Planetary Rover Absolute Localization by Combining Visual Odometry with Orbital Image Measurements

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Introduction

• Planetary exploration increasingly depends on planetary rovers

• Accurate localization is essential to planetary rovers

• This talk is concerned with increasing the accuracy of rover localization by employing images collected on the ground and from orbit

• Reported work was pursued in SEXTANT, an ESA-funded activity aiming to develop visual navigation algorithms suitable for use by ExoMars Martian rovers
Background

- Visual odometry (VO) is a technology that has been used with considerable success by Martian rovers (e.g., MERs and MSL)
- VO works by tracking natural features in successive images
- VO provides only relative pose estimates and suffers from drift that accumulates without bound over time
- Countering drift with techniques such as visual SLAM or local bundle adjustment, challenges the limited computational capacity of current rovers
- Non-visual sensors (e.g., IMU) can only reduce the rate of drift but do not eliminate it completely
Using prior knowledge

• Localization accuracy can be increased by using prior knowledge regarding the environment (e.g., maps)

• Orthorectified aerial images of planetary surface (aka orbital images) are nowadays available, e.g. Mars HiRISE / MRO

• Several “map”-based localization techniques tailored to terrestrial environments exist, employing features such roads, line segments and building footprints or sensors such as GPS only available on Earth

• Here we choose to use as features boulders which abound on Mars
Orbital and ground images differ dramatically in appearance!
Using boulders for localization

• We seek to extract boulders visible in the orbital images and match them to those seen in the ground images

• Two boulder detection pipelines, i.e. orbital – ground

• Boulder matching is the primary challenge; cannot be based on appearance cues such as local patch descriptors

• The relative geometric arrangement of boulders remains the same, thus their matching is based on geometry and strives to align constellations of ground and orbital boulders

• This provides absolute localization as the orbital boulder locations are determined offline in a cartographic system
Overview of the approach

• Boulders are extracted offline from orbital images and their locations are recorded

• Boulders are detected online in the ground stereo images acquired by the rover

• Ground boulders are combined with VO to build a local ground map with relative boulder positions

• The rover periodically matches its local ground map against the map originating from the orbital images

• Successful matching permits absolute pose refinement, thus accounting for drift
Visual odometry

- VO estimates the inter-frame camera motion
- Binocular camera system
- Harris corner detection
- SIFT descriptor extraction and matching
- Sparse stereo triangulation
- Pose determination from two matched 3D point clouds
Boulder detection

- Boulders have to be detected both in ground and orbital images
- Boulders differ with respect to their morphology, size, texture, color, etc.
- Shadows, changes in illumination and occlusions complicate things further
- Literature reports attempts to develop “boulder detectors” for ground images; these are not yet very reliable
- Boulder detection in orbital images is somewhat easier
Boulder detection: orbital images

- Image binarization with adaptive thresholding
- Noise reduction with median filtering
- Detection of boulders via connected components labeling
- Size filtering for eliminating very small components
- Boulder locations are computed from the centroids of detected regions; pixel coordinates then converted to cartographic coordinates
- Centroids are a coarse approximation of true boulder locations; this nevertheless suffices, as will be shown later
Boulder detection in orbital images example

Part of an orbital image (left) and the boulders detected in it
Boulder detection: ground images

- Ground images segmentation into boulders & ground
- Formation of boulder point clouds via 3D reconstruction and temporal matching
- Refinement of boulder point clouds via clustering
- Computation of boulder point cloud centroids
- Transformation of centroids to world origin using VO estimates
- Down-projection by dropping Z coordinates
- Local map update with the centroids of detected boulders
Ground boulder detection: segmentation

- Segmentation is based on the mean shift algorithm
- Small regions are ignored
- Performs reliably, suffers from over-segmentation
- Post-processing: neighboring regions are merged when they have similar intensity properties
- Triangulated points are also merged in 3D (more later)
Ground boulder detection: sparse reconstruction

Features extracted from segmented regions and matched in stereo are reconstructed in 3D to form point clouds.
Ground boulder detection: temporal matching

- Features extracted from segmented regions are also tracked over time and used to temporally match boulder regions.
- Points reconstructed from matching regions are presumed to be on the same boulder and are assigned to the same point cloud.
Ground boulder detection: clustering

Point clouds refined with agglomerative clustering
**Ground – orbital boulder matching**

- Key assumption: the rover knows its approximate location (i.e. the VO estimate can be trusted)

- Boulders extracted locally from the ground images are matched with the ICP algorithm against the overhead boulders located in the vicinity of the presumed rover location

- A byproduct of matching is the 2D transformation (Z-axis rotation and XY-axes translation) aligning the ground with the overhead boulders

- The VO estimate is refined with the 2D aligning transformation

- VO continues to estimate the relative displacement from the refined estimate

- The VO refinement is executed every few meters
Dataset for evaluation

• Graphically rendered images of a synthetic Mars-like environment *(courtesy GMV)*

• A stereo image sequence with accurate ground truth poses that corresponds to an S-shaped, 100m long traverse
  - Ground images are $512 \times 384$ pixels

• An orbital image with size $15360 \times 15360$, corresponding to an area of size $76.8 \times 76.8 \text{ m}^2$ (resolution: 0.005 m/pixel)
  - Orbital image consists of 236 Mpixels
  - Coarser resolutions generated by sub-sampling
Results: boulders extracted & matched

Ground boulders along the entire trajectory: 3D view (left) superimposed on orbital image (right)
• Red is the plain VO positional error in all frames of a 100m traverse

• Green, blue, cyan and magenta are resp. the results of the proposed method in orbital images of the original, 25%, 50% and 75% lower resolutions
Results: rotational accuracy

- Red is the plain VO rotational error in all frames of a 100m traverse
- Green, blue, cyan and magenta are resp. the results of the proposed method in orbital images of the original, 25%, 50% and 75% lower resolutions
Summary & conclusions

• Improving VO localization using boulders is a promising idea
  • A very terse representation consisting of only approximate 2D locations was shown to bring significant accuracy improvements
  • Same approach can potentially solve the “kidnapped robot” problem (substituting ICP with geometric hashing for matching)
  • More work on boulder detection and matching is needed
  • Testing on more datasets is also necessary

• Accuracy of localization corrections is limited by the resolution of the orbital image; they actually degrade performance at the beginning of the sequence

• Vertical displacements and out-of-plane rotations are not corrected; full 3D info necessary
Thank you

Any questions?
Schematic of the approach

Overhead Images → Orbital Boulder detection → Ground-Orbital image registration

Stereo Images → Visual Odometry → Ground Boulder Extraction → Pose correction
Ground – orbital boulder matching example

Ground boulders (blue) matched against ground ones (red)