Precise Image-Based Motion Estimation for Autonomous Small Body Exploration

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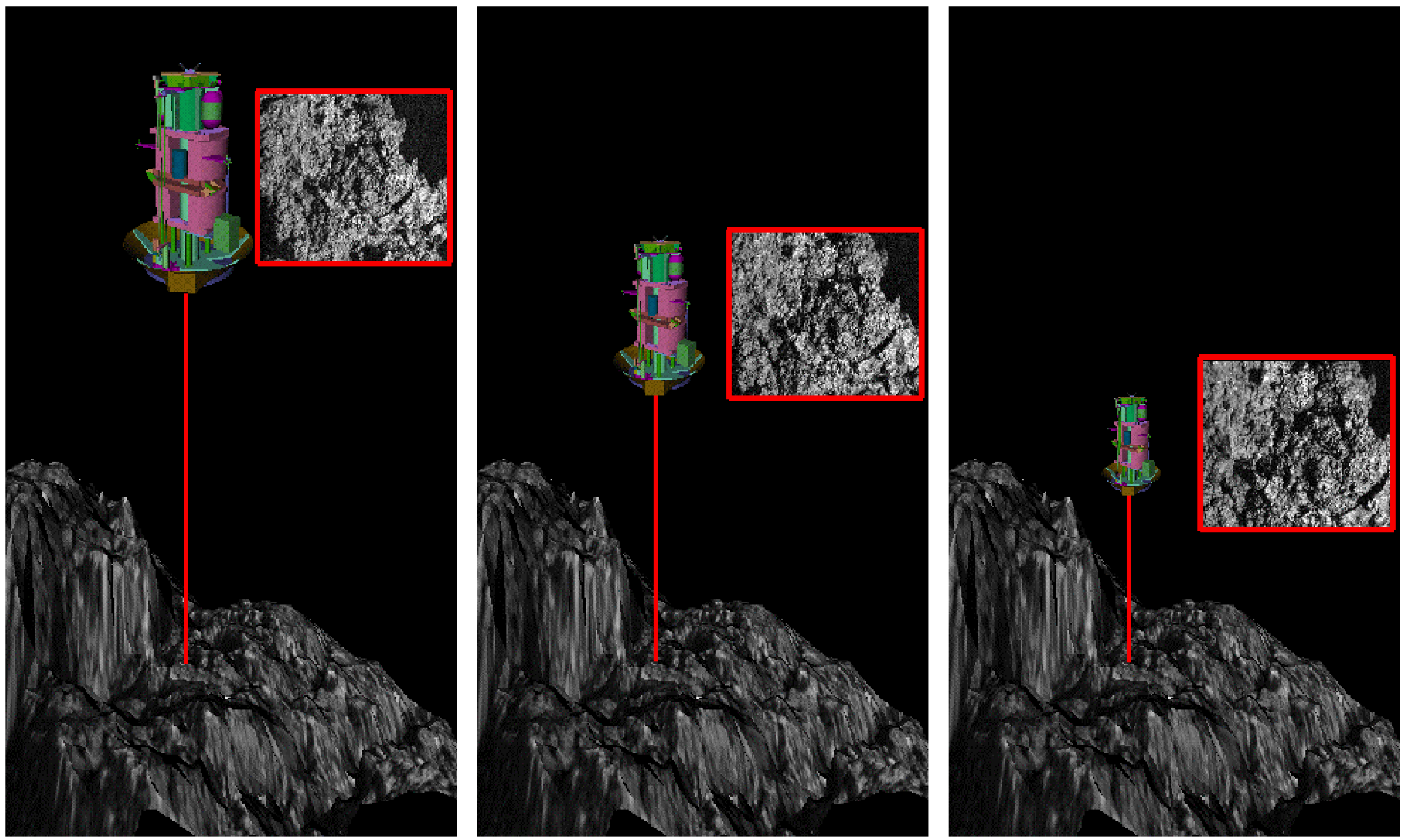
Problem Statement

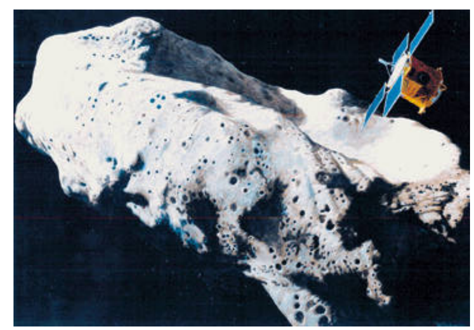
To estimate spacecraft motion during small body descent using a descent camera and laser altimeter.



Motivation

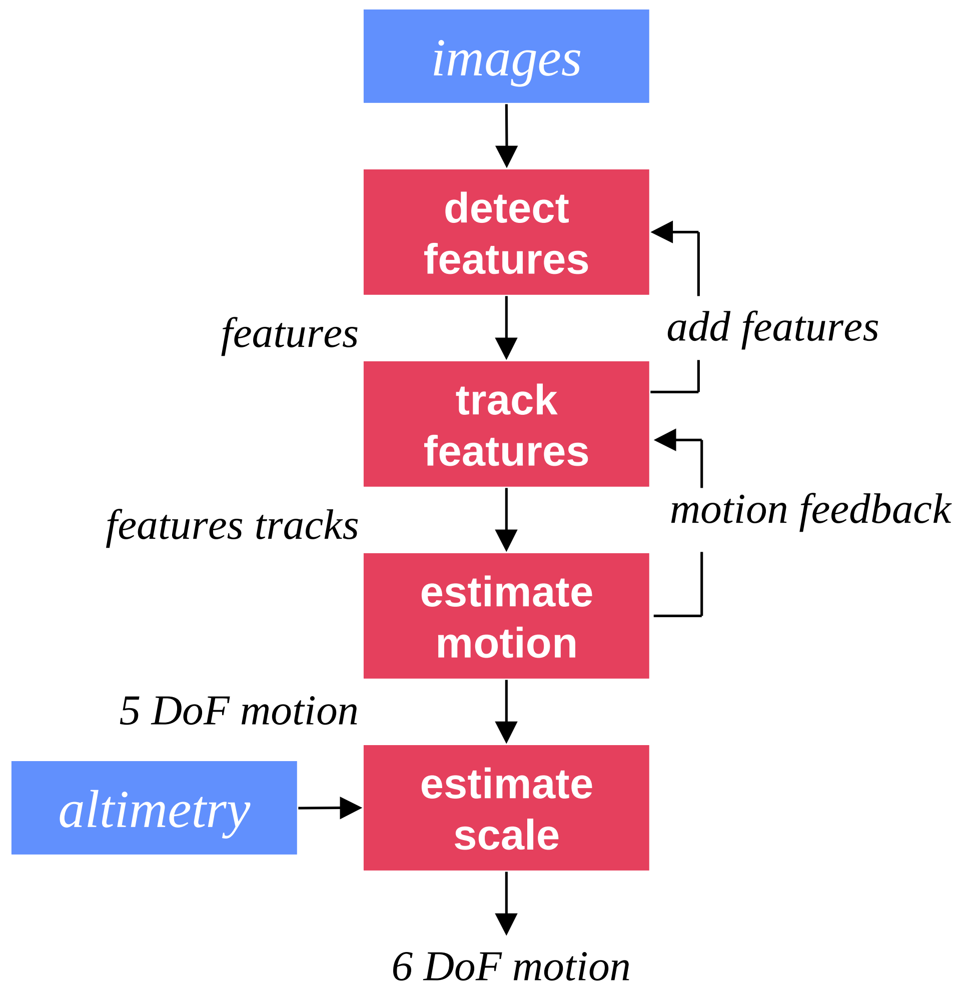
Applications
- ➤precision guidance for landing
- ➤hazard detection
- ➤rendezvous and docking for sample return
- ➤precision pointing of science instruments

Relevant Missions
- ➤ST-4/Champollion
- ➤Mars Sample Return



Related Work
- ➤DS-1: autonomous optical navigation
- ➤NEAR: landmark based navigation
- ➤MUSES-C: autonomous landing

Algorithm



images
detect features
features
add features
track features
motion feedback
features tracks
estimate motion
5 DoF motion
altimetry
estimate scale
6 DoF motion

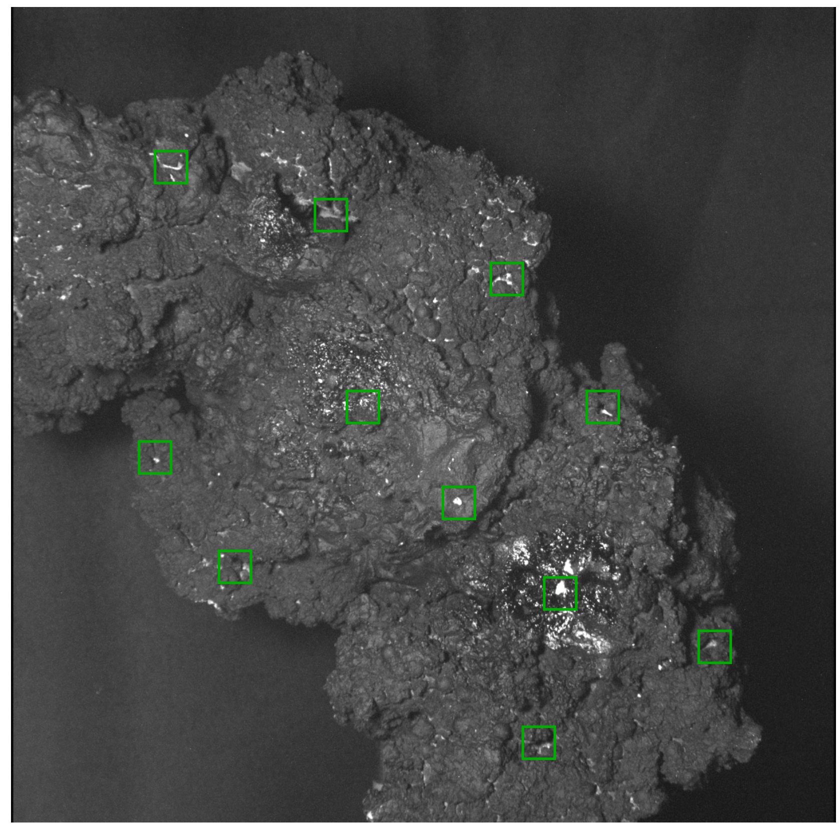
Feature Detection

Features

- ➤localized image windows
- ➤appearance robust to viewing and illumination changes

Feature Detection

- ➤find windows with large variation in intensity
- ➤use random search speedup



Feature Tracking

Features

- localized image windows
- appearance robust to viewing and illumination changes

Feature Detection

- find windows with large variation in intensity
- use random search speedup

Feature Tracking

- find feature disparity $\mathbf{d}$
- use Shi-Tomasi tracker

$$\min_{\mathbf{d}} \sum_{W} (I'(\mathbf{p}+\mathbf{d}) - I(\mathbf{d}))^2$$

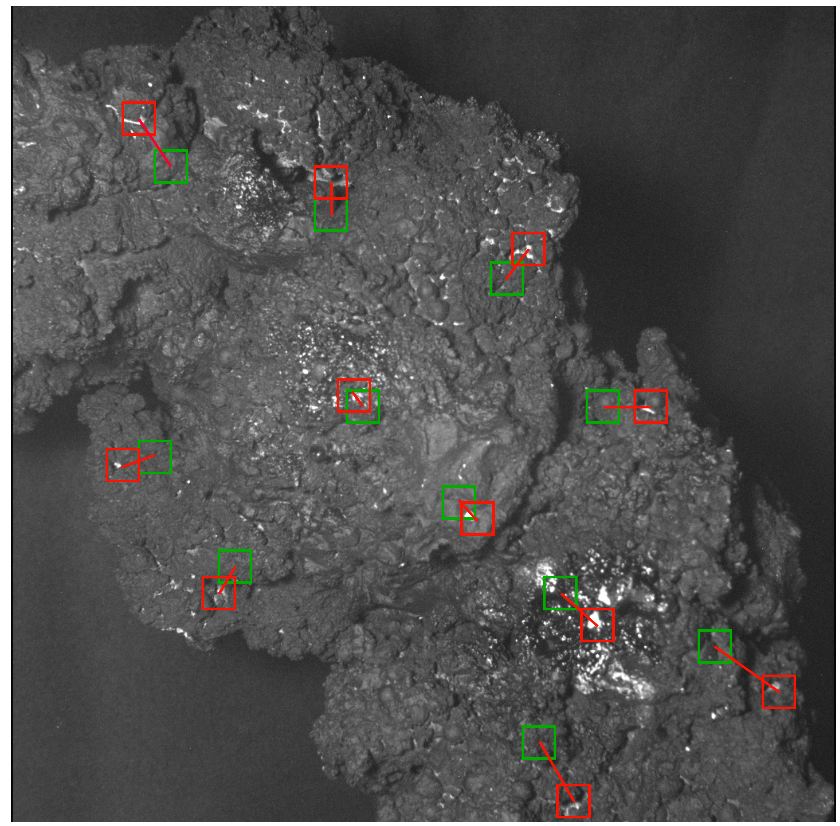
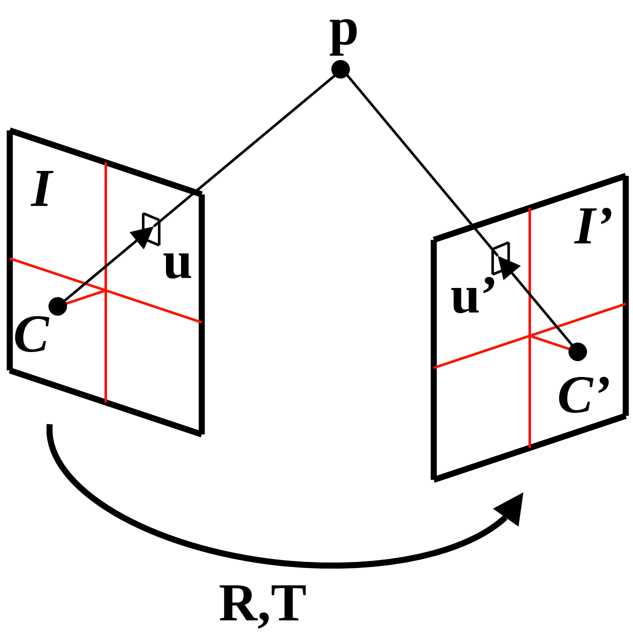


Image-Based Motion Estimation

Feature tracking leads to 5 DoF motion estimation

- ➤rotation $\mathbf{R}(\mathbf{q})$
- ➤unit translation $\mathbf{t} = \mathbf{T} / ||\mathbf{T}||$
- ➤5 DoF covariance



Two Stage Algorithm

1. Robust Linear Algorithm
   - ➤ **utilize linear epipolar constraint**

$$\min_{\mathbf{E}} \sum_i \mathbf{u}'_i \mathbf{E} \mathbf{u}_i$$

   - ➤ **from E compute motion: $\mathbf{E}=[\mathbf{t}]_x\mathbf{R}$**
   - ➤ **efficient closed form solution**
   - ➤ **provides initial motion estimate**
   - ➤ **robust algorithm eliminates feature track outliers**

2. Precise Nonlinear Algorithm
   - ➤ **solve directly for (R,t) that aligns features**

$$\min_{\mathbf{R},\mathbf{t}} \sum_i ||\mathbf{u}'_i - f(\mathbf{u}_i, \mathbf{R}, \mathbf{t})||^2$$

   - ➤ **use Levenberg-Marquardt**

Scale Computation

Laser altimeter provides final DoF: scale of translation $\|\mathbf{T}\|$

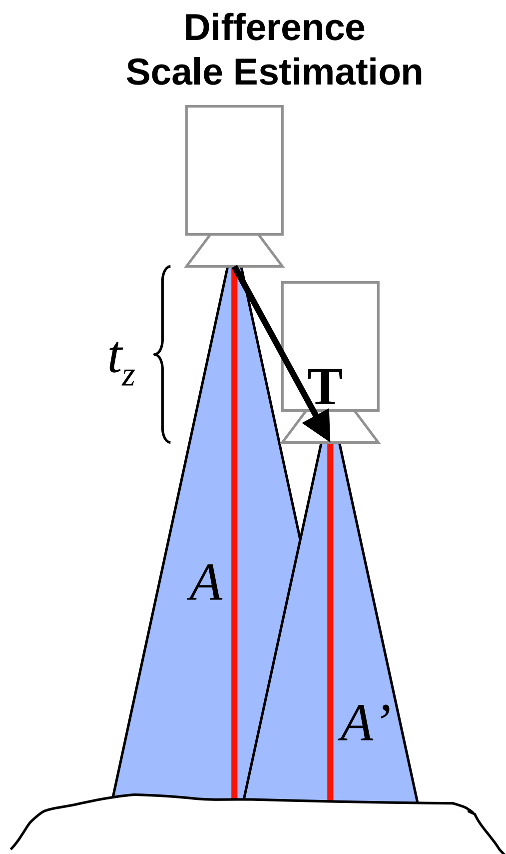
Two Methods

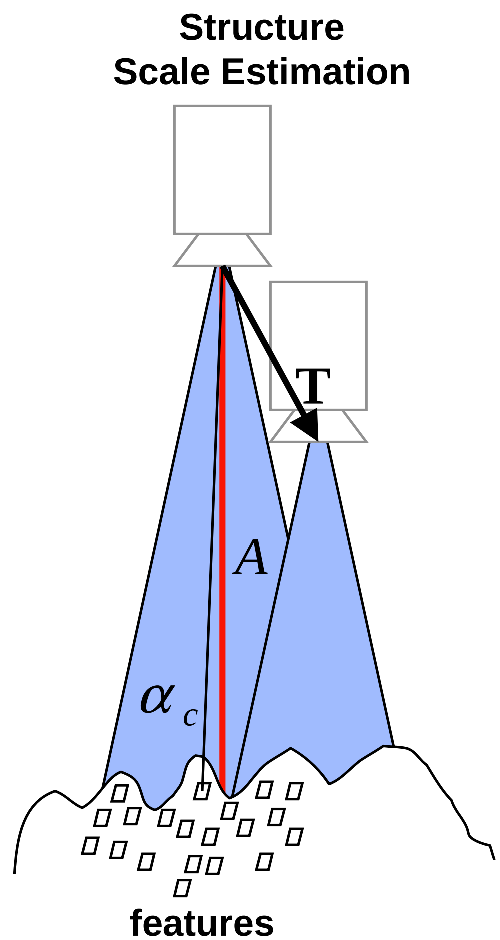
1. Difference
   - **flat terrain**
   - **straight descent**

$$\|\mathbf{T}\| = \frac{A - A'}{t_z}$$

2. Structure
   - **rough terrain**
   - **any motion**

$$\|\mathbf{T}\| = \frac{A}{\alpha_c}$$





Two Frame Motion Test

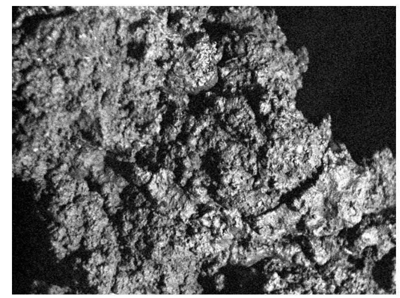
Parameters

50 features
640x480 imager
15º FOV
T = (0,0,1.0)cm

Results

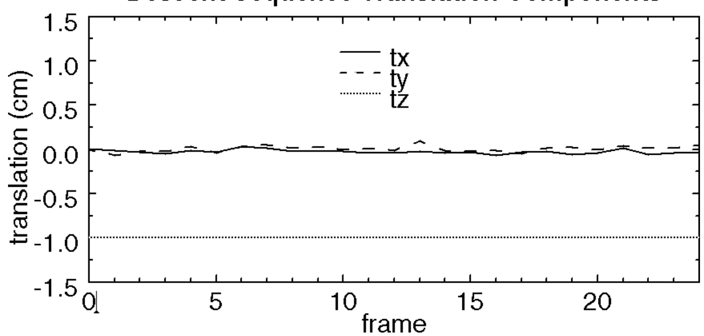
4 Hz frame rate
ε_t = 0.045 cm
ε_R = 0.063°

frame 0

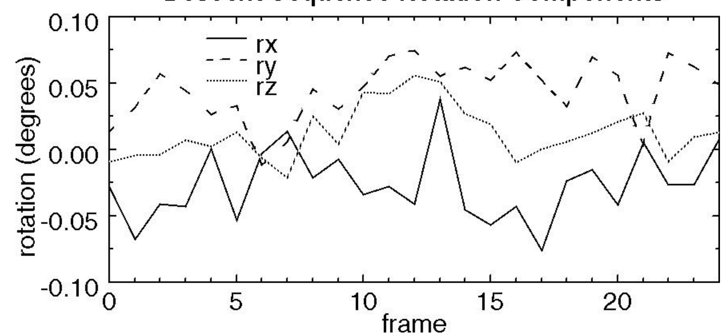


frame 25

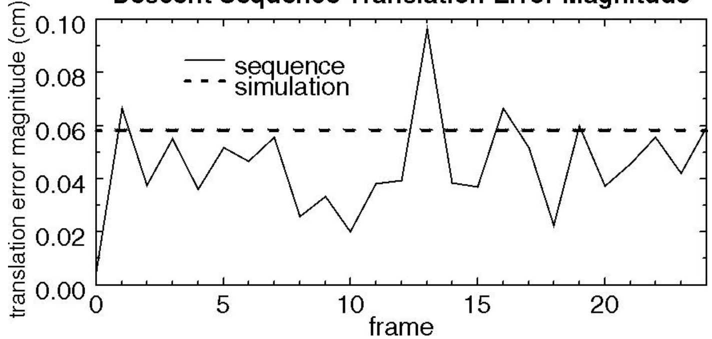
Descent Sequence Translation Components



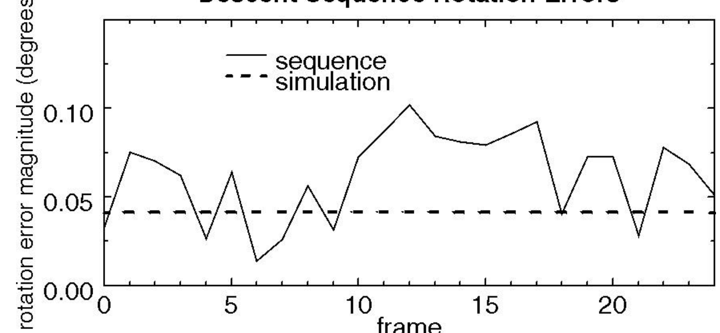
Descent Sequence Rotation Components



Descent Sequence Translation Error Magnitude



Descent Sequence Rotation Errors



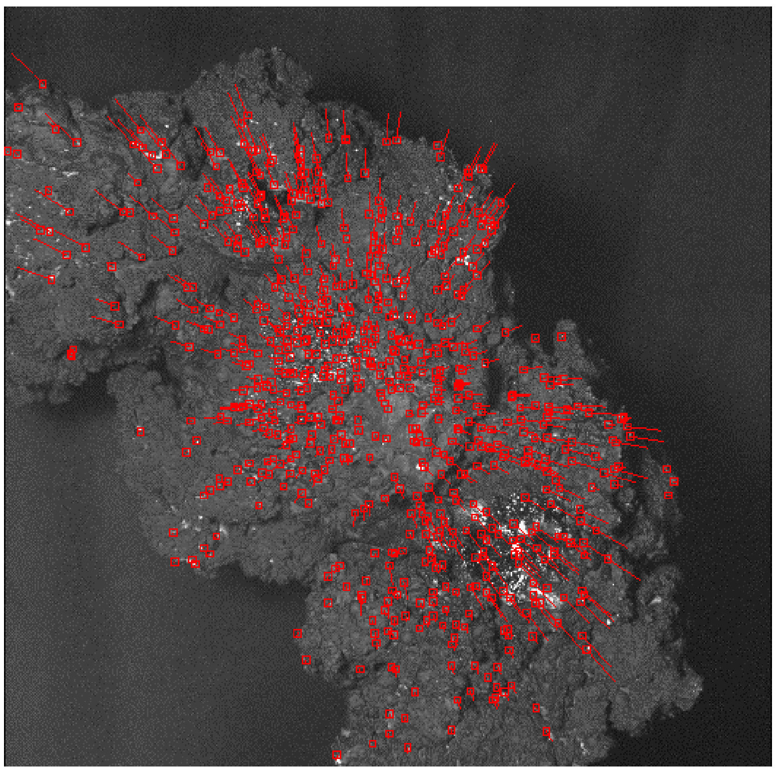
Multi-Frame Motion Laboratory Test

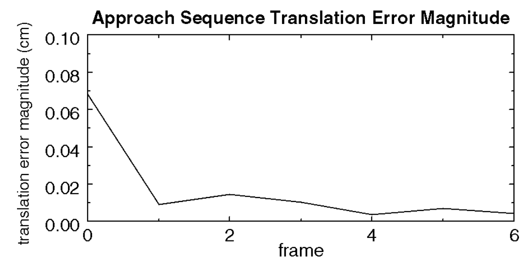
Parameters

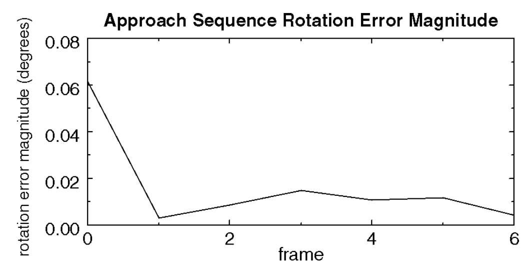
500 features
1024x1024 imager
25º FOV

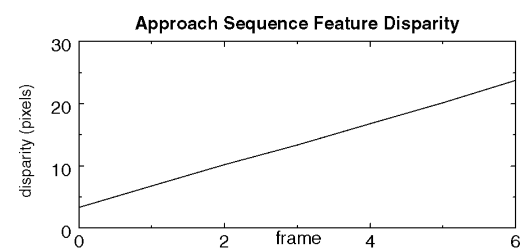
Results

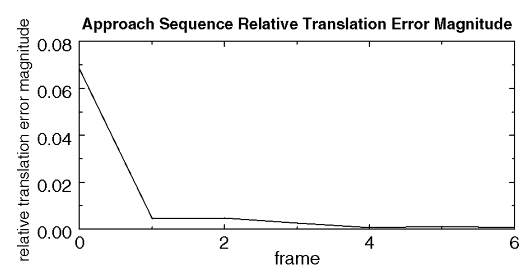
$\varepsilon_t = 0.02/6.00$ cm = 0.33%
$\varepsilon_R = 0.01°$







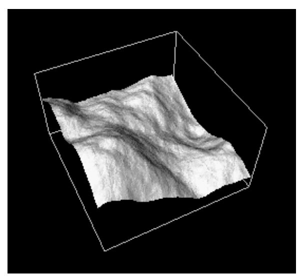




Monte Carlo Simulations

Procedure

- generate synthetic terrain
- select random pixels for features
- assume perfect tracking with gaussian noise
- intersect optical axis with synthetic terrain for altimeter readings
- compute motion

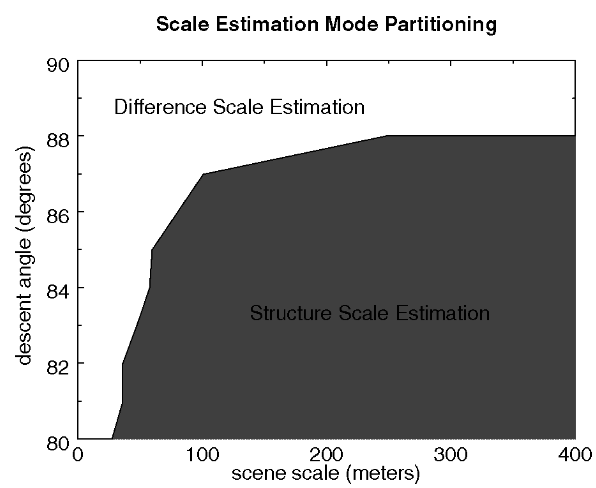


Assumptions

- 30º FOV
- 1024x1024 imager
- 1/6 pixel tracking noise
- 1000 m altitude
- 0.2 m altimeter error
- 20 pixel feature disparity
- 500 features

Results

- two frame descent
  - **vertical descent: 0.22m/65m = 0.34%**
  - **45° descent: 0.22m/17m = 1.3%**
  - **horizontal motion: 0.22m/12m = 1.8%**
- multi-frame landing
  - **horizontal landing error of 3.6m from 1000 m altitude = 0.36%**
- pointing
  - **0.006º error for 0.6º off axis pointing**
- scale estimation mode



Motion Estimation from Optical Sensors: A Comparison

Scanning Laser Radar

+ complete 3-D shape sensing
+ efficient algorithms (10 Hz)
+ no ground processing
+ dark side landing possible

- low resolution (100x100)
- short range (~2km)
- continuous data acquisition
- slow frame rate (1 Hz)
- possibly moving parts
- unproven sensor

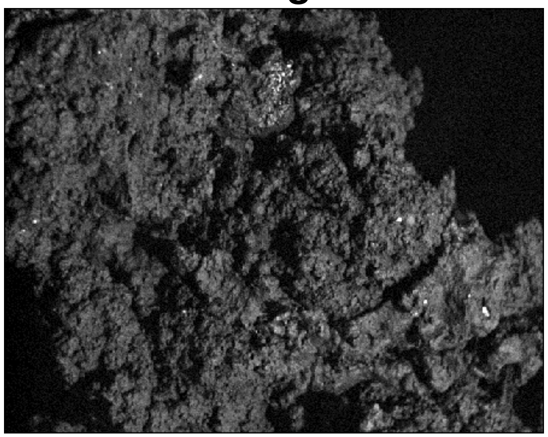
Imager and Altimeter

+ high resolution (1000x1000)
+ long range (50 km)
+ instantaneous data acquisition
+ rapid frame rates (30 Hz)
+ no moving parts
+ no ground processing
+ efficient algorithms (4 Hz)
+ proven sensors

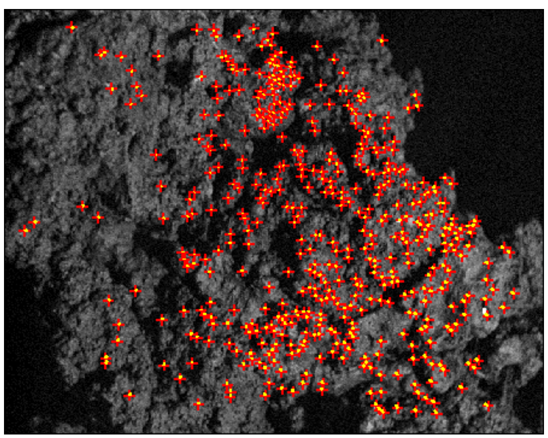
- requires target illumination
- shape requires processing
- requires two sensors

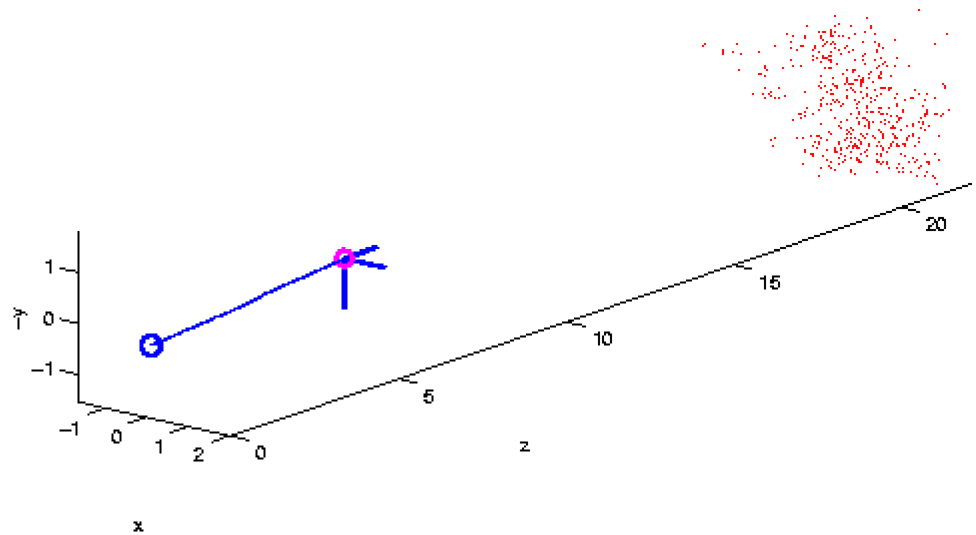
Descent

image

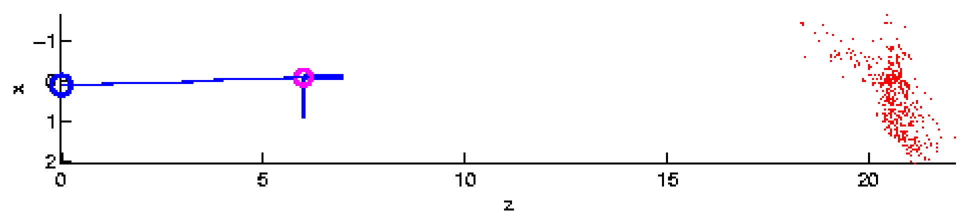


features



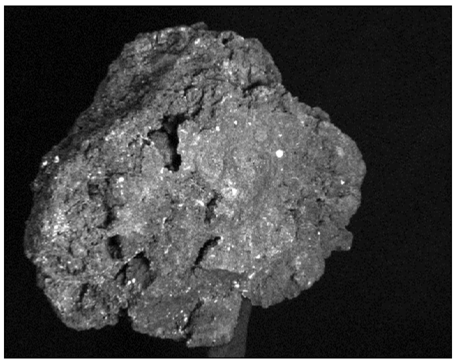


structure from motion

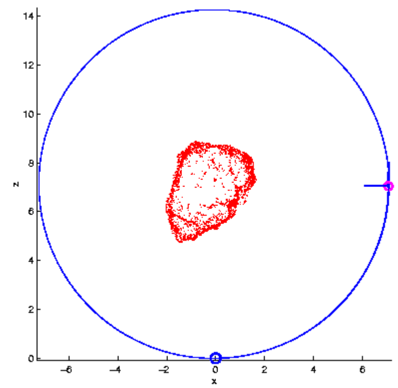


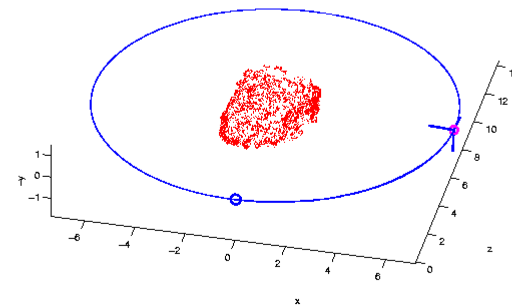
Orbit

images

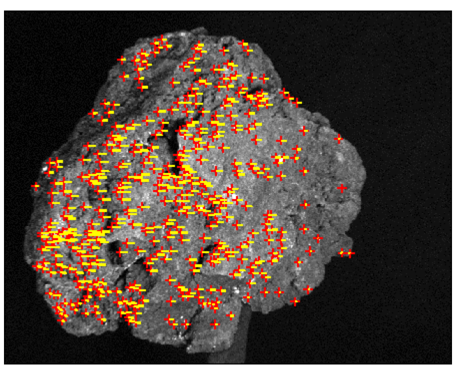


structure from motion

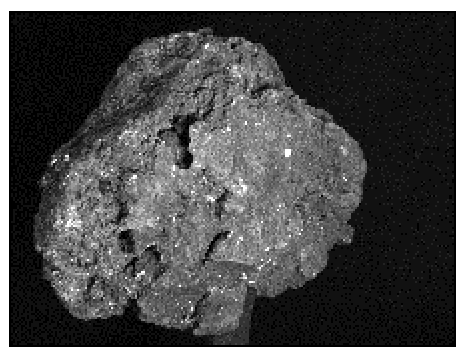


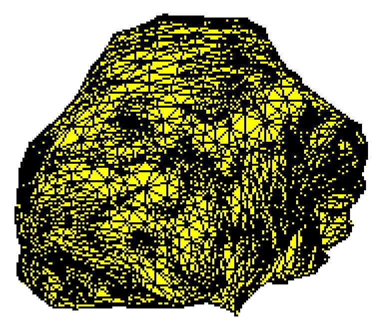


feature tracks



shape verification





Autonomous Position Estimation

Autonomous Spacecraft Position Estimation from Comet Orbit

Objective: To develop techniques for autonomous position estimation through onboard processing of orbital comet imagery.

Significance: By providing comet absolute position estimates, this technology enables autonomous small body navigation.

Recent Advances: Developed novel approach based on structure from motion for 3-D modeling followed by surface matching for position estimation. Approach validated with real imagery acquired of a comet analog in laboratory