The Evolution of Three Dimensional Visualization for Commanding the Mars Rovers

Frank R. Hartman,* John Wright, Brian Cooper

Jet Propulsion Laboratory, California Institute of Technology

ABSTRACT

NASA's Jet Propulsion Laboratory has built and operated four rovers on the surface of Mars. Two and three dimensional visualization has been extensively employed to command both the mobility and robotic arm operations of these rovers. Stereo visualization has been an important component in this set of visualization techniques. This paper discusses the progression of the implementation and use of visualization techniques for in-situ operations of these robotic missions. Illustrative examples will be drawn from the results of using these techniques over more than ten years of surface operations on Mars.

Keywords: Mars rovers, stereo visualization, robotic operations, augmented reality.

1 INTRODUCTION

The Jet Propulsion Laboratory, California Institute of Technology, has operated four rover missions on the surface of Mars. These missions, beginning with Mars Pathfinder and the Sojourner rover in 1997, Mars Exploration Rovers with Opportunity and Spirit landing in 2004, and Mars Science Laboratory with Curiosity landing in 2012, have all utilized a combination of 2D and 3D visualization techniques to support mission operations. Visualization serves the critical purpose of aiding the operators in building a mental model of the local terrain to use for planning traverses and interactions between the robotic arm and terrain.

The original Rover Control Workstation (RCW) designed for Mars Pathfinder utilized primarily a stereo image based display. Targets were designated within the stereo display and the rover's interactions with the terrain were visualized there. The capability of generating polygonal terrain models and displaying them within an immersive, rendered view came relatively late in the development process. The immersive fully rendered view, based on visualizing a combination of polygonal terrains meshes derived from the stereo cameras using computer vision techniques and a simplified CAD model of the rover came to be know as the "flying camera" view due to its ability to simulate the view of an arbitrarily positioned camera. See Figure 1 for an example of a rendering of the rover and Martian surface from an arbitrary viewpoint above the vehicle.

For the Mars Exploration Rover (MER) mission operations, the flying camera view became the primary visualization and interaction mechanism. However, the image based stereo display was still a critical component of the tool as it gave a complementary view of the environment that better fit the operator's natural way of comprehending the Martian terrain.

The stereo view for MER left something to be desired so its implementation was thoroughly reworked to support the Mars Science Laboratory (MSL) mission. The new implementation was layered on top of a new graphics library and utilized different interaction modes to achieve a significantly better visualization experience. This new implementation better supports multiple images with on-the-fly mosaicking to allow panning within the entire field of view of the imaging instruments.

2 COMPARISON OF IMAGE BASED STEREO AND RENDERED MODES FOR OPERATIONS

From the time of the Pathfinder mission, the mission operations tools have included both an image based stereo visualization capability and a flying camera tool for viewing polygonal terrain models [1]. All the JPL rovers have carried stereo cameras for imaging the in-situ environment and have returned the stereo imagery to Earth. Processing of the stereo image pairs using a correlation algorithm results in range data, XYZ position data, and eventually textured polygonal terrain meshes and digital elevation models (DEM) [2,3]. The image based stereo tool displays the left-right stereo pair on the screen using quad-buffering and LCD shutter glasses and then overlays onto these image pairs rendered imagery using augmented reality techniques. The flying camera tool loads the terrain mesh for visualization and the DEM for modeling interactions between the rover wheels and the terrain. The user switches back and forth between the views as desired.

In one sense, the flying camera view (see Figure 1) should provide all the information necessary for planning mission operations. The terrain's shape is represented by the polygonal mesh being visualized and the underlying DEM. The captured images are overlaid as texture maps onto the mesh to provide the necessary visual cues. Rover interactions with the terrain can be viewed from any angle as closely as desired. A simplified CAD model of the rover is present in the visualization and the motions of the wheels as they drive over rocks are represented as well as other ancillary glyphs such as tracks, targets, and measurement tools.

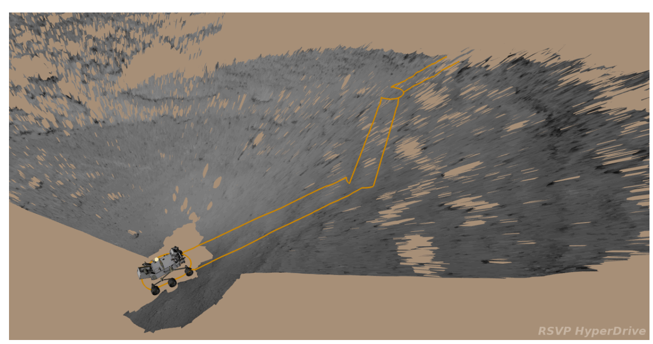

Figure 1: Figure 1. MSL "Flying Camera" visualization

However, the image based stereo view can provide a view of the terrain that is superior to that of the rendered view in some respects. In the earliest implementations of the system, the texture memory could not hold a full resolution version of the original image to map onto the polygonal terrain mesh. Thus, the view of the mesh was always degraded as compared to the stereo view that displays the images at their full resolution. In addition, the correlation software that produces the position data for the polygonal meshes is still not as good as the human visual system

* frank.hartman@jpl.nasa.gov

at resolving edges and low texture features when building the meshes. Small ridgelines that are invisible in a monoscopic image become obvious when viewed in stereo. Since these ridgelines obscure regions of the terrain that are unknown, the rover cannot be allowed to traverse through these regions due to lack of information about hazards. Understanding this subtle geometry is a key to safely commanding the vehicle.

The correlation process generally locates such ridgelines successfully and easily displays the hidden regions, or rather the holes in the mesh that correspond to each hidden region, so safe traverses can be planned around the unknown regions within the flying camera view. However, correlation does have a problem with regions of uniform texture such as sand pits and dunes. Sometimes a hole in the mesh is just such a region and visual inspection using the stereo view shows the region to be safe to traverse.

The image based stereo view does have one significant disadvantage over the flying camera. When viewing a stereo pair of images, it is often difficult to estimate distances. This is primarily due to the difference in separation of the cameras as compared to human eyes and the difference in height above the ground. Thus, it is difficult to determine if the rover can fit between two rocks at different distances from the original camera position. The flying camera view makes it trivial to make such determinations by moving the rover model to the region of the mesh between the two rocks and measurement tools are provided to allow measurements such as these.

3 Past and Current Missions

Over the course of the Martian surface missions, comprised of four rovers, both the visualization hardware and software has undergone many changes. What was possible only for high end graphics workstations in the early years was readily achievable with commodity class Linux hardware more recently. As the experience base of operating planetary rovers remotely grew over the years, the software tools were revised to better reflect the best operational practices and operator preferences. Many thousands of Martian days (sols) worth of command sequencing have generated countless lessons learned that have been incorporated into the ongoing evolution of this line of software. The following sections consider this evolution in somewhat more detail.

3.1 Rover Control Workstation for Mars Pathfinder

The Rover Control Workstation (RCW) was the original mission operations tool for commanding the Sojourner rover on the Mars Pathfinder mission. The image based stereo viewing tool was named CARD (from an earlier earth based Computer Aided Remote Driving project) and it provided quad-buffer stereo with liquid-crystal shutter glasses at a high frame rate to minimize flicker. See Figure 2 for a view of a rendered Sojourner rover overlaid onto camera imagery collected in the JPL test-bed.

Figure 2: CARD view of Sojourner Rover in the test-bed.

The original CARD view was only able to be run on Silicon Graphics Reality Engine class hardware and as can be seen in the figure, only a fixed number of images could be viewed in a pre-defined 2 row by 3 column layout. Each cell of the image matrix represented a distinct perspective projection completely separate from any adjoining cell. Despite these limitations, stereographic viewing of the imagery returned from Mars immediately proved essential in gaining correct situational awareness of the vehicles condition. After landing on Mars, the Sojourner rover was positioned on one of the petals of the Pathfinder lander's deck and in order to reach the surface it was necessary to drive the rover down one of two ramps located on either side of the petal. Thus there was an immediate decision to be made - which ramp to drive down. Viewed in the monoscopic imagery both ramps seems equally good and the choice inconsequential (See Figure 3.) Upon viewing the imagery in stereo however it became clear the left ramp pictured was positioned well above the terrain, and was in fact akin to a "diving board." This configuration, while obvious in the stereo imagery was not apparent when viewing only a single image and could have resulted in an early end to the Sojourner rover's mission.

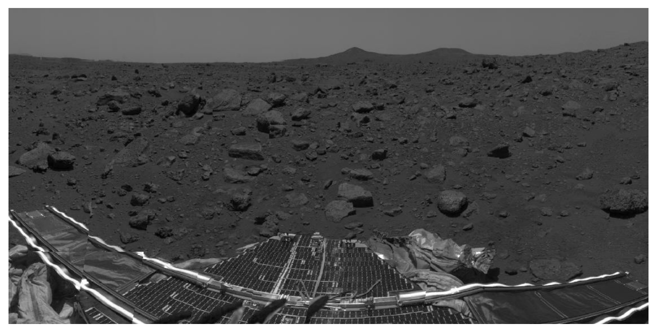

Figure 3: The "diving board" from Mars Pathfinder

3.2 Card View for the Mars Exploration Rovers

The RCW software was completely re-implemented for the MER missions and renamed the Rover Sequencing and Visualization Program (RSVP) [4,5]. Its visualization capabilities were based on the OpenGL Performer graphics library, and originally developed on and for high-end workstations from Silicon Graphics, Inc. Shortly before the mission however, commodity Linux-based workstations with graphics cards were released with OpenGL Performer and OpenGL libraries that supported quad-buffer stereo. After experimentation showed that these systems were able to support the 3D stereo modes utilized for mission operations, the development was switched over and several systems were acquired for development and operations.

The basic mechanism for stereo display in this iteration of the tool was termed "bug's eye" view. Each stereo image pair is still attached to a unique virtual perspective camera for the purpose of rendering the synthetic graphics onto the camera imagery just as in the earlier RCW software. Here, instead of a fixed 2x3 matrix of images a 2D canvas is provided by the graphics library and each perspective camera is allowed to draw onto this canvas. This allows somewhat greater flexibility than the fixed matrix. The term "bug's eye" was used to capture the fact of a compound image comprised of individual perspective projections.

This mechanism works fine for a single stereo pair and is often used in that mode. However, sometimes a planned rover traverse crosses the field of view of multiple images. In this mode, an individual camera and viewport is defined for each stereo pair.

The viewports cannot overlap in screen space so displaying multiple pairs is done with a rectangular array of viewports. This requires that the specified number of pairs to display must be 1, 2, 4, 6, or 9. No other arrangements are allowed. In addition, because the viewports and associated cameras are positioned relative to the camera that actually took the images, and that moved between stereo pairs, the viewports do not align well. An example of this is displayed in Figure 4.

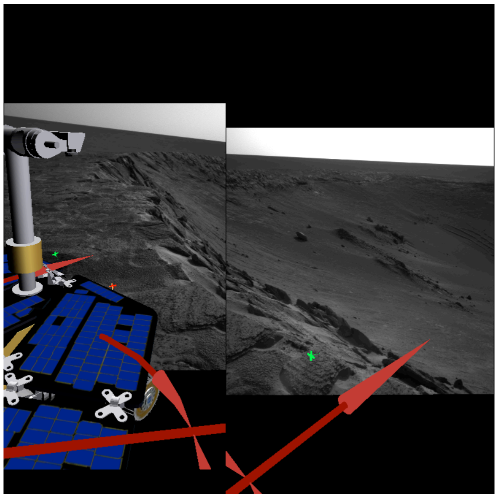

Figure 4: CARD view of Opportunity Rover, sol 124.

3.3 Qard View for the Mars Science Laboratory

RSVP for the MSL mission was again revamped from the MER version [6]. The underlying graphics library was replaced with Open Inventor and the GUI toolkit was replaced with Qt. The Card tool was completely re-implemented and renamed Qard. The intent of Qard was to eliminate the viewports and provide seamless stereo viewing of multiple left/right image pairs at once.

The implementation of Qard utilizes a single viewer for all the stereo pairs. Each image of a stereo pair is projected as a texture map onto a billboard located beyond the expected distance of any actual geometry. The left and right eye quads are stored in separate sub-graphs of the Open Inventor scene graph. The terrain is stored in another separate sub-graph and the rover model, glyphs, targets, tracks, and other visual elements are stored in a third sub-graph. Then one higher-level graph includes the billboard sub-graphs and the other elements and a second higher-level graph contains the terrains and the other elements. Thus, the polygonal terrain meshes are not visible in the stereo Qard window and the image billboards are not visible in the rendered flying camera window.

When rendering to the stereo view window, a function detects the left/right flag when in stereo mode and alternately enables and disables each side's sub-graph so that only the appropriate quads are displayed. The LCD shutter glasses are synced to the rendering of the appropriate sub-graph. The rendering library also provides easy methods to render the stereo view using red/blue anaglyph or other less common stereo hardware such as lenticular screens etc.

For a single stereo pair, the left and right virtual camera positions match the locations of the actual cameras on the rover. The camera models associated with each image contain the position and pointing of each side of the camera pair. Then the Inventor cameras are positioned at the same location for rendering the scene graph containing the billboard for that eye and the other visual elements.

However, the camera positions for one single stereo pair are not correct for another different pair that are part of a mosaic shot at a single rover location. The rover's articulating mast head rotates in both azimuth and elevation moving both the left and right eye cameras to different positions for each stereo pair in a larger panorama. When displaying multiple stereo pairs, a single pair of camera positions must be chosen for rendering the entire set of a larger mosaic. Multiple methods were implemented to provide an optimal display for the user.

The first virtual camera positioning method is designed to provide best support for panning and zooming within a mosaic of stereo pairs. Basically, it interpolates between the nearest images to the viewing window boresight. If the boresight passes through the center of a particular stereo pair, the camera locations for rendering are coincident with the camera positions of that pair of images. As the user pans left-right or up-down, the tool interpolates between the image camera positions closest to the boresight and locates the rendering cameras at the interpolated locations. This method provides optimal rendering of the image nearest the center of the display.

A second method locks the camera positions to that of a selected image pair. Some users prefer to have a list of stereo pairs and manually select the pair of interest rather than panning and zooming the display interactively. This mode optimally renders the 3D stereo of the selected pair at the expense of other pairs in the vicinity.

A third method locks the camera up vectors to the gravity vector of the location of the rover. This method provides the capability of viewing all the images with a level horizon. The other methods all display relative to the rover's orientation so a tilted rover causes a tilted horizon. However, this method does not maintain the proper epipolar alignment of scan lines within the display so 3D viewing is more difficult.

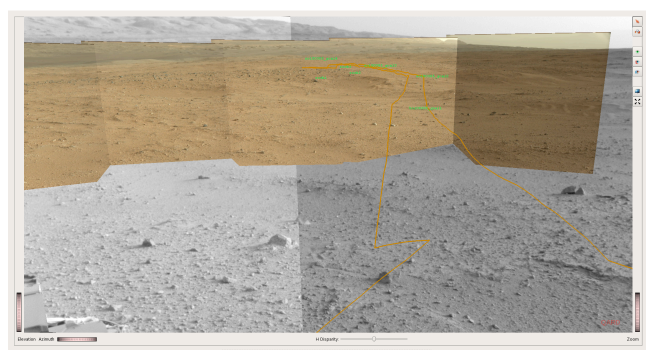

Figure 5: Qard view for MSL showing the planned sol 385 drive overlaid onto both Navcam and color Mastcam images.

In all cases when displaying multiple image pairs, using a single virtual camera to represent several independent perspective cameras causes some distortion in both the placement of the overlay of rendered graphics and in the epipolar alignment of the underlying stereo imagery. In practice, the misalignment in position is negligible at the scale of interest but the epipolar misalignment does cause difficulty in stereo viewing near the edge of the displayed combined imagery. It is believed that by employing a modified projection rather than the standard OpenGL perspective projection this difficulty may be eliminated. This will be an area of continued research.

4 Future Missions

At least two upcoming JPL planetary missions are expected to utilize RSVP for performing mission operations. The proposed Mars 2020 mission would be a rover similar to MSL's Curiosity. It would feature similar stereo cameras and overall the visualization toolset for utilizing it's imagery for rover commanding would generally be similar. The other, more challenging, mission in terms of visualization is InSight. InSight is a lander with an arm somewhat similar to JPL's Phoenix lander. InSight is planned to study the interior of Mars with a seismometer and other deployable instruments. One unique aspect of InSight is that the arm will be used to pick up instruments initially located on the deck of the lander and place them on the ground. Another, more relevant, aspect is that the lander does not have stereo cameras. Instead, it has a single camera mounted on the arm. To acquire stereo images, the arm must be moved from one stereo location to the other.

The InSight arm has four degrees of freedom. Acquiring stereo images by moving the arm from one position to the other results in significant rotation of the camera. For comfortable 3D stereo viewing, the images must be linearized such that the scan lines in the left and right images are epipolar aligned. The linearization process causes the actual image data to occupy only a fraction of the epipolar aligned image space. Viewing a single linearized stereo pair of images works fairly well. However, when attempting to view multiple stereo pairs at one time within the Qard tool becomes problematic. See Figure 6 as an example.

One facet of moving the camera from the left eye position to the right eye position is that the right eye position can become the left eye of another stereo pair. However, the stereo offset is generally less than the desired pair separation as the camera FOV is relatively large (around 45 degrees). The left and right eye views should overlap by a large percentage in order to maximize the correlation region but the stereo pairs and the resulting meshes and DEMs should have a smaller percentage of overlap to minimize the bandwidth required to return the total set of images to Earth.

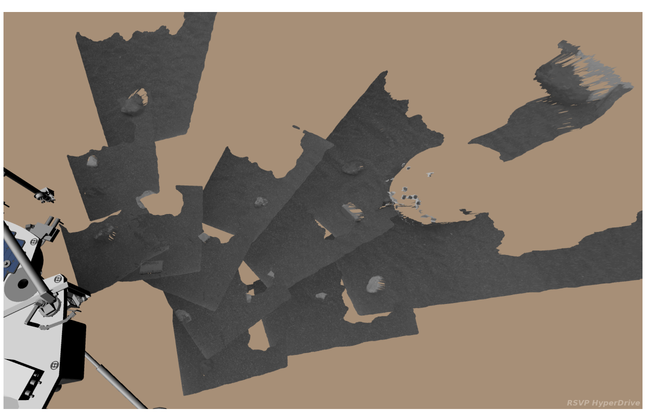

Figure 6: INSIGHT lander view using arm mounted camera imagery.

5 Conclusion

The image based stereo viewing capability of the mission operations tools over the generations has provided an important complementary capability to the rendered flying camera view with polygonal terrain models for safe and successful rover operations on the surface of Mars. The capabilities of the tools have increased through improvements in graphics hardware and software as well as updated use methodologies. These provide the rover operators with a clear view of the terrain in the vicinity of the rover to enable the construction of an accurate mental model of hazards and optimal paths. The improved understanding of the terrain has enabled greater science return from the missions through safer driving over greater distances than previous missions could support. The complete suite of tools brings all the needed capability together to support the operator's needs.

Acknowledgments

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