Immersive Visualization for Navigation and Control of the Mars Exploration Rovers

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The Rover Sequencing and Visualization Program (RSVP) is a suite of tools for sequencing of planetary rovers, which are subject to significant light time delay and thus are unsuitable for tele-operation. The tools build on the heritage of the Mars Pathfinder mission and its lessons learned [1][2]. The two main components of the RSVP suite are the Rover Sequence Editor (RoSE) and HyperDrive. These two tools and several others in the RSVP suite communicate sequence information using a unique data bus architecture implemented using the Parallel Virtual Machine (PVM) library. This paper will focus on HyperDrive, the immersive visualization component of the system, and its role in analyzing past rover performance and in generating command sequences for future rover activities.

HyperDrive is based on providing several immersive views into a unified three dimensional database which consists of CAD models of the MER rover, instrument deployment device (IDD) and lander, raw image data, three dimensional terrain models derived from stereo image data, a spatial representation of the sequence under development, and time ordered histories of rover state values which may originate from received telemetry or ground based kinematic simulation. HyperDrive also maintains interfaces with ground versions of the flight software as run on the vehicle. This allows the simulations to provide the highest fidelity available in determining how the on-board arm or mobility software will respond to the commands being issued in the current environment. By building a unified model of the rover and its environments and modeling our data classes to reflect real world interactions the process of adding new data or interfaces has been greatly simplified.

The most important data source for HyperDrive is terrain data, which has been generated from stereo imagery captured by the rover's cameras. The process of stereo correlation allows range data to be calculated on a pixel-by-pixel basis for imagery acquired as a stereo pair by cameras whose properties have been well characterized [3][4]. When used as a base model for a unified three dimensional database of the rover's environment, these models allow the rover's operators to view the scene from any angle, not only the ones captured by the rover's on board cameras. This ability has proven crucial to understanding the rover's environment well enough to sequence challenging traverses and IDD deployments with high confidence of success. Figure 1 illustrates the rover in its test environment and another view from a similar perspective synthesized entirely from imagery captured from the rover's current location in the test facility.

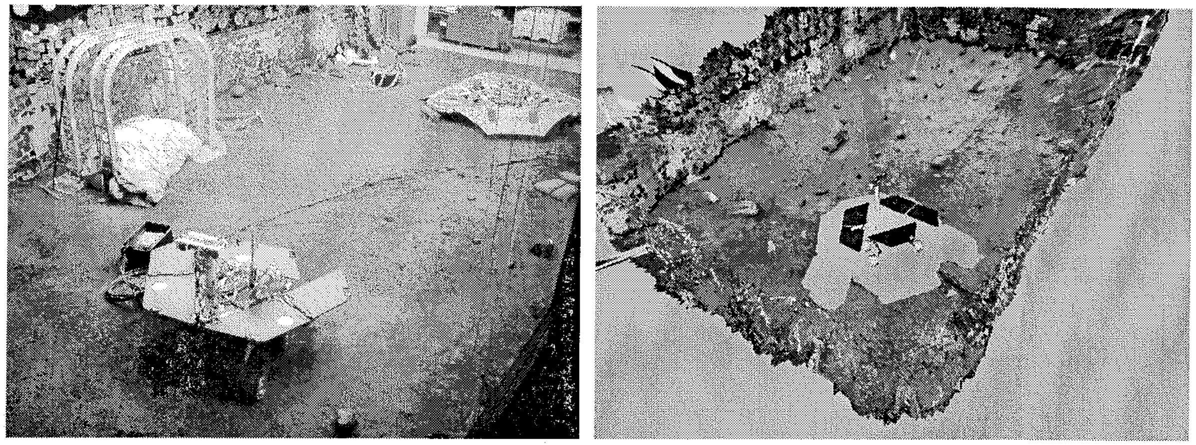

Figure 1. Actual and simulated views of the rover in its testbed.
Note arch and lander not represented in synthesized view

HyperDrive provides various views into this virtual world in order to facilitate operator understanding of the rover's state and interaction with it's environment on the surface with the goal of improved analysis of the telemetry returned from the rover and improved efficiency and safety in generating command sequence loads. Provided views include a virtual camera in which the operator may position a camera anywhere in the 3-d environment and view the rover and terrain from any angle. This works in conjunction with an augmented reality view in which renderings of the rover and sequence are overlaid on the telemetered imagery. The following figure shows a purely synthetic view of the rover conforming to a stereo generated terrain and imagery from the Gusev landing site overlaid with iconography representing a planned rover traverse using both low-level and autonomous commands.

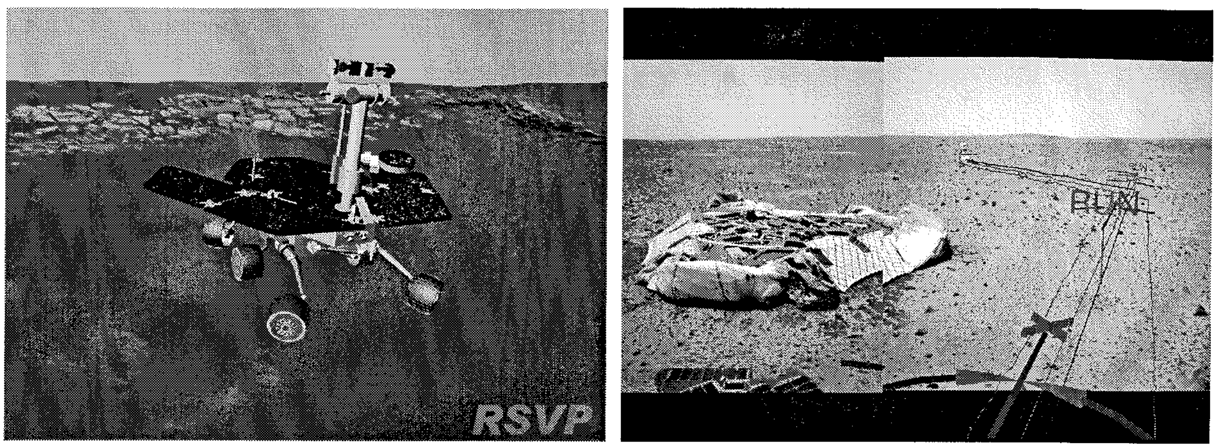

Figure 2. Simulated "flying camera" view of Meridiani landing site and
augmented reality view of initial traverse away from Gusev landing site.

Another important feature of HyperDrive is its ability to maintain a list of and correctly calculate transformations between some of the many coordinate frames utilized by the rovers for commanding. This allows all rover cameras to be accurately simulated to assist in generating imaging sequences and predicted future image data return. The imaging system can be commanded in any one of seven coordinate frames and these must be correctly aligned with the terrain data and CAD models to enable imaging commands to be correctly simulated. This is particularly important for imaging that is to be completed post traverse where there is no data on the ground that represents necessary pointing after the drive. The figure below represents the highest level of accuracy achieved for predicting the post traverse camera pointing necessary to image a specific feature, here a trench created by the front wheel the preceding day. This sequence was designed with pointing based on azimuth and elevation relative to the rover itself.

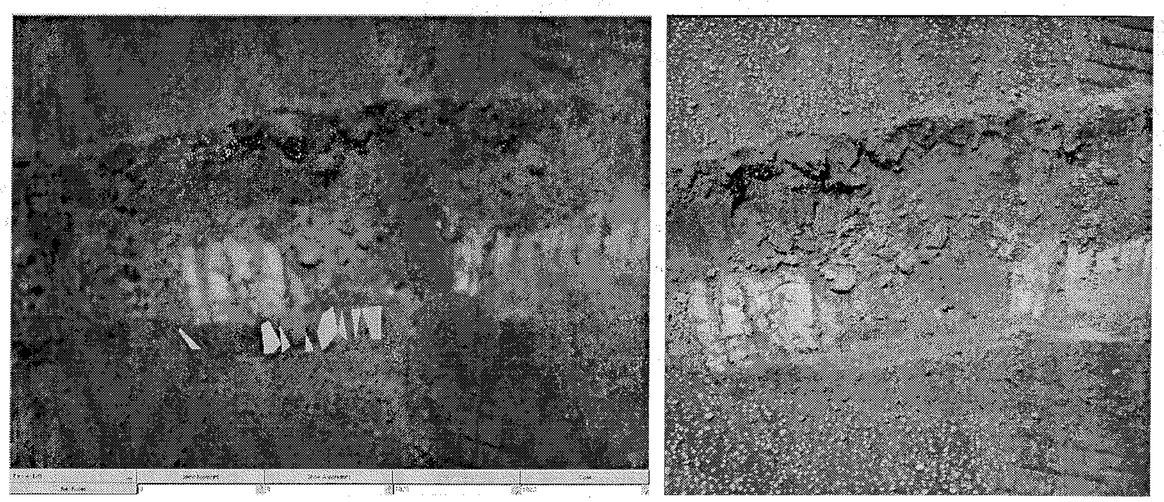

Figure 3. Predicted camera pointing and actual captured image based on this pointing
Red bars represent letterboxing. The image is a false color composite of a MER-B trench.

An additional interface maintained by the HyperDrive application is to the NAIF/SPICE ephemeris system in use at JPL. NAIF provides a C++ library for querying ephemeris data for all planetary bodies of interest and is capable of generating very accurate pointing vectors from spacecraft to any of the bodies of interest at any time. Additionally this library can very accurately calculate transformations between the many time systems necessary to operate a rover on the Martian surface. Of particular interest are the related Local Solar Time (LST) and the pointing vector from the rover to the sun. LST is based on the elevation angle of the sun at the landing site and so LST12:00 represents high noon with the sun directly overhead. Armed with the ability to generate a pointing vector to the sun at the time a given command sequence if scheduled to be run allows the scene to be rendered with accurate shadows in real time. Originally incorporated into the software based on the programmers' feelings of potential utility, this feature has become very heavily used by scientists and image sequencers to optimize camera pointing and/or the time of day for the sequence to be run to minimize shadowing of important science targets. A variation of this functionality is also provided to warn of pointing that is too close to the sun by the thermal emission spectrometer (MTES.) The figure below show the results that were achieved using SPICE ephemeris calculations coupled with real time shadow calculations and the actual scene as imaged at the same time.

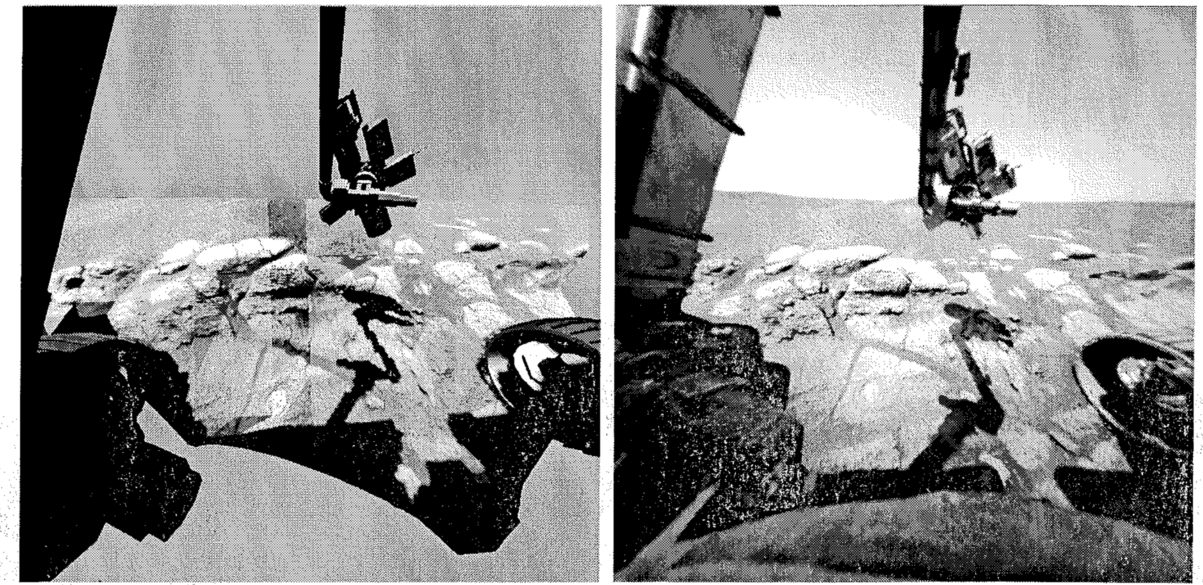

Figure 4. Predicted and actual shadowing at the Meridiani Planum landing site

Operation of the rover's robotic arm (IDD) comprises a large portion of the rover driver's workload. Most Sols (Martian days) contained at least some IDD operations and others were complete IDD observational campaigns, which could exceed 500 commands. Fortunately a good working relationship between RSVP and flight software developers for the arm was achieved early in the process. This allowed the tools provided for arm operation to become quite robust through testing and iteration. These tools provided transformation between science targets as input and IDD commands with designation arguments correctly transformed. The tight coupling between HyperDrive and the flight software allowed potential problem such as self-collisions, transformation across kinematic configuration changes, and collision with the terrain to be caught early in the process and rectified. The visualization and animation of the arm sequences generated by the simulation have been instrumental in providing context for and comprehension of these complex arm operations to mission management and other ops team members. The following figure shows the planning of an arm placement on a hole previously created with the Rock Abrasion Tool (RAT.) The resulting Microscopic Imager (MI) image is shown at the right.

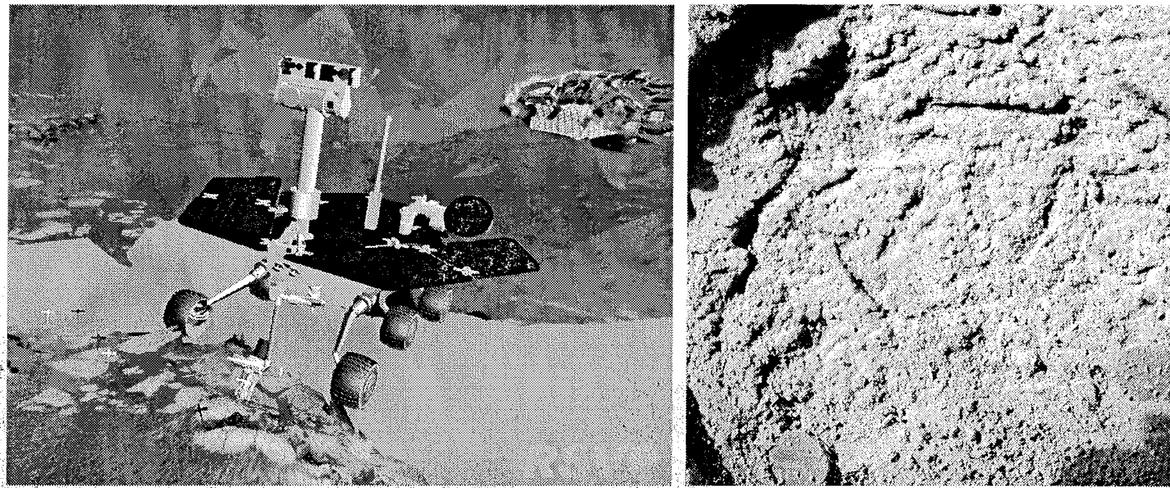

Figure 5. Planning placement of the Microscopic Imager (MI) using the flying camera view and the resulting image

HyperDrive provides several tools that are focused on analyzing downlinked telemetry. The CAD model of the rover may by animated three dimensionally by applying the telemetered state values to it in the correct time sequence. Time series graphs are also available for comparing results numerically with each other or predetermined alarm values. By comparing the telemetered behavior with the three dimensional terrain, errors in the rover's on-board position estimation may be revealed. Additionally, tools are provided to measure and analyze the three dimensional terrain itself as an aid to understanding its traversability and potential hazards for planned rover driving or arm placement. These tools include the standard position, distance, and angular measurements as well as higher level regression tools, which are useful in determining rock height, shape, distribution, and overall slope.

Understanding how the rover's autonomy system perceives the scene is critical in predicting how it will traverse a given patch of terrain. Tool are provided in HyperDrive to analyze a terrain patch with the same algorithm used on-board the vehicle and present the color-coded results to the operator. Varying colors from green to red represent the "goodness" of the terrain for driving as assessed by the rover. Using this tool in conjunction with the high level GOTO_WAYPOINT command allows the rover drivers maximum flexibility and safety in designed a sequence which utilizes both high level, autonomous commands and low level "blind" movements. The figure below illustrates using several autonomous waypoint commands to sequence a traverse that threads the needle across a very complex and challenging terrain.

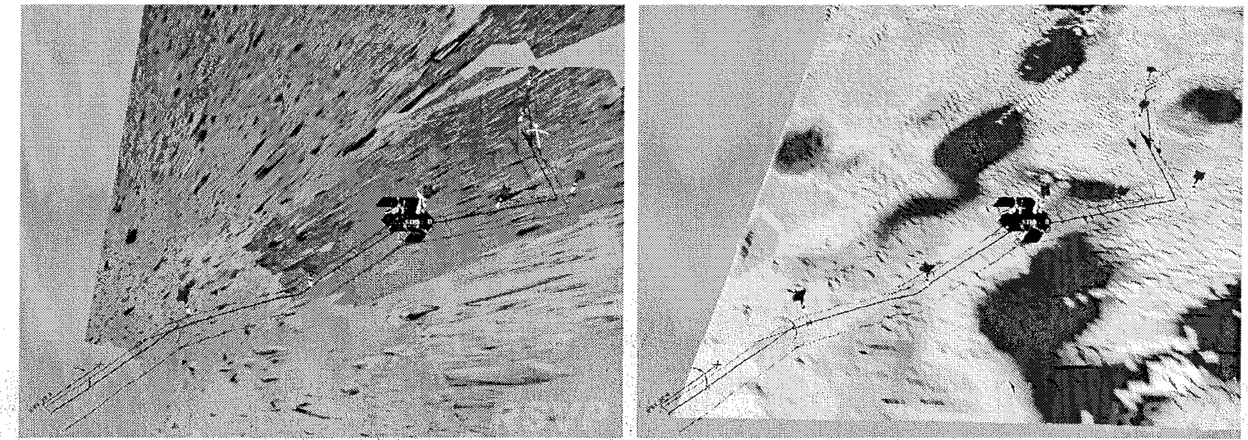

Figure 6. An overhead view of a planned traverse and how the rover's autonomy system sees the terrain ahead. Darts represent GOTO_WAYPOINT commands

HyperDrive's primary purpose is to provide the rover sequencer with a coherent view of the rover in its surface environment to enable generation of traverse, arm placement, and imaging sequences. In this role, it is essential that the operator quickly gain an unambiguous understanding of the rover's state relative to the surrounding terrain so that dangerous errors in traverse or arm planning do not occur and valuable resources are not wasted acquiring data of incorrect targets. To this end, the numerous coordinate frames and systems related to the rover, the arm, the imaging system, the environment, and the sequence itself are fused and presented to the operator as a unified view. We have found that this greatly reduces confusion regarding the relationship of the frames among ground personnel. HyperDrive has been used with great success to plan all rover traverses and arm motion sequences for both Spirit and Opportunity. It has proven invaluable as a tool that enables quick understanding of the rover's state relative to its environment, which is essential to the rapid generation of new sequences on a daily timeline. A picture is really worth a thousand text-based telemetry displays when it comes to driving rovers on Mars.

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