3D Visualization for Phoenix Mars Lander Science Operations

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Abstract - *Planetary surface exploration missions present considerable operational challenges in the form of substantial communication delays, limited communication windows, and limited communication bandwidth. To productively operate a remote robotic probe from Earth requires scientists and engineers to quickly synthesize an understanding of the remote site. Of particular value in this regard are visualization and simulation tools that improve situational awareness and science understanding. In this paper we describe 3D visualization software developed by NASA Ames Research Center and delivered to the 2008 Phoenix Mars Lander mission to enhance science operations productivity. The components of the system include an interactive 3D visualization environment, "Mercator," terrain reconstruction software, the "Ames Stereo Pipeline", and a server providing distributed access to terrain models. The software was successfully utilized during the mission for science analysis, site understanding, and science operations activity planning. We elaborate the capabilities of the components and how they relate to other mission tools.*

Keywords: Phoenix Mars Lander mission, 3D visualization, simulation, terrain reconstruction, automated stereo image processing, 3D modeling, 3D rendering, planetary science, planetary exploration.

1 Introduction

The Phoenix Mars Lander (PML) mission landed a robotic spacecraft in the north polar region of Mars on May 25, 2008 to investigate the history of water in the region and the potential for biological activity. The lander incorporates a number of scientific instruments, sensors and mechanisms including: the Robotic Arm (RA) for acquiring soil samples, the Robotic Arm Camera (RAC) for close-up examination of soil samples, and the Surface Stereo Imager (SSI) science camera for imaging the RA sampling area and surrounding landing site. To operate the lander from Earth required scientists and engineers to synthesize an understanding of its state and the remote environment from sensor and science instrument data. Compounding the difficulty of operations is the approximately 15 minute communications time delay due to the distance between Earth and Mars, and the limited high-bandwidth communication windows to relay satellites orbiting Mars. In this operational regime, careful offline planning of activities is necessary to mitigate risk and enhance productivity. Of particular value are visualization and simulation tools that enhance situational awareness and site understanding. To this end, the NASA Ames Research Center (ARC) provided the PML science team with 3D visualization software for site understanding and science activity planning.

The ARC 3D visualization software is comprised of two principal components: an interactive 3D visualization environment, called "Mercator", and a stereo correlation based terrain reconstruction implementation called the "Ames Stereo Pipeline." In addition, a "terrain server" was implemented which provided distribution of terrain models from a central repository to clients running the Mercator software. The Ames Stereo Pipeline was originally developed for the Mars Pathfinder (MPF) mission [1] and was subsequently provided to the Mars Polar Lander (MPL) mission and Mars Exploration Rover (MER) mission science teams. The Ames Stereo Pipeline generates accurate, high-resolution, texture-mapped, 3D terrain models from stereo image pairs. These terrain models can then be visualized within the Mercator environment. Although first deployed in a mission setting for PML, Mercator leverages ARC experience developing the "MarsMap" and "Viz" 3D planetary exploration visualization environments provided to the MPF, MPL, and MER mission science teams [2].

The central crosscutting goal for these tools is to provide an easy to use, high quality, full-featured visualization environment that enhances the mission science team's ability to develop low risk productive science activity plans. In addition, for the Mercator and Viz visualization environments, extensibility and adaptability to different missions and application areas are key design goals. Mercator and Viz have both been used for ARC rover field tests as well as missions, and Mercator has been adapted to a variety of application areas including atmospheric visualization and flight planning.

2 Mercator

Mercator is a cross-platform, adaptable, extensible, interactive 3D visualization software tool that enables users to manipulate and interrogate a simulated 3D environment. It is implemented in the "Java" programming language within "Ensemble", a NASA-developed ground data systems software component framework based on the "Eclipse" open source platform. Designed as a general-purpose visualization tool, Mercator was adapted for the PML mission to simulate lander operations, utilize PML data products, and interface with PML science operations ground data systems. Mercator provided the PML science team with capabilities for enhanced science understanding, and a 3D environment for the conceptual design of science activities. Mercator implemented the following functionality for the PML mission:

- Visualization of an articulated 3D lander model in context with terrain models generated from SSI or RAC images.
- Interactive time of day lighting and shadow simulation.
- Interactive RA and SSI pose simulation, with joint angle feedback.
- Synthetic camera views and camera frustum visualizations for the SSI and RAC.
- An RA reachability map overlay.
- Simulated RA trenching.
- Science analysis and site understanding tools including location and distance measurement, terrain profiles, and polar and Cartesian grids.
- Automated determination of SSI pan/tilt angles necessary to image a user specified location.
- False color-coding of terrain models by elevation.
- Visualization of science "targets" (named 3D locations or directions used in planning arm activities).
- A terrain model browser/catalog.

The Mercator User Interface (UI) is divided into a number of tiles or "elements" presenting control panels and views into the 3D scene (see Figure 1). The central UI element is an interactive 3D viewer with site interrogation and analysis capabilities. By default, a tabbed UI element with panels for controlling the 3D terrain model rendering and the simulated lander appears on the left side of the Mercator window, and on the right are UI elements presenting simulated views from the SSI and RAC cameras. At the bottom of the Mercator window are UI elements presenting additional output such as terrain profile graphs and status messages. Each UI element can be repositioned, resized, iconified, or dragged out of the window frame.

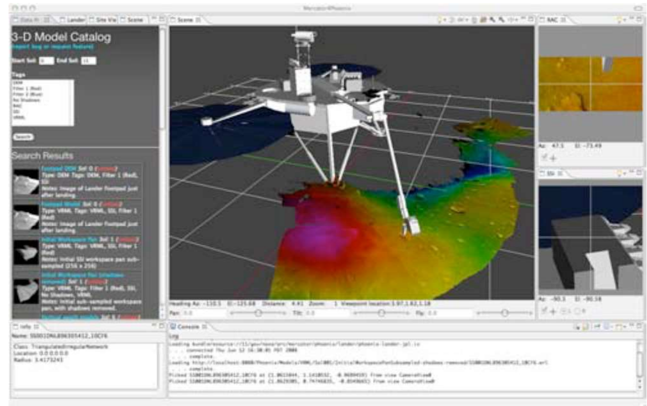


Figure 1. The Mercator 3D visualization environment with simulated Phoenix lander and a terrain model, false color coded by elevation (Lander model credit: NASA/JPL).

The 3D viewer UI element (see Figure 2) provides an interactive environment for site understanding and conceptual planning of science operations.

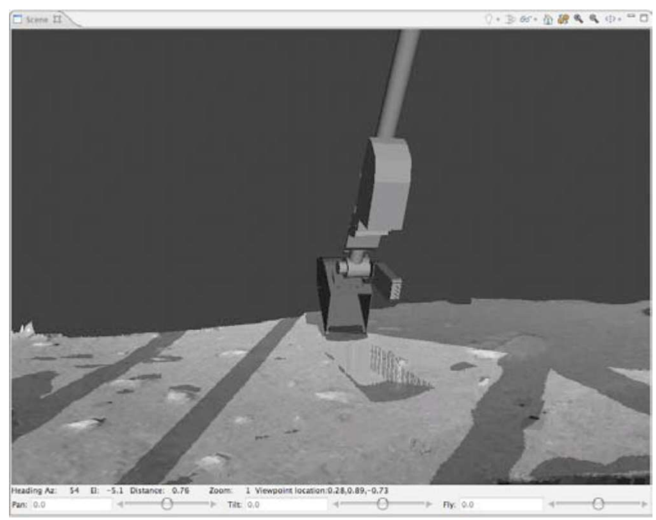


Figure 2. The Mercator interactive 3D viewer with time of day shadows enabled and a simulated trench shown.

In an effort to achieve simple natural interactions, object oriented, direct manipulation techniques were chosen where practical, and persistent user interface "modes" were minimized. For example, to measure distances the user manipulates a 3D representation of a measuring tool in the scene (see Figure 3). There is no explicit mode for measurement, and the user can continue to interact with the 3D environment (e.g., changing the viewpoint) as usual.

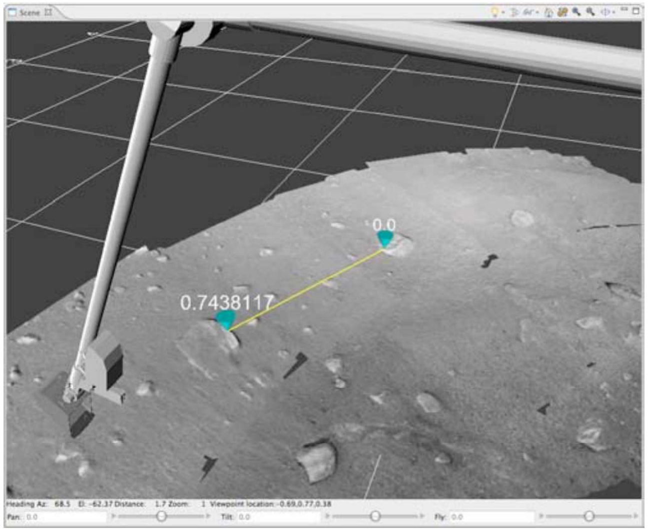


Figure 3. The distance measurement tool in the 3D viewer. The end markers of the tool follow the surface and can be directly positioned with mouse and cursor.

In addition to lander and terrain models, the location of science targets can be displayed in the 3D scene with markers (see Figure 4).

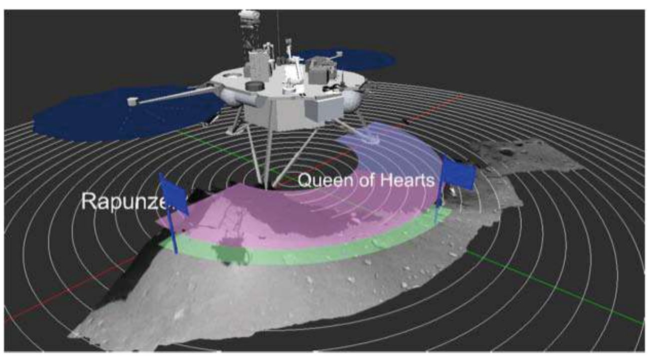


Figure 4. The 3D viewer showing named science targets, reachability map overlay, and polar grid.

To the right of the interactive 3D viewer, two smaller views onto the 3D scene display simulated views from the SSI and RAC cameras (see Figure 5). These views interactively update based on the pointing direction of the SSI and RAC (and the focus distance in the case of the RAC), but cannot otherwise be directly manipulated by the user.

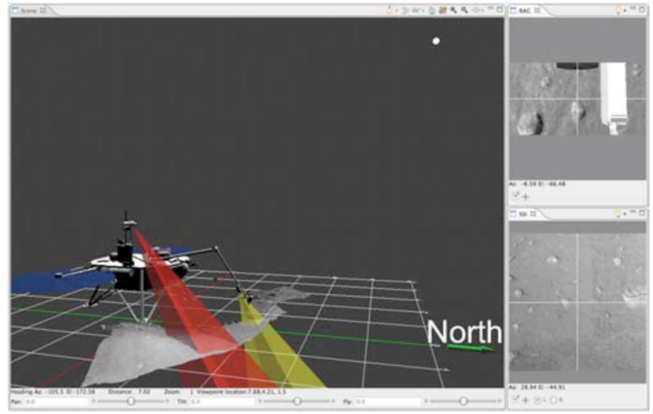
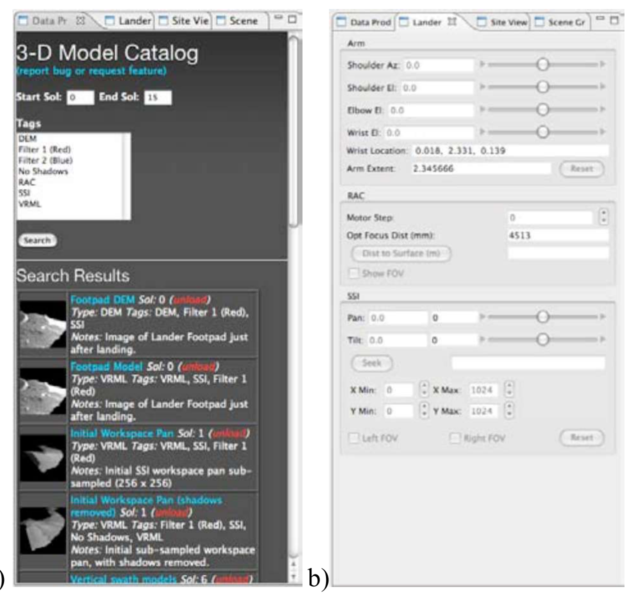


Figure 5. The 3D viewer together with simulated RAC and SSI camera view UI elements. The 3D viewer is displaying RAC and left SSI camera view frustums as well as a glyph (upper right) indicating the location of the sun.

The tabbed panels on the left side of the Mercator UI provide a terrain model data browser and a lander control panel (see Figure 6), as well as a hierarchical schematic representation of the 3D scene, and a panel for controlling various 3D viewing conditions including time of day lighting and shadow simulation settings.



a) b)

Figure 6. Mercator tabbed UI element. a) terrain model browser panel, b) lander control panel.

The data browser panel provides an interface to a database of terrain models that the user can search based on a number of criteria including the “Sol” (the number of Martian days since landing), camera, and filter number associated with the original source images used to construct the model.

3 Surface Reconstruction

The Ames Stereo Pipeline implements a fast 3D-from-stereo capability for automatically producing accurate, high-resolution, texture-mapped, 3D terrain models. This capability was used during PML operations to generate terrain models for visualization in the Mercator environment. The Stereo Pipeline determines 3D location based on parallax present in an overlapping pair of images (a "stereo-pair") taken from slightly different viewpoints. Utilizing an area correlation method, corresponding points are matched in a stereo-pair and their difference in position due to parallax, their "disparity", is used to determine their 3D location. Once a set of 3D points is determined for a given stereo-pair, a triangle mesh is constructed with the points as vertices, and one of the images from the stereo pair is mapped onto the mesh for the purposes of visualization. The Ames Stereo Pipeline implements a variety of optional pre-processing and post-processing stages for increased robustness, noise reduction, and terrain model optimization. As input, the Stereo Pipeline utilized calibrated, rectified SSI images provided by the Jet Propulsion Laboratory's (JPL) Multi-Mission Image Processing Laboratory (MIPL). A schematic diagram illustrating the various processing steps implemented by the Stereo Pipeline is shown in Figure 7.

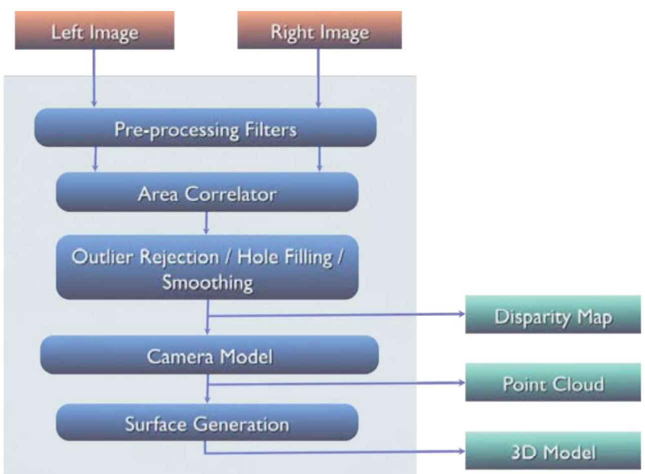


Figure 7. Ames Stereo Pipeline data flow diagram.

An example terrain model generated for the PML mission from approximately 20 stereo image pairs is shown in Figure 8.

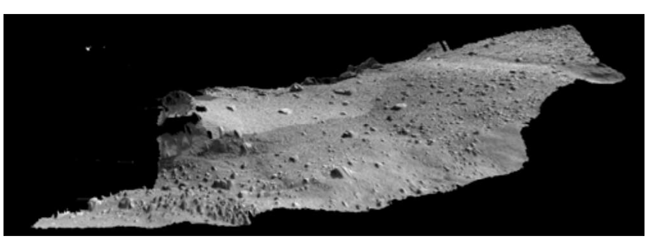


Figure 8. A composite 3D terrain model of the RA sample acquisition area generated by the Ames Stereo Pipeline.

3.1 Terrain Server

NASA ARC deployed a terrain server at the PML Science Operations Center (SOC) for generation and distribution of 3D terrain models to Mercator clients running on SOC workstations. Generated terrain models were distributed via HTTP services running on the server. Mercator clients provided users with a data browser view that displayed all models available on the terrain server. In addition to terrain models, the terrain server distributed science targets to Mercator clients. The terrain server interfaces with the PML SOC "ROME" database for access to images used for terrain model generation and access to science targets. A schematic diagram of the overall data flow from source images to rendered terrain models is shown in Figure 9.

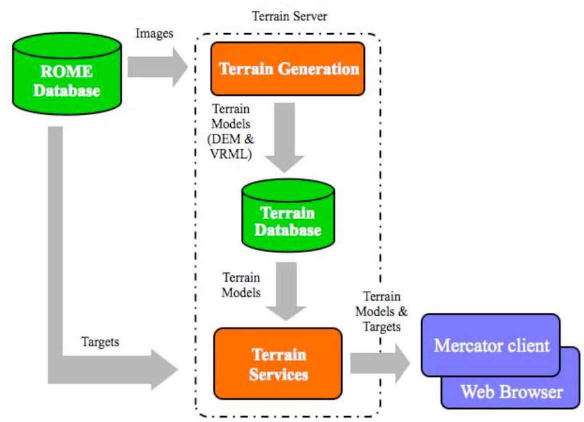


Figure 9. Overview of ARC 3D visualization data flow.

4 Discussion

The ARC 3D visualization software described above was provided to the PML science team as a mission enhancement, augmenting baseline PML Ground Data Systems (GDS) capabilities. With respect to visualization, these baseline capabilities were primarily realized in the form of the Phoenix Science Interface (PSI) and the Rover Sequencing and Visualization Program (RSVP). Both of these GDS software tools addressed the need for good visualization during mission operations, and PSI was the primary tool used for developing science operations activity plans. However, PSI's visualization capabilities are limited to 2D, and RSVP's primary focus is lander engineering operations – i.e., *how* to implement a desired science activity. The ARC tools are focused on providing a highly functional 3D environment that helps scientists decide *what* they want to do.

The Mercator visualization environment provided a number of capabilities not present in PSI or readily accessible to the science team in other tools, including:

- Shadow simulation in an interactive 3D environment with terrain self-shadowing.
- Simulated SSI and RAC camera views, and camera view frustum visualizations.
- Simulated trenching for conceptual planning of RA operations.

Based on informal observation of the science team during mission operations, the most widely used and valued capabilities were the shadow and camera view simulation functionality.

Due to overall Phoenix mission cost uncertainties, funding for ARC tool development was not released until very late in the mission, and was done so at a reduced level. As a result, not all of the originally envisioned functionality was implemented.

Limitations to originally desired Mercator functionality and design include:

- Lack of tight integration with PSI:
  - Two distinct executable programs to run.
  - No tie-in to PSI's plan timeline functionality (enabling 3D visualization of a science activity plan over time).
  - No capability to create or define science targets in Mercator.
- No RA inverse kinematics (supports ability to directly drag the RA scoop to a desired location).
- Reduced extent of science analysis tools, e.g., no tools to quickly determine mound volume or terrain "strike" and "dip."

As alluded to in preceding sections, one of the design goals for the Mercator UI, and the 3D viewer in particular, was to achieve a degree of interaction simplicity suited to a broad range of computer literacy and experience. To that end, well-known Human Computer Interaction (HCI) approaches to improved ease of use were followed, including an emphasis on direct manipulation techniques, and minimization of the number of persistent interaction modes. The development team also worked directly with PML scientists to determine capabilities that were important to the team.

The ARC terrain generation tools provided to the science team were in some ways redundant to MIPL terrain generation capabilities – the ARC stereo correlation algorithms and terrain model products are similar to MIPL's. However, the ARC tools are tuned for the purposes of science visualization rather than lander engineering operations. The ARC stereo pipeline provides a number of optional pre-processing and post-processing stages that serve to reduce noise and interpolate areas of failed stereo correlation. While perhaps more risky from an engineering operations standpoint, this approach provides a more coherent visualization of the surrounding terrain.

The ARC deployed terrain server provided a simple mechanism to query and access 3D terrain models generated by the ARC tools both from within the PML SOC and remotely from scientist's home institutions. Due to the limited development time available, capabilities such as local caching of terrain models, and multi-resolution representations for improved initial loading time were not implemented. However, because of the relatively limited extent of the terrain models, and high bandwidth networking, this did not significantly affect usability.

5 Conclusions

NASA ARC provided the PML mission science team with an enhanced 3D visualization capability for science operations. The ARC system provided support for both local and distributed access to 3D terrain models. The Mercator interactive 3D visualization environment represents the first implementation of 3D visualization capabilities within the NASA Ensemble GDS software framework to be deployed in a planetary mission science operations setting. These capabilities were successfully utilized during the PML mission for science analysis, site understanding, and science operations activity planning.

Acknowledgment

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