Machine Vision Algorithms for Autonomous Small Body Navigation

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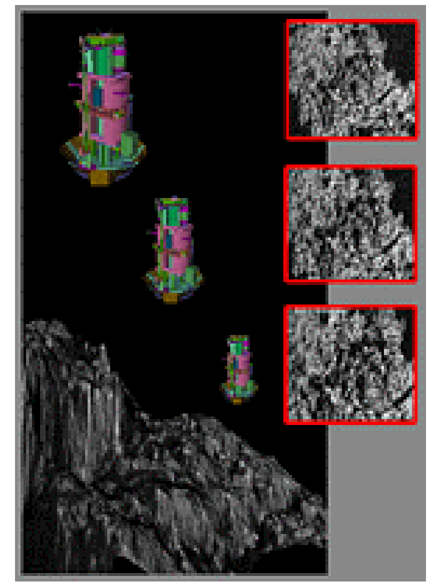
Problem Statement

Objective

To develop machine vision algorithms for near surface small body navigation that provide estimates of

- ➤ spacecraft body relative motion
- ➤ spacecraft body absolute position
- ➤ 3-D surface topography

through on-board processing of optical sensor data.

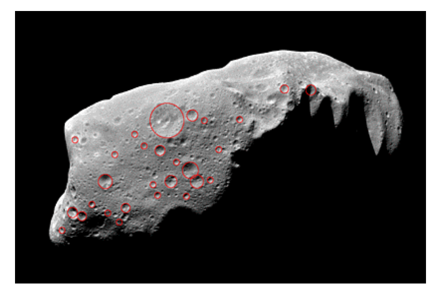


Benefit

These algorithms enable

- ➤ precision guidance and landing
- ➤ hazard avoidance
- ➤ sample return

from comets and asteroids.



Mission Motivation

SSE

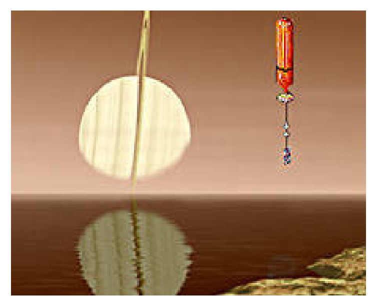
- ➤ Comet Nucleus Sample Return
  - ➤ **multiple landing sites**
  - ➤ **sample return**
  - ➤ **autonomous operations**
- ➤ Large Asteroid Sample Return
- ➤ Titan Organics Explorer
- ➤ Europa Precision Landing
- ➤ Mars Precision Landing

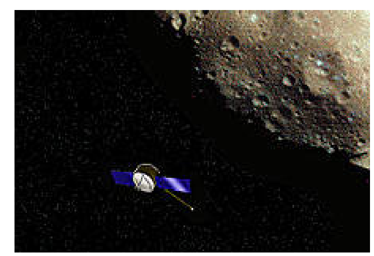
ESE

- ➤ Intelligent sensor web
- ➤ Reconfigurable sensing

HEDS

- ➤ Operations
- ➤ Robotic Partners
- ➤ Soft Landing





Approach

Problems

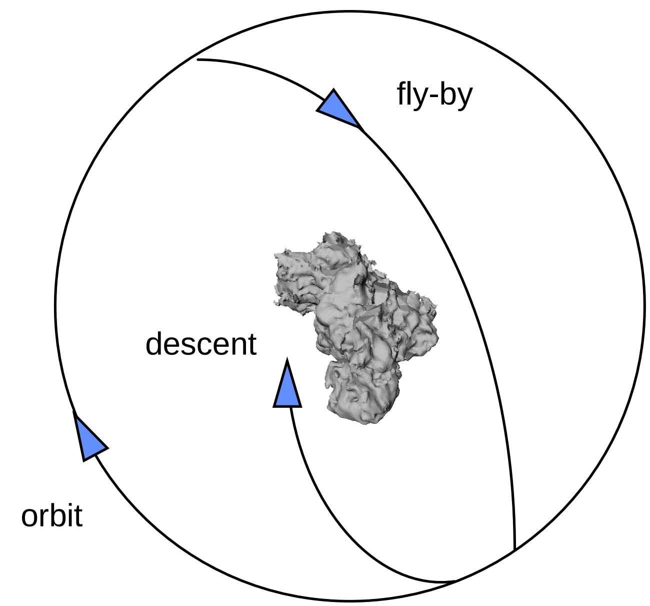
- ➤ estimate spacecraft motion and position
- ➤ reconstruct surface topography
- ➤ detect and avoid hazards

Challenges

- ➤ variable body and spacecraft motion
- ➤ variable illumination
- ➤ variable altitude/scene scale
- ➤ robust and autonomous

Methods

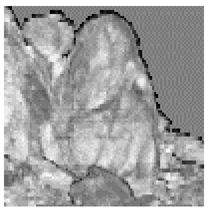
- ➤ feature tracking
- ➤ structure from motion
- ➤ landmark recognition
- ➤ surface matching
- ➤ motion stereo



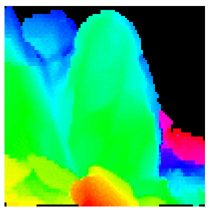
Sensing Modalities

Rangefinder Imagery

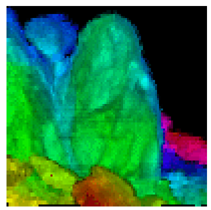
laser intensity



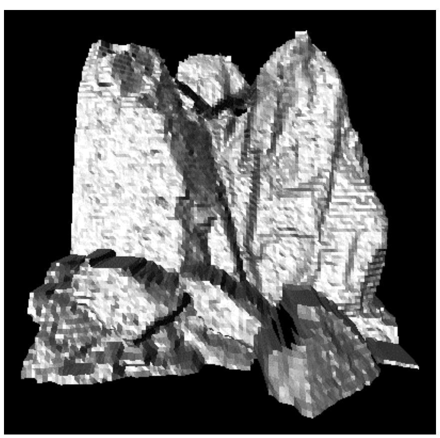
color-coded range



range & intensity



shaded surface mesh



Camera Imagery

Single Images

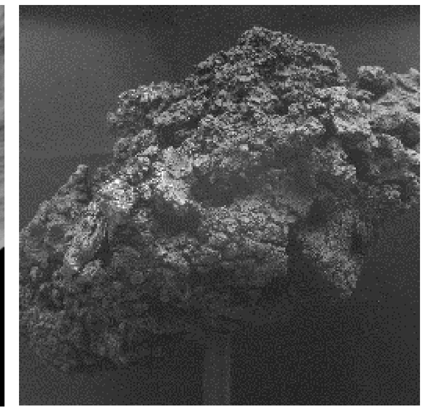
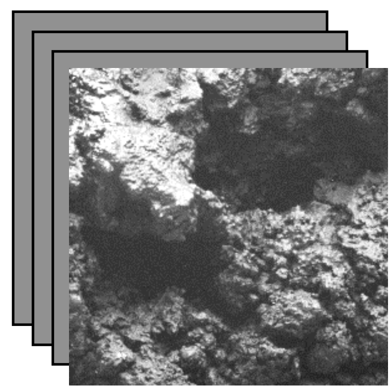
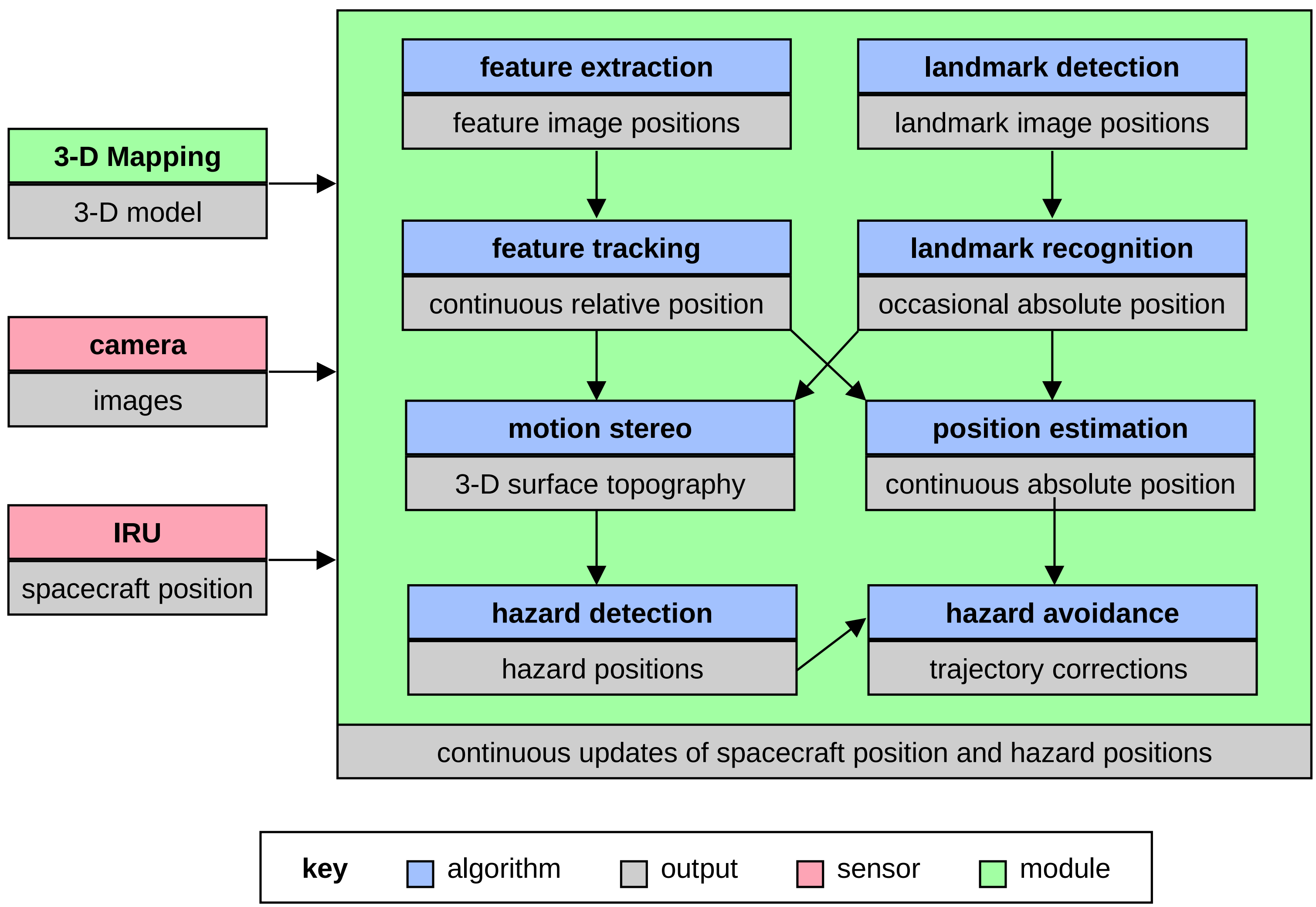


Image Streams



Imaging Approach



Imaging Approach

Feature Tracking and Motion Estimation

Objective

- ➤ determine motion of spacecraft based on surface imagery

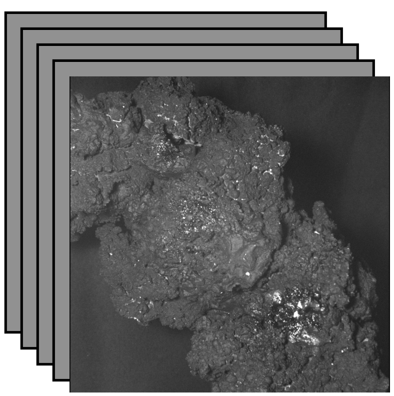
Approach

- ➤ track features (Shi & Tomasi CVPR94)
- ➤ estimate motion (Johnson & Matthies ISAIRAS99)

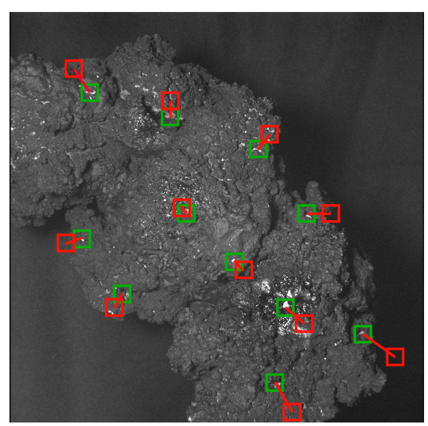
Application

- ➤ precision guidance and landing
- ➤ comet and asteroid exploration

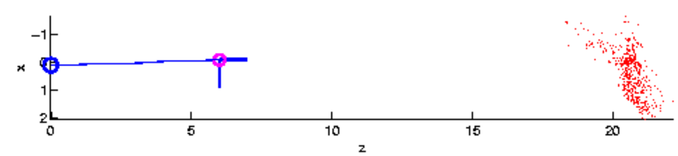
images



feature tracks



motion estimation



Two Frame Motion Laboratory Test

Parameters

50 features

640x480 imager

15º FOV

T = (0,0,1.0)cm

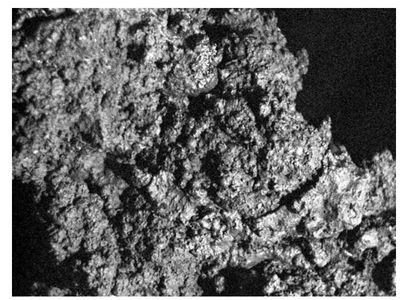
Results

4 Hz frame rate

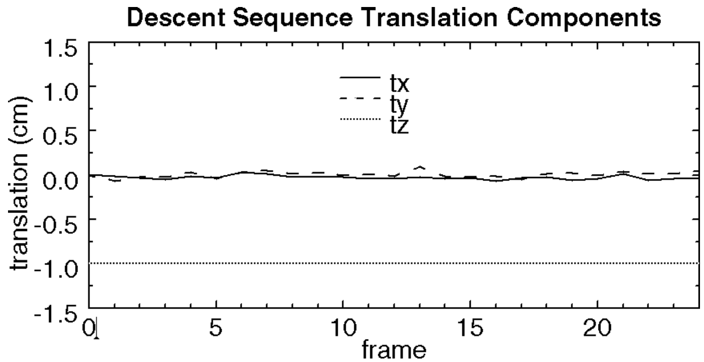
ε_t = 0.045 cm

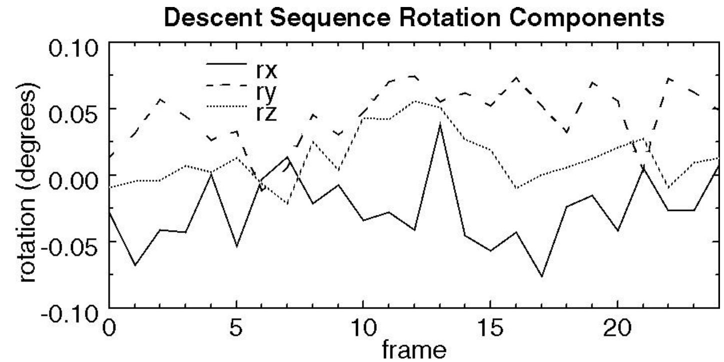
ε_R = 0.063°

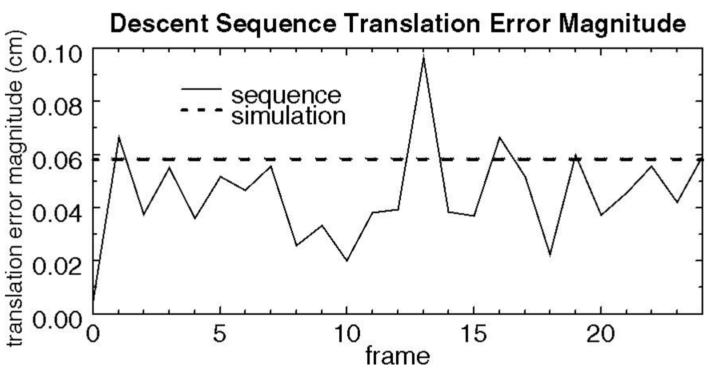
frame 0

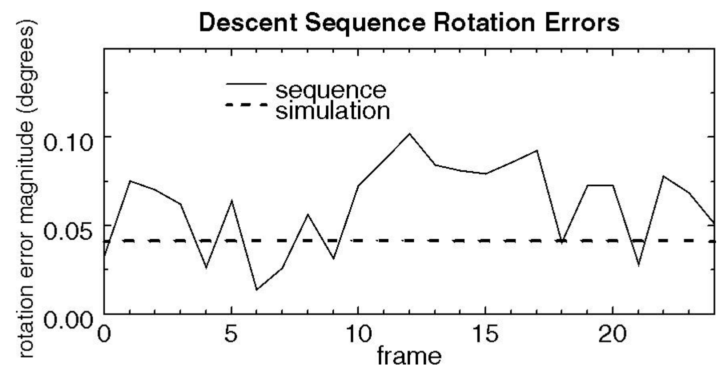


frame 25









Multi-Frame Motion Laboratory Test

Parameters

500 features

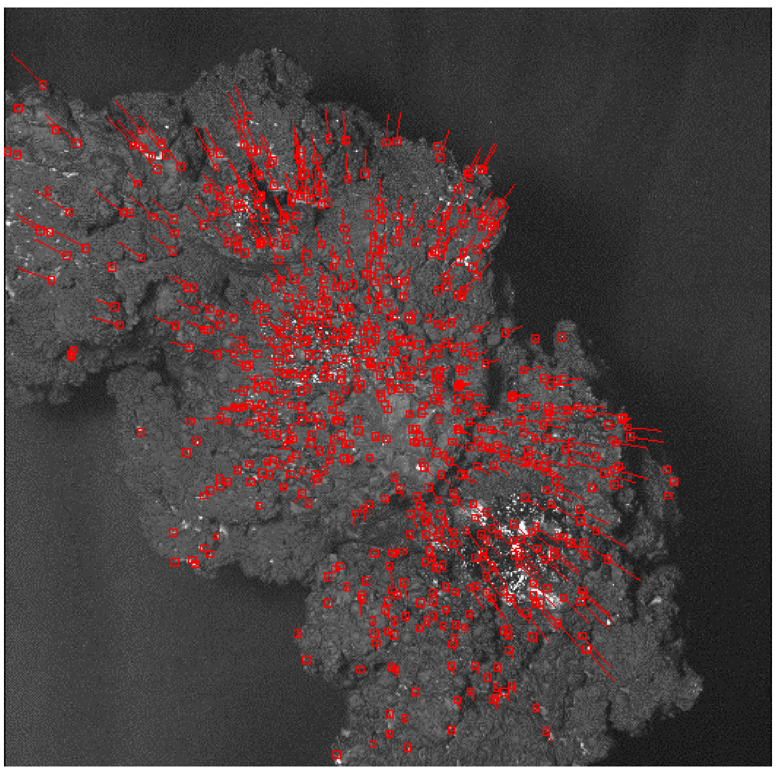
1024x1024 imager

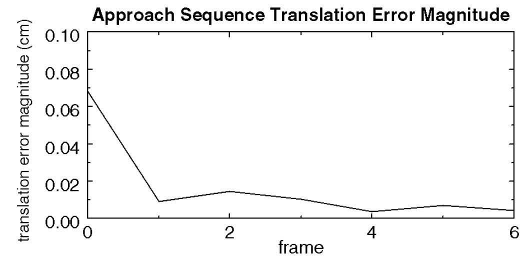
25° FOV

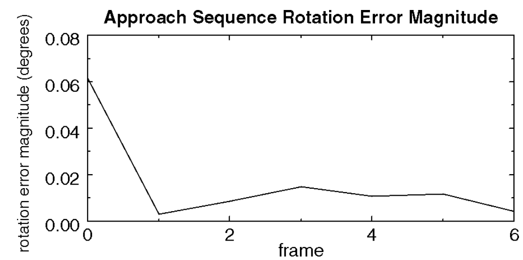
Results

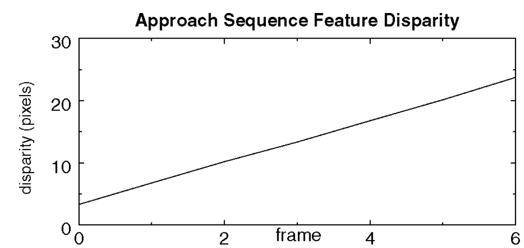
ε_t = 0.02/6.00 cm = 0.33%

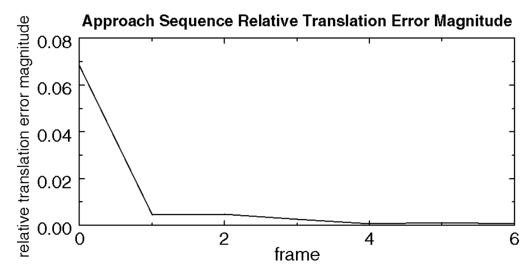
ε_R = 0.01°











Monte Carlo Simulations of Motion Estimation

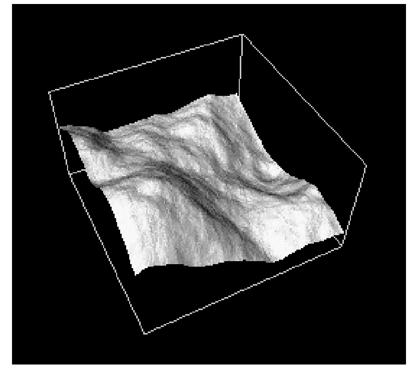
Procedure

- 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

synthetic terrain map

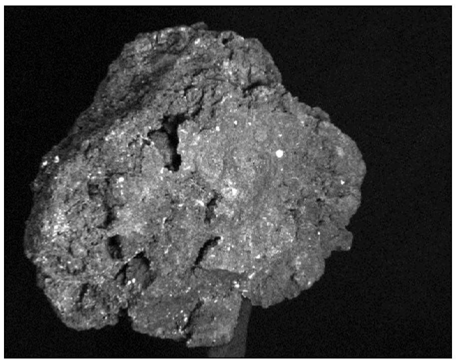


Results

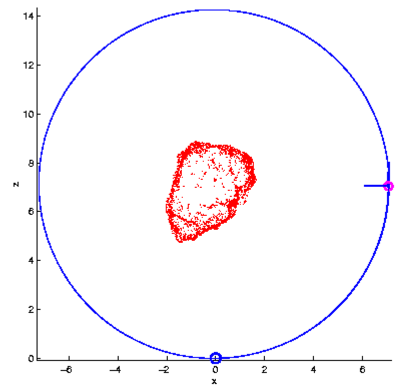
- two frame descent
  - **vertical descent: 0.22m/65m = 0.34%**
  - **45° descent: 0.22m/17m = 1.3%**
  - **horizontal motion: 0.22m/12m = 1.8%**
- multi-frame landing
  - **horizontal landing error of 3.6m from 1000 m altitude = 0.36%**
- pointing
  - **0.006º error for 0.6º off axis pointing**

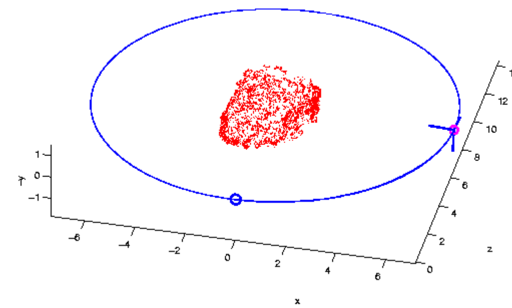
Orbit Structure From Motion Result

images

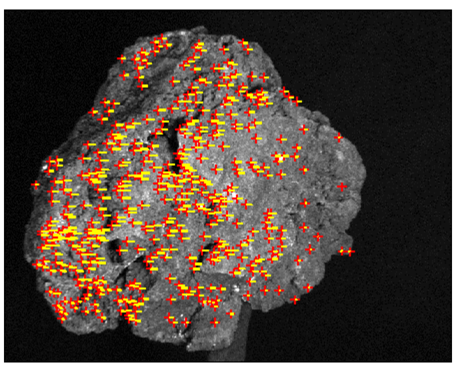


structure from motion

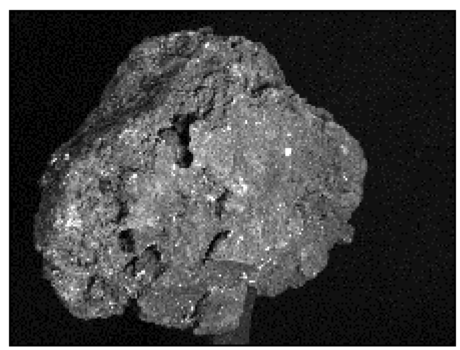


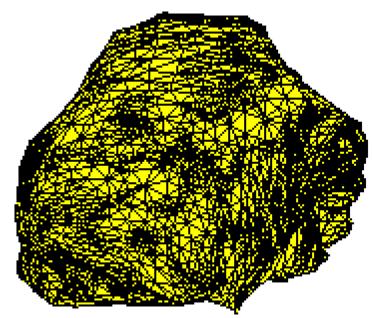


feature tracks



shape verification



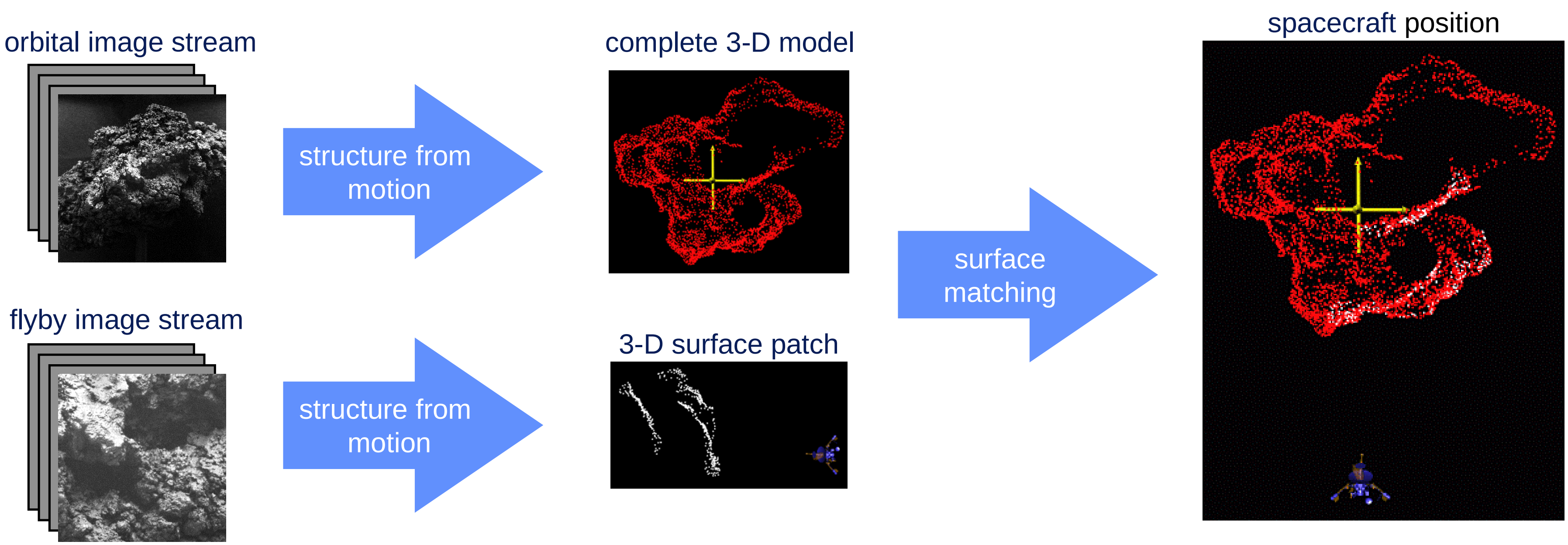


Comet Absolute Position Estimation

Objective
- determine comet absolute position from orbit

Application
- precision guidance & landing
- comet exploration

Approach
- structure from motion (Johnson & Matthies ISAIRAS99)
- match surface topography (Johnson & Hebert CVPR 1997)
- estimate position



Imaging Approach

Motion Stereo

Objective

- ➤ reconstruct dense 3-D surface topography from monocular image streams

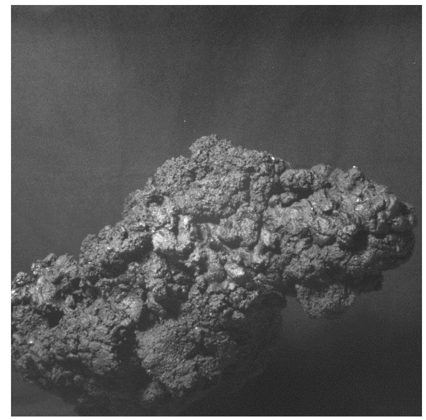
Approach

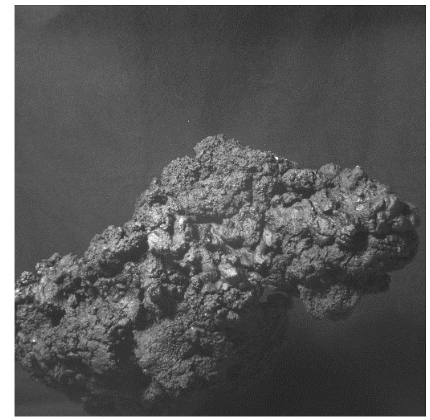
- ➤ rectify images based on motion
- ➤ dense stereo matching (Xiong & Matthies CVPR97)

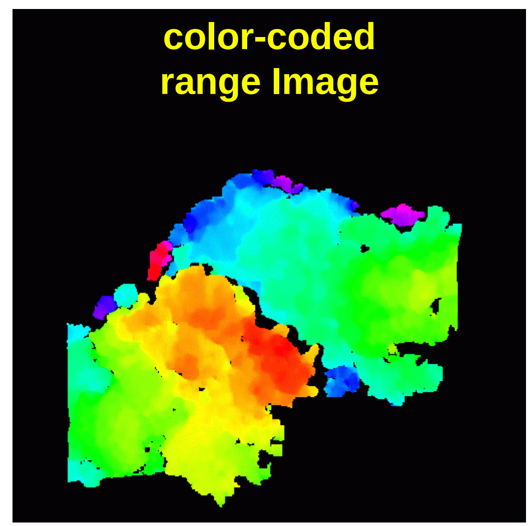
Application

- ➤ hazard detection
- ➤ comet landmark detection
- ➤ 3-D modeling

motion stereo images







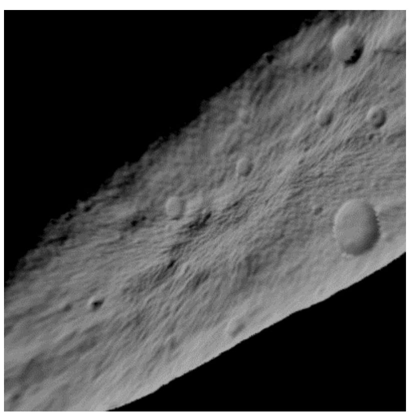
Imaging Approach
Asteroid Absolute Position Estimation

Objective
- ➤ determine asteroid absolute position from orbit

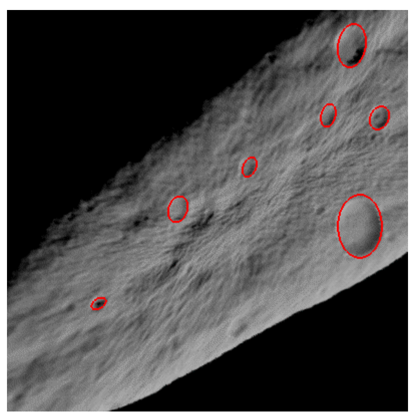
Application
- ➤ precision guidance and landing
- ➤ asteroid exploration

Approach
- ➤ take image
- ➤ detect craters (Leroy & Medioni CVPR 1999)
- ➤ match craters to data base
- ➤ estimate position

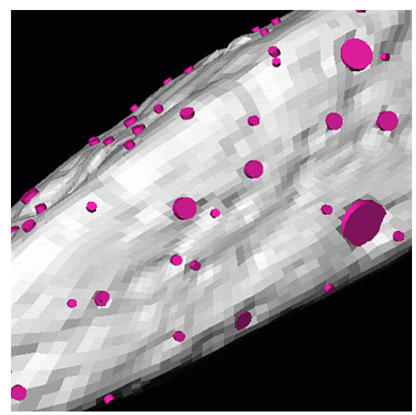
Acquire asteroid image



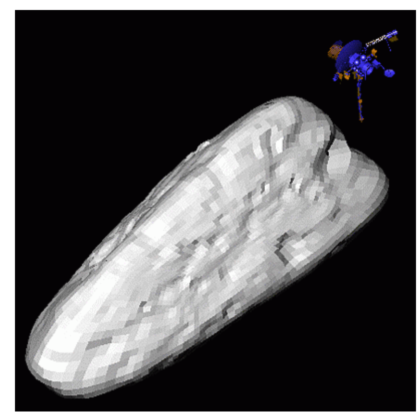
Extract crater landmarks using perceptual grouping



Match 2D image craters to 3D database of craters

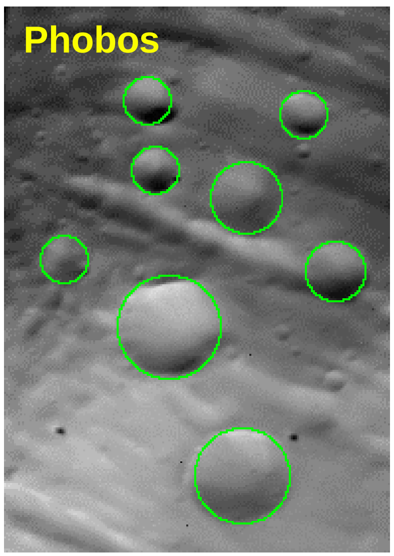


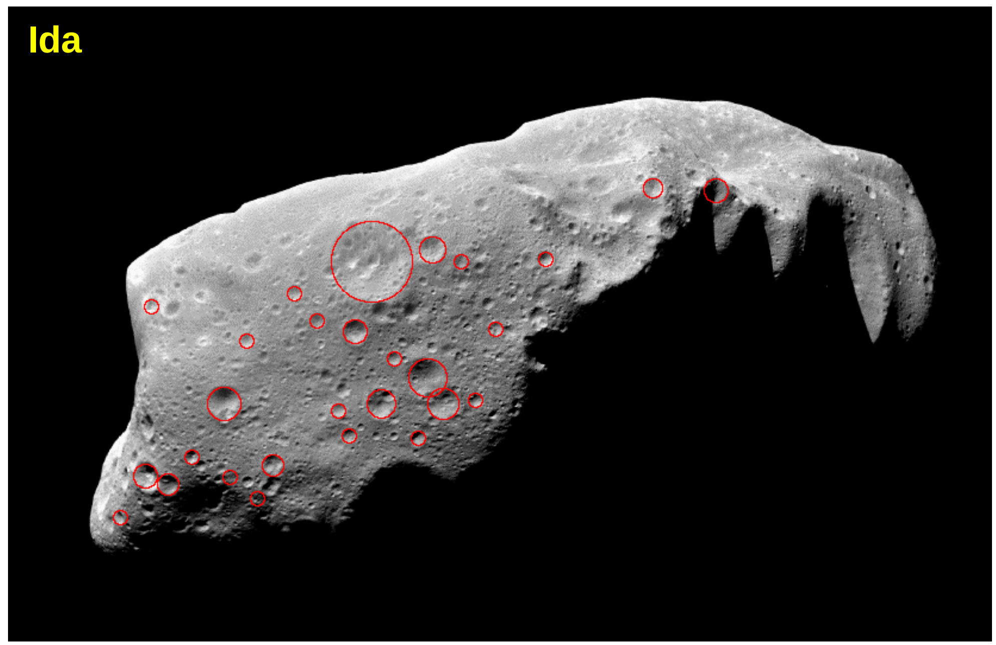
Estimate S/C position from crater matches



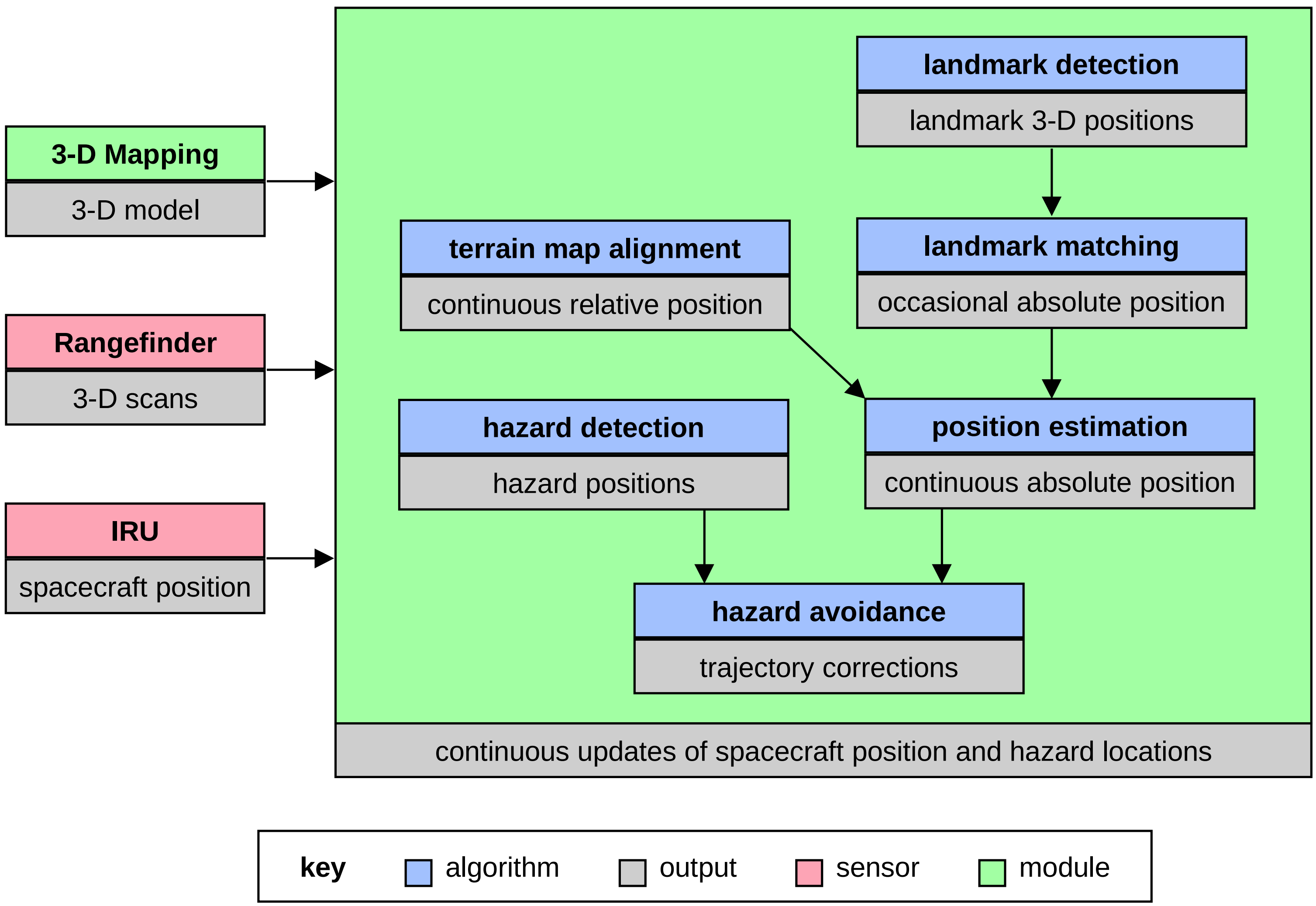
Imaging Approach

Crater Landmark Detection





Rangefinder Approach



Rangefinder Approach

Terrain Map Alignment and Motion Estimation

Objective

- ➤ determine translational motion using rangefinder scans

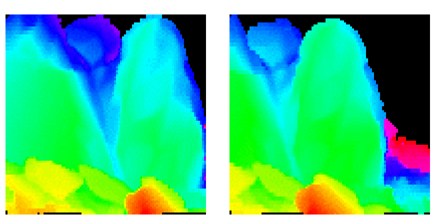
Approach (Johnson & SanMartin 1999)

- ➤ generate terrain maps
- ➤ align terrain maps

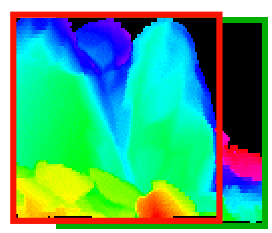
Application

- ➤ precision guidance and landing
- ➤ comet and asteroid exploration

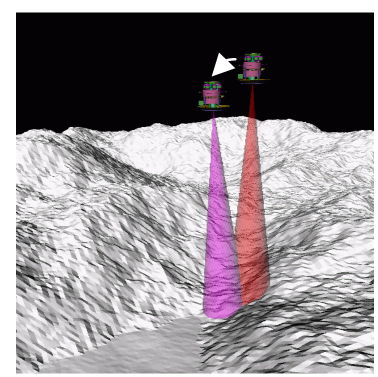
terrain maps



align terrain maps in 3-D

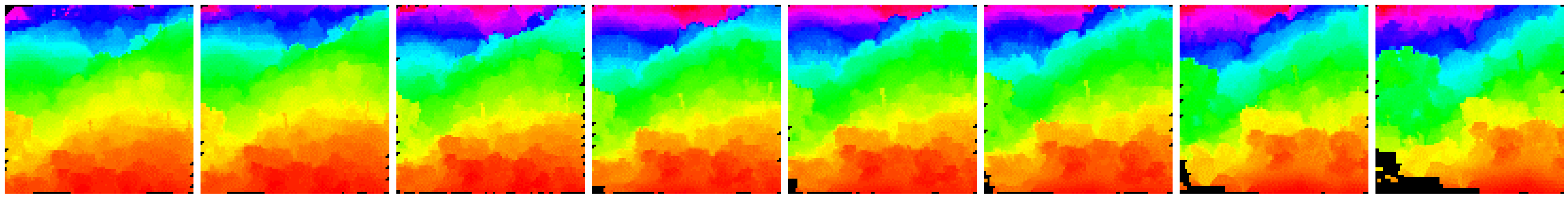


estimate motion



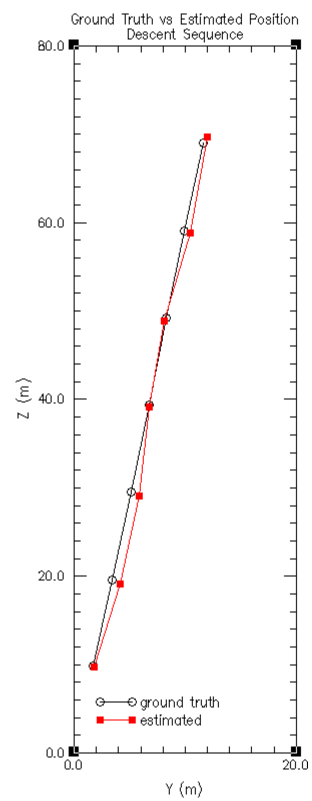
Rangefinder Approach
Vertical Motion Estimation Result

terrain maps

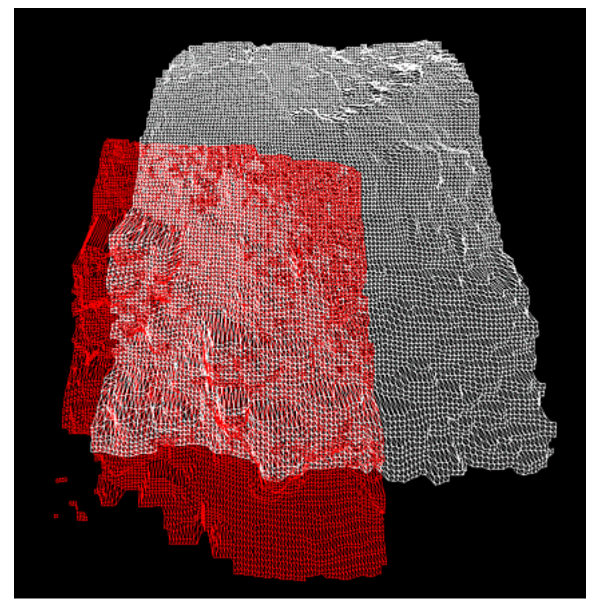


Parameters
100x100 image
10º FOV
300 m altitude
motion toward hill
ground truth from surveying

Results
4.4 Hz frame rate
ε_t = 0.52m/70.0m = 0.7%

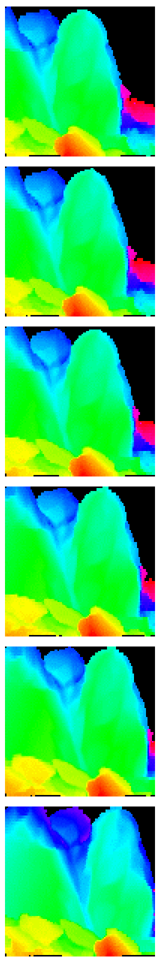


alignment of first and last scans



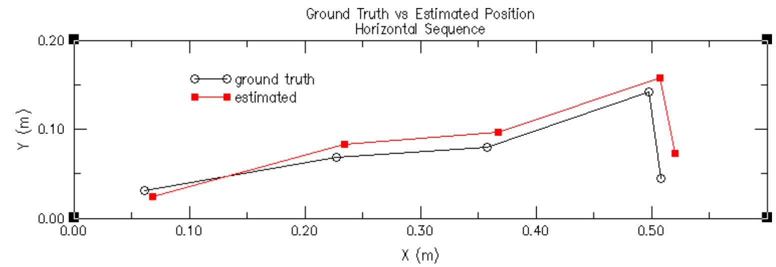
Rangefinder Approach
Horizontal Motion Estimation Result

terrain maps

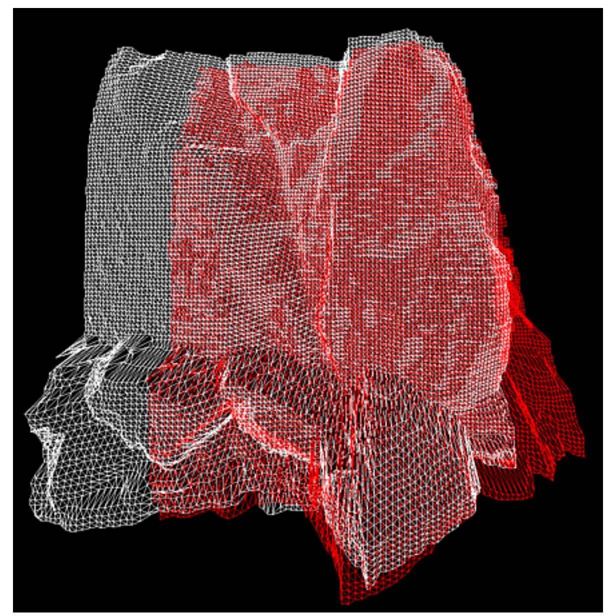


Parameters
100x100 image
10º FOV
16 m altitude
motion parallel to rocky face
ground truth from surveying

Results
4.2 Hz frame rate
ε_t = 0.038m/0.51m = 7.4%



alignment of first and last scans



Rangefinder Approach

Monte Carlo Simulation of Motion Estimation

Procedure

- generate synthetic terrain
- generate 2 range scans
- align terrain maps
- compute motion

Parameters

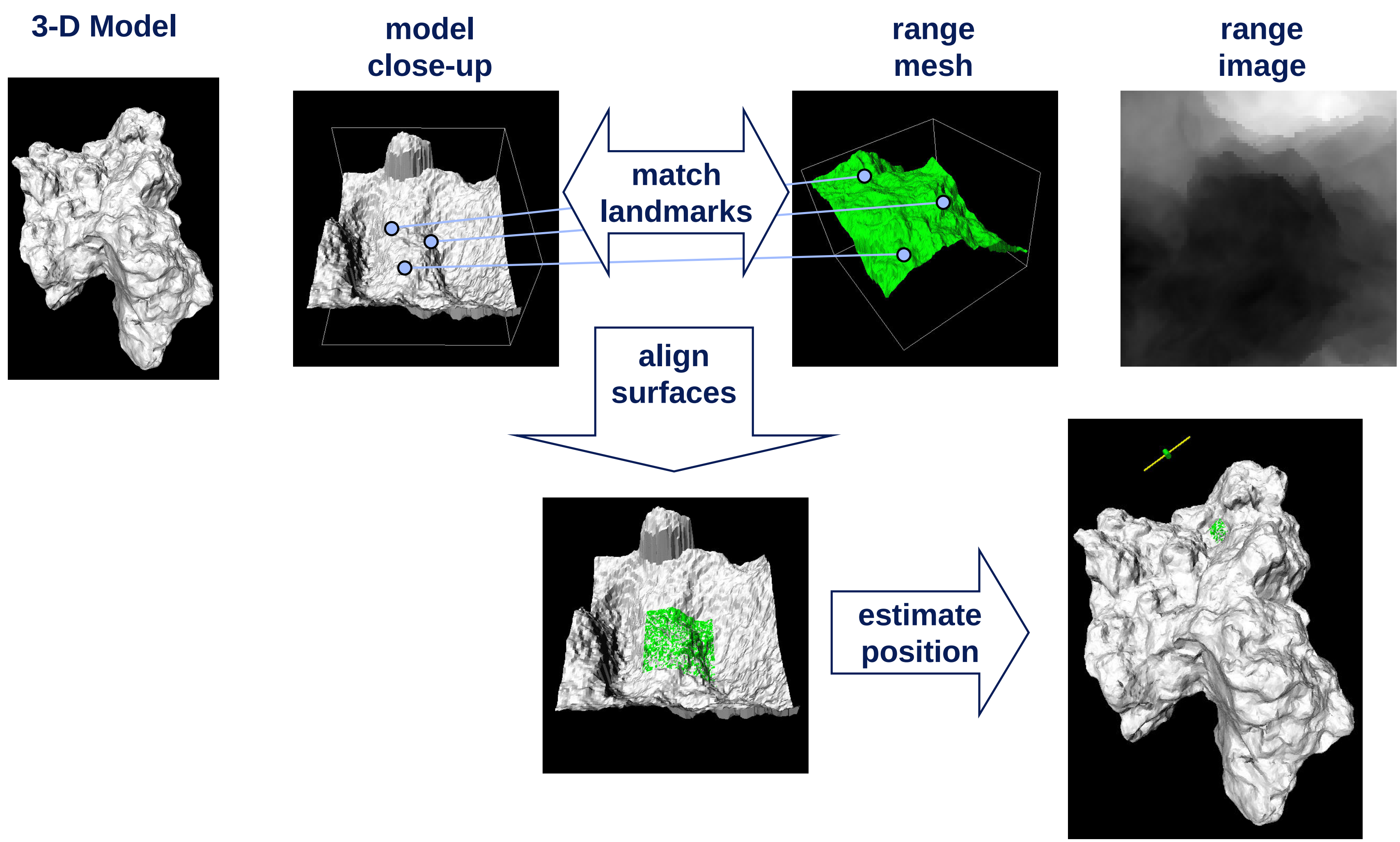
- 10º FOV
- 100x100 image
- 100 m altitude
- 1.0 m/s motion
- 0.02 m range error
- 0.1 º divergence
- 0.01º attitude error

Results

- motion accuracy
  - **vertical descent: 0.02m/3.0m = 0.7%**
  - **45° descent: 0.03m/5m = 0.5%**
  - **horizontal motion: 0.04m/25m = 0.2%**
- max travel distance between scans
  - **vertical descent: 3.0m**
  - **45° descent: 5.0m**
  - **horizontal motion: 25.0m**
- horizontal landing accuracy
  - **0.16m from 100 m altitude**
- timing
  - **400 ms first frame**
  - **200 ms each additional frame**
  - **4-5 Hz**

Rangefinder Approach

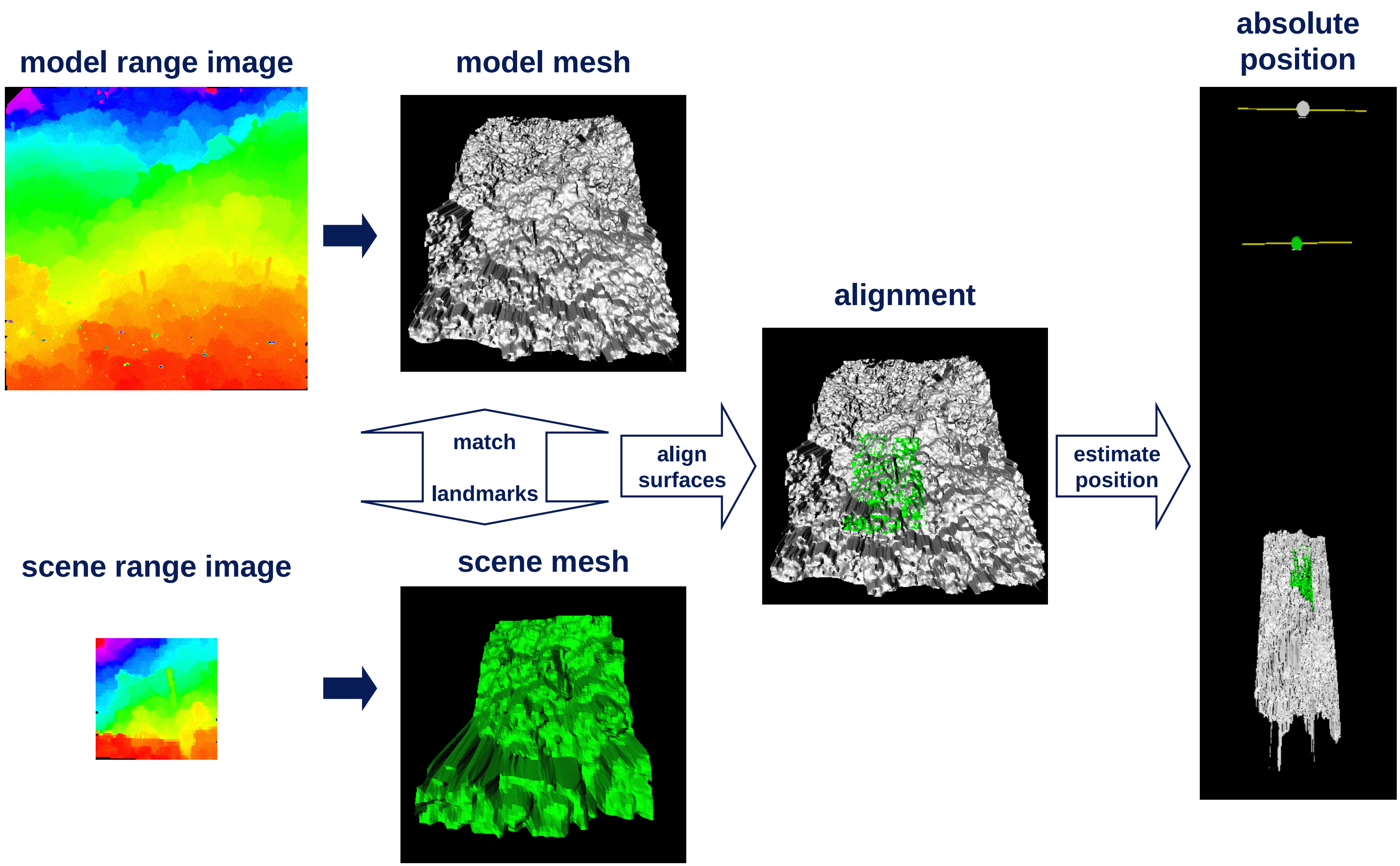
Absolute Position Estimation



Rangefinder Approach

Absolute Position Estimation Result

Jpl East Lot Scans



Comparison of Sensing Modalities

Scanning Laser Radar	Imager and Altimeter
+ no ground processing	+ no ground processing
+ efficient algorithms (5 Hz)	+ efficient algorithms (4 Hz)
+ enables autonomous exploration	+ enables autonomous exploration
- low resolution (100x100)	+ high resolution (1000x1000)
- short range (~2km)	+ long range (50 km)
- continuous data acquisition	+ instantaneous data acquisition
- slow frame rate (1 Hz)	+ rapid frame rates (30 Hz)
- possibly moving parts	+ no moving parts
- unproven sensor	+ proven sensors
+ does not require illumination	- requires surface illumination
+ complete 3-D shape sensing	- shape requires processing
+ provides altimetry	- requires altimeter