rocks using solely local path planning

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Figure 2. During Sol 1160, Opportunity used Field D* assisted hazard avoidance to navigate around medium height rocks (blue) and short rocks (yellow) to the left of a small crater named Granada. The tall rocks and the crater that are on the right side of the image were designated as keep out zones. In the panorama image looking backwards, the wheel tracks of Opportunity, and a portion of its solar panel are clearly visible in the image.

3. VISUAL TARGET TRACKING

Visual target tracking is directly related to feature tracking and visual servoing, which is a well-established field in computer vision. Visual servoing uses visual feedback such as feature tracking to control a robot. Some of the very first versions of visual target tracking were demonstrated on the Marsokhod rover at Ames Research [4] and on the Rocky 7 rover at the Jet Propulsion Laboratory [5]. A follow-on effort by both teams resulted in the first visual target tracker that was developed within the CLARAty (Coupled Layer Architecture for Robotic Autonomy) framework [6], and delivered on the Rocky 8 rover for formal validation. The first version of the tracker included affine trackers at

multiple image resolutions. Extensive validation indicated shortcomings of the affine tracker. This led to the development of the normalized cross-correlation (NCC) with template image magnification. During the infusion of VTT into the MER, further improvements were made such as 1) template image roll compensation (the MER mast does not provide roll control), 2) auto exposure over a subframe image, 3) specification of target position in rover and site (world) frames as well as target position update in site frame, 4) target loss detection and fault protection, 5) 10× speedup of NCC and point stereo, 6) integration with MER Autonav and VO, and 7) VTT command interface.

3.1 Concept of Operations

Visual target tracking (VTT) enables the rover to approach the designated target 10 to 20m away within a few centimeters error. The stereo range 3-σ error is as much as 40 cm for a target at 10m. Thus, even if the rover has a perfect rover pose estimator, without VTT the final target position could be as much as 40 cm off. By contrast, VTT employs a closed loop control around the designated target enabling the rover to track the target within a few pixels.

3.2 Integration and Operational Checkouts on Mars

VTT is fully integrated into the existing MER flight software (FSW). VTT can run in any combinations of rover driving: blind driving (with IMU-based estimator), VO (visual odometry) [7], and/or Autonav (autonomous navigation with hazard avoidance to drive the rover to a goal Cartesian location). If visual odometry is enabled, this is done first.

Three operational checkouts are planned for VTT. So far, two operational checkouts were performed on Opportunity roaming along the rim of the Victoria Crater, and both were successful. In the first checkout performed on sol-992 (November 8, 2006), VTT was instructed to only track the target without controlling the rover's movement. A small 7-cm wide rock located about 4 m away from the rover was chosen for the target. Despite the viewing yaw angle change exceeding the usual 0.1 radian limit (10% of the target distance), VTT tracked over all 8 images successfully. In the second checkout of sol-1100 (February 26, 2007), the Opportunity drove autonomously from about 10m to within 2m of a target rock at 10 m in 15 steps, while performing VTT using Navcam subframe. VTT tracked well over all 18 images.

4. AUTOPLACE: AUTONOMOUS INSTRUMENT PLACEMENT

Each MER vehicle has three science instruments and a rock abrasion tool mounted on a 5-DOF robotic arm called the Instrument Deployment Device (IDD) [8]. Normally, the target for an instrument placement is identified in stereo imagery acquired at the rover's current location—that is, no driving occurs between the imaging and the instrument placement. This allows rover operators to manually create a sequence of joint-space and cartesian commands and verify in simulation that the sequence is safe. Joint limits, static deflection, structural limits, self-collisions, and current limits are all checked both in the sequence simulation and by the on-board rover software. But other safety checks require knowledge of the terrain: checking for collisions between the arm and the surface, and ensuring that intentional collisions between an instrument and the surface--an instrument placement—do not result in high loads being generated. One centimeter of overdrive is typically used, which is usually sufficient to account for uncertainty in surface position while keeping loads within safe limits given the stiffness of the arm.

A command cycle, and a sol of operations, can be eliminated by moving the target selection, trajectory generation, and terrain collision analysis into the on-board software. This software is called AutoPlace, shorthand for Autonomous Instrument Placement. Given the IDD's inherent ability to damage itself and other parts of the rover, the highest priority of AutoPlace is ensuring the safety of any autonomous operations.

4.1 Approach

AutoPlace builds on existing capabilities of the flight software, including joint-space and cartesian-space motion commands, self-collision checking, deflection compensation and checking, structural limit checking, and stereo range map generation. The additional capabilities required for autonomous instrument placements are:

1 - stereo range mapping
2 - terrain model construction
3 - visibility analysis
4 - candidate target selection
5 - safe-to-unstow determination
6 - surface normal determination
7 - target reachability assessment
8 - trajectory generation

Operations 1-5 are performed by two new commands which acquire and process the "ultimate" and

"penultimate" pairs of stereo images. The "ultimate" image is taken at the rover's final position after a drive and is used for steps 1-5 above. The "penultimate" image is needed to view the area beneath the rover in rough terrain, since the cameras cannot see beneath the IDD in its stowed position, and is not used for target selection. If safe to do stow, the IDD is deployed from its stowed-for-driving configuration by another existing command, and autonomous placements performed by a third new command that contains operations 6 through 8.

4.2 Algorithms

The most important aspect of AutoPlace is safety. This focus on safety builds on an existing capability for detecting self-collisions--that is, collisions between the IDD and itself, or the IDD and other parts of the rover [9]. Safety is assessed by testing each *via-point* along a potential trajectory for collisions with an octree-based terrain model built from stereo data (see Figure 2). This terrain model also explicitly models volumes that are unknown due to occlusions and stereo dropouts, so that any volume not confirmed to be free of obstacles is considered unsafe. The visibility analysis is performed by tracing the line of sight from one or both cameras to 3D points sensed by the stereo vision system, and marking cells in a separate octree as verifiably free of obstacles. After finalizing the volume that is free of obstacles, the negation of this volume is added to the obstacle octree. This visibility analysis is absolutely essential for autonomous deployments: the stereo vision system is unable to sense the surface in heavily shadowed areas, or when obstacles are very close the camera, and treating this lack of data as a lack of obstacles could be mission-ending.

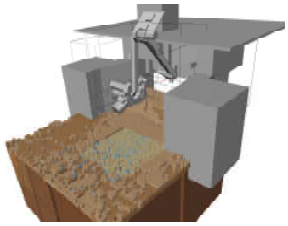

Figure 2. Rover, arm, and stereo-derived terrain models used for on-board collision detection

After building the terrain model, AutoPlace begins selecting targets by finding the closest point on the terrain to the commanded target.

Once the closest surface point is identified, it and other points at a regular spatial sampling in a list are candidate targets. The candidate targets are examined one at a time until a feasible target is found. The first step in evaluating a candidate target is to compute its surface normal, since AutoPlace must approach the surface within 10 degrees of the local surface normal to ensure that the contact sensors on the instruments will trigger correctly. Surface roughness (maximum variation in surface height relative to the normal) is also computed at this point. After finding a target that passes these checks, the target (including surface normal) is assessed for feasibility by searching for a safe trajectory to the target.

4.3 Results from Mars

At the time of writing, AutoPlace is still undergoing initial checkout on both Mars Exploration Rover vehicles. It has been used to command 2 placements each of the Mossbauer and Microscopic imager instruments on Opportunity, and one placement of each instrument on Spirit. Half of the commanded placements resulted in AutoPlace finding and executing safe trajectories (e.g. Figure 4). In the other three instances, AutoPlace refused to move the IDD due to missing data from stereo dropouts (twice) or incorrect parameter settings used in for reachability analysis (once).

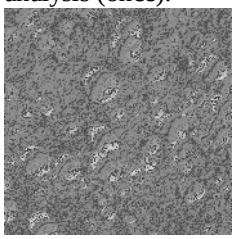

Fig. 4. Microscopic Imager image of hematite-rich “blueberries” and soil acquired after an autonomous placement on sol 1069 near the rim of Victoria Crater. The patch of terrain viewed in the image is roughly 3cm

5.0 ONBOARD SCIENCE: CLOUD AND DUST DEVIL DETECTION

Dynamic atmospheric phenomena observed by MER include dust devils and clouds. These scientifically interesting events are typically rare, especially when out of season. Traditionally, dust devil and cloud campaigns on MER have been conducted by collecting a set of images at a fixed time pre-specified in the command sequence and then downloading the image set. When few images contain events of interest, this can result in an inefficient use of downlink bandwidth. Recently, a new approach has been developed and deployed on the rovers.

We have developed algorithms that analyze images onboard the rovers to identify the presence of events of interest (clouds and dust devils). By selecting those images that capture the events many images can be collected onboard resulting in a much greater time range for capturing the rare phenomena. Even when the images cannot be down-linked (such as

when too many events are detected), compact summary statistics on the number and type of events can be still be down-linked to provide valuable information.

The code implementing these algorithms has been integrated with the MER flight software and uploaded to the MER rovers as part of the R9.2 software upgrade. Both the dust devil and cloud algorithms have successfully run on the MER rovers and have successfully passed initial checkouts. The first image collected for cloud detection is shown in Figure 1.

5.1 Cloud Detection

In detecting clouds, a single image algorithm was used rather than an image differencing approach as the time frame over which the clouds may change significantly is too long to require the rover to remain motionless on a regular basis. The approach assumes that large variations in intensity within the sky correspond to clouds. The algorithm first locates the sky (equivalently, the horizon) in an image and then determines if there are high variance regions within the sky. This algorithm, which operates on individual images, achieved over 93% accuracy in testing on 210 hand-labeled images taken by the Mars Exploration Rover Opportunity. In these tests, there were three misses (false negatives) and eleven false positives. All of the three misses were labeled as a possible cloud (low confidence) by the scientist performing the labeling. No high confidence clouds were missed. For more details on the algorithms and experimental testing see references [10].

5.2 Dust Devil Detection

A second type of dynamic atmospheric phenomena of interest on Mars is dust devils. The two most common methods for detecting dust devils are the comparison of two or more spectral bands of the scene and the motion detection using a temporal sequence. Our approach is based on motion detection. This does not require multiple color bands. On Mars changes observed in a sequence of images taken over a short time period are typically from dust devils. Dust devils are high dust opacity features on a dusty background and often have a faint signature in an image. The main challenge is to detect these often subtle features in the presence of significant image noise. The algorithm consists of a preprocessing step to reduce image noise followed by an image averaging. The difference between the average image and the input or test image is then computed. Noise effects are removed from the difference image and blob detection is performed on the remaining differences. A buffered bounding box is formed around each detection to ensure that the full dust devil is captured. The dust devil algorithm was tested on 385 images divided into 25 image sequences acquired by the MER Spirit rover. The sequence lengths varied between 6 and 20 images. The algorithm achieved an 85% accuracy. The first automatically detected dust devil was detected on Spirit sol 1147 (Figure 5).

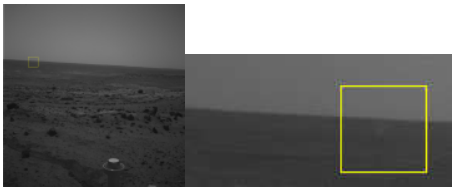

Figure 5. Dust devil correctly detected on Spirit Sol 1147. The image on right shows close-up of the dust devil.

6.0 DEVELOPMENT AND TESTING ON EARTH

The four technologies described above were integrated into the existing version (R9.1) of MER FSW to produce a new version labeled R9.2. This process began in April 2005 and progressed through several stages of development and testing, before completing in June 2006.

The development phase for the new technologies went through several cycles of design, software writing, and unit testing, each time adding more functionality and fixing problems found during the unit testing of the previous cycle. This lasted from April 2005 to January 2006. In some instances, previously developed code was leveraged, but rewriting was necessary to conform to the MER FSW coding standards and to integrate it with the existing FSW.

The next phase involved several cycles of regression testing with the integrated system. Both the new code and the pre-existing FSW were run through a series of tests to ensure that no degradation of the existing functionality occurred. During each cycle, bugs were fixed, but no new capabilities were added. The cycles continued from January 2006 until April 2006, at which time the regression testing produced only bugs which were deemed acceptable due to schedule constraints and the existence of operation workarounds.

Next, system tests were conducted in May 2006. While the regression tests focused on testing the

individual pieces of the integrated system, the system tests focused on running the rover through a series of realistic operational scenarios.

6.1 Validation on Mars and Conclusions

After transmitting the new FSW to the rovers on Mars, we booted up using the R9.2 version in September 2006. Then, we began the currently ongoing process of validating the FSW on the Mars rovers. Each of the four new technologies has a checkout plan for the validation which involves several tests. The tests start with simple and safe activities and progress to using the full capabilities of each technology.

There are constraints on the checkout process. We try to insert the checkouts into the science plan when they will have the least impact on the science activities. In the case of D*, Visual Target Tracking (VTT), and Onboard Science, once a capability is validated on one rover, it is cleared for use on the other. Since the parameters for the IDD are slightly different on the two rovers, the AutoPlace technology is being validated separately on both rovers. Since Spirit is hobbled by a stuck right front wheel drive motor, the D* and VTT checkouts, which require significant driving, are restricted to Opportunity. Opportunity is currently nearby a large crater called Victoria. To prevent any chance of driving into Victoria, the checkouts which involve driving must be conducted during the occasional drives away from the crater rim. Furthermore, some of the checkouts require the presence of hazard-free terrain, while some require hazards or trackable features.

For example, the checkout plans for D* is described below. There are five steps in the D* checkout plan:

1. D* in a “No Update” mode. This involves using the pre-existing autonomous driving capability (Autonav). D* performs its computations and generates telemetry at each drive step, but the D* results have no influence on the driving behavior.
2. D* on hazard-free terrain.
3. D* on hazardous terrain.
4. D* for a long drive.
5. D* using an uploaded map.

7. ACKNOWLEDGMENTS

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