Mapping Mars Using Virtual Reality: The Pathfinder Experience

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Photo-Realistic Terrain Modeling
Objectives

1. Automatically generate photo-realistic terrain models at downlink rate and with low latency

2. Validate the use of virtual reality interfaces for science analysis and day to day mission planning

- Remote Processing of the Data at NASA Ames (limited space at SFOF)
- Turn around time under 30 minutes
- Render the models at frame rate allowing real time user interaction

Clients

- Pathfinder Scientists
- Mission controllers and rover operators
- Low Resolution VRML Models Available to the General Public via the Internet
- Public Outreach
The Stereo Pipeline

Preprocessing
- Crop and Scale Original Stereo Images
- Calibrate and Process Image Intensity
- Align Left/Right Images

3 Pass Cross-Correlation
- 1st Pass: Bound Disparity Range
- 2nd Pass: Rough Pixel Disparity Value
- 3rd Pass: Fine Pixel Disparity Value

Disparity Map Filtering
- Remove Outliers
- Extrapolate Missing Disp. Values
- Smooth Disparity Map
- Correct Map for Lens Aberations

Dotcloud Creation
- Compute Range from Disparity
- Compute X Y Z Pixel Position
- Change Reference Frame

Mesh Creation
- Create Regular Reference Grid
- Create Triangle Mesh
- Remove Long Edges
- Create and Reference Texture to Mesh

Original Stereo Images
- Preprocessed Images
- Raw Disparity Map
- Filtered Disparity Map
- Dotcloud
- 3D Mesh
- Texture
Network Data Flow

Deep Space Network

Multi Mission Image Processing Laboratory (MIPL)
File Exchange Interface (FEI)

Space Flight Operation Center
Virtual Reality Workstation

Jet Propulsion Laboratory
Pasadena, California

Spacecraft Network

WWW
VRML Models

Intelligent Mechanisms Group

ATM Link (T1)
Stereo Processing Workstation

NASA Ames Research Center
Moffett Field, California

Jet Propulsion Laboratory
Pasadena, California
Preprocessing Step

Raw stereo Pair

Rotational and vertical Alignment

Histogram Normalisation

Edge Enhancement

Convolution with:

\[
B = \begin{bmatrix}
-1 & -1 & 0 \\
-1 & 0 & 1 \\
0 & 1 & 1
\end{bmatrix}
\]

Where:

- \( I_o \): Output pixel intensity value [gray level]
- \( I_i \): Input pixel intensity value [gray level]
- \( G \): Number of gray levels [gray level]
- \( M \): Margin [gray levels]
- \( T_1 \): Gray level under which 1% of the pixel values are.
- \( T_2 \): Gray level under which 99% of the pixel values are.

\[
I_o = \frac{G - 2M}{T_2 - T_1}(I_i - T_1 + M)
\]
Correlation

\[ \text{Correlation} = \text{SOAD} (d) \]

Cross-correlation

Reference Kernel

Sliding Kernel

Valid Match
Left Image

Non-valid Match
Right Image

\[ \begin{array}{c|c|c}
\text{Valid Match} & \text{Non-valid Match} \\
\hline
\text{Left Image} & 1 & 2 & 1 & 3 & 2 \\
\end{array} \]
Correlation and Disparity Map

Correlation

- Texture-based correlation
- Sum-of-Absolute-Differences correlation algorithm
- Correlation and cross-correlation to remove wrong matches

Filtering

- Subpixel approximation
- Outliers removal
- Adaptative gap filling
- Smoothing
- Lens abberation correction
Mesh Reconstruction

Disparity Map

Range Map

Coordinate Transform:
Camera frame → Lander Frame

Dotcloud
(Lander Frame)

Wireframe Mesh
Texture Overlay

Original texture from the left image of the stereo pair (created automatically)

Color texture created manually from the Gallery Pan Images

Color coded elevation (mars local level) created automatically by the Stereo Pipeline
Calibration of the Terrain Models

- Survey of 150 rock and ground feature positions in the Mars Garden at the University Of Arizona.
- Imaging and removal of the markers.
- Acquisition of the stereo datasets.
- Generation of the terrain models.
- Comparison between survey data and terrain models (51 positions compared)
Calibration and Accuracy: Results

On a sample of 51 points ranging between 2 and 10 meters from the camera:

- 33% are within 1% of their surveyed position
- 89% are within 2% of their surveyed position
- 98% are within 5% of their surveyed position

<table>
<thead>
<tr>
<th>Distance From Camera [m]</th>
<th>Average Error in Position</th>
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</thead>
<tbody>
<tr>
<td>2-3</td>
<td>1.3%</td>
</tr>
<tr>
<td>3-4</td>
<td>1.7%</td>
</tr>
<tr>
<td>4-5</td>
<td>1.6%</td>
</tr>
<tr>
<td>5-6</td>
<td>2.6%</td>
</tr>
<tr>
<td>6-7</td>
<td>2.0%</td>
</tr>
<tr>
<td>7-8</td>
<td>3.2%</td>
</tr>
<tr>
<td>8-9</td>
<td>1.4%</td>
</tr>
<tr>
<td>9-10</td>
<td>3.2%</td>
</tr>
</tbody>
</table>
Factors affecting the Model accuracy

Terrain Related
- Nature and geometry of the terrain.
- Distance from the camera.

Data Related
- Pointing error of the camera
- Image scale
- Image quality and camera parameters characterization

Processing Related
- Correlation algorithm (pixel artifacts and kernel size)
- Meshing algorithm
VR Interface: Marsmap
### Marsmap Utilization for MPF

#### Science Analysis
- Rock measurements
- Direction of wind streaks
- Topographical ridges and flow channels

#### Mission Operation and Planning
- Rover ramp deployment
- IMP pointing coordinates
- Long range Sojourner path planning

#### Data Archiving
- End of Day Rover positions
- Sojourner science experiments
- Rock locations and sizes

#### Outreach
- JPL-SFOF / NASA Ames demos and tours
- Virtual Mars on the World Wide Web (VRML)
Measurements

Point 1 (Mars Local-level Coords) (x,y,z): ( -4.61, -1.89, -0.01) m
range: 2.49 m

Point 2 (Mars Local-level Coords) (x,y,z): ( -3.98, -2.32, -0.39) m
range: 4.62 m
distance: 2.44 m
Slope and Heading Angles

Slope = 1.62 deg  Heading = 305.18 deg
Image Billboards
Data Archiving
Conclusion

“IMG operational experience in Mars Pathfinder demonstrated that virtual reality interfaces displaying photo-realistic terrains were of tremendous value to scientists and rover operators”

- Allow to clearly visualize all relevant information
- Facilitate rapid interpretation and decision making

Technologies

- Improve correlator
- Mesh optimization and levels of details
- Merging terrain models taken from multiple vantage points
- Development of science and visualization tools
- Development of simulation and archiving tools

Ongoing and Future Projects

- Pioneer (mapping Chernobyl unit 4)
- Mars 98
- Mars 01