Challenges in Planetary Mapping and Surface Navigation

Ara Nefian
Navigation Challenges

- Lack of surface imagery
- Low gravity
- Terrain uncertainty impacts
  obstacle avoidance
  direct communication with Earth
  illumination conditions
- Lunar Polar reflectance conditions (albedo, reflectance models)
- Rock distribution
- Gaps in regolith and surface characterization
- Lunar temperature conditions
- Low computational complexity available
- Low power systems
- High radiation environment
Lunar Reflectance and Illumination

Lunar Lambertian Reflectance Model

\[ R = A\left[1 - L(\alpha)\cos(i) + 2L(\alpha)\frac{\cos(i)}{\cos(i) + \cos(e)}\right] \]

Incidence, emission and phase angles

Lunar Albedo

Solar Radiation Spectrum
Stereo Reconstruction from Orbital Imagery

Apollo Zone reconstructed color shade over Clementine imagery in Google Earth (left) and reconstructed oblique view of Apollo landing site (right).
Albedo Reconstruction

http://byss.arc.nasa.gov/oleg/albedo_04_09_2012/albedo_04_09_2012.kml

Apollo Zone reconstructed albedo over Clemntine imagery (Google Earth)
LOLA to Image Coregistration

Alignment of LOLA altimetry data to Apollo Imagery using the Lunar Lambertian reflectance model.
Planetary Rover Navigation

Orbital Terrain Mapping

Off board Localization Planning

On board Hazard Avoidance
On-board Navigation

- IMU
- Structure Light Projection and Image Acquisition
- Stereo Image Acquisition

- Wheel based Odometry
- Dots Segmentation and Triangulation
- Subframing/compression/packaging/transmission
- Onboard Pose Estimation
- Onboard Hazard Detection

- Sun/Star tracker

- Off board processing
  - Stereo, visual odometry horizon matching, path planning

- Localization and Hazard Detection Update

Monday, August 15, 16
Structured Light: Onboard Hazard Detection

“Virtual Bumper”
Uses projected dots
Triangulation
Structured Light: Onboard Hazard Detection

Ref Subtraction

Thresholding

Clustering

Filtering by Size

Decision
Structure Light Day Time with Color Filter
Structure Light at Night Time
Planetary Rover Navigation

- Orbital Terrain Mapping
- Off board Localization Planning
- On board Hazard Avoidance

Monday, August 15, 16
Impact on automatic localization for planetary rover missions

MSL mission localization through odometry is shown in purple lines in both top (top) and oblique (bottom) views.

The final partially automatic localization is shown by the rover panorama positions over the Gale crater HiRISE terrain.

The offset between odometry and final rover localization is generally of about 10-20m.

Fully or partially automatic localization using the system prototyped here will allow MSL and future missions for rapid turn around localization and support long traverse autonomous navigation.
Off board Localization System

wheel odometry and IMU

Visual Feature Extraction → Matching/ Homography →
3D pose estimation from visual matches

rover pose
rover terrain map

Joint Pose and Terrain estimation

Disparity to 3D pts

Image → Horizon detection

Image → Stereo

Orbital Map
Off board localization system

- Wheel odometry and IMU
- Visual Feature Extraction
- Matching/Homography
  - 3D pose estimation from visual matches
  - Rover pose
  - Rover terrain map
- Joint Pose and Terrain estimation
  - Orbital Map
- Image
  - Stereo
    - Disparity to 3D pts
  - Horizon detection
Stereo Processing

calibration package using OpenCV
block matching based disparity computation OpenCV
outlier rejection using morphological filtering
run time 6 fps
terrain reconstruction at 40m, 30cm baseline, 1388x1088 image size
Off board Localization System

wheel odometry and IMU

Visual Feature Extraction → Matching/Homography → 3D pose estimation from visual matches

rover pose → rover terrain map

Joint Pose and Terrain estimation

 orbital Map

Disparity to 3D pts

Image

Stereo

Horizon detection

Image
Stereo Visual Odometry

BRISK Visual Feature Matching.

SURF Visual Feature Matching.
Stereo Visual Odometry

Uses stereo reconstructed terrain.
Visual feature extraction SIFT, SURF, BRISK, ORB.
Descriptor matching using FLANN, homography based outlier detection (RANSAC).
Pairwise 3D pose estimation using stereo results.
3D outlier rejection
Running time: 8 fps (BRISK)

Mapping results of the stereo visual odometry system.
Off board Localization System

wheel odometry and IMU

Visual Feature Extraction → Matching/ Homography → 3D pose estimation from visual matches

Stereo Image → Disparity to 3D pts → rover pose

Image → Horizon detection

Joint Pose and Terrain estimation

Orbital Map
Horizon Detection

Real time horizon detection. Method for gray scale imagery to be used in various planetary environments. No training set imagery is used.
Horizon Detection

Edge detection

Block average (integral image)

Intensity and edge density pixel probability computation

Column probability computation

\[ P(O_{ij}|Q_{ij}) = \prod_{i=1}^{k} P(q_{ij} = s) \prod_{i=k+1}^{H} P(q_{ij} = g) \]

Left to right segmentation smoothing

Edge detection response.

Intensity and edge density pixel segmentation
Horizon Detection

Q_1 → Q_2 → Q_W

q_{11} → O_{11}
q_{12} → O_{12}
q_{1H} → O_{1H}
q_{21} → O_{21}
q_{22} → O_{22}
q_{2H} → O_{2H}
q_{W1} → O_{W1}
q_{W2} → O_{W2}
q_{WH} → O_{WH}
Horizon Rendering

rendered (red) horizon from rover pose and high res low coverage terrain

rendered (red) horizon from rover pose and high res low coverage + low res high coverage terrain

rendered rover view from rover pose and high res low coverage terrain

rendered rover view from rover pose and high res low coverage + low res high coverage terrain (red) terrain
Horizon Rendering and Matching

**Horizon Matching Cost Function**

\[ Q_h(R, T) = \sum_i (Hd_i - Hr_i(R, T))^2 \]

*i* is the image column

\(Hd_i, Hr_i\) are the rows corresponding to the detected and rendered horizon.

- multiple restart solution
- number of restarts increases over time to account for accumulated errors
- every 500 frames, <5s/frame.

\[ Conf(R, T) = \frac{Q_h(R, T)}{\sum_k Q_h(R_k, T_k)} \]

**Horizon Rendering**

Orbital Terrain Generation Ames Stereo Pipeline form Digital Globe Imagery 0.5m/pixel
Overlay over USGS Terrain models at 10m/pixel.
OpenGL or Mesa based solution for terrain rendering.
Localization Results

Localization errors wheel odometry (red) vs advanced navigation (blue)

Estimated traverse tracks over Basalt Hills area