FY23 Strategic University Research Partnership (SURP)

Multi-Phase Autonomous Vision-Based Navigation for Planetary and Small Body Exploration

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Objectives

Enable **robust** autonomous optical-based navigation for the approach, proximity operations, and landing phaess on small bodies.

Background

Navigation to/around small bodies is challenging, due to **large appearance changes** of its surface. Today, navigation heavily relies on operator engagement.

Significance/Benefits

Provides key capabilities to enable autonomous access to **near-Earth Objects**, **main-belt asteroids**, **comets**, airless **planetary satellites**, **centaurs**, and **trans-Neptunian bodies**.

Approach and Results

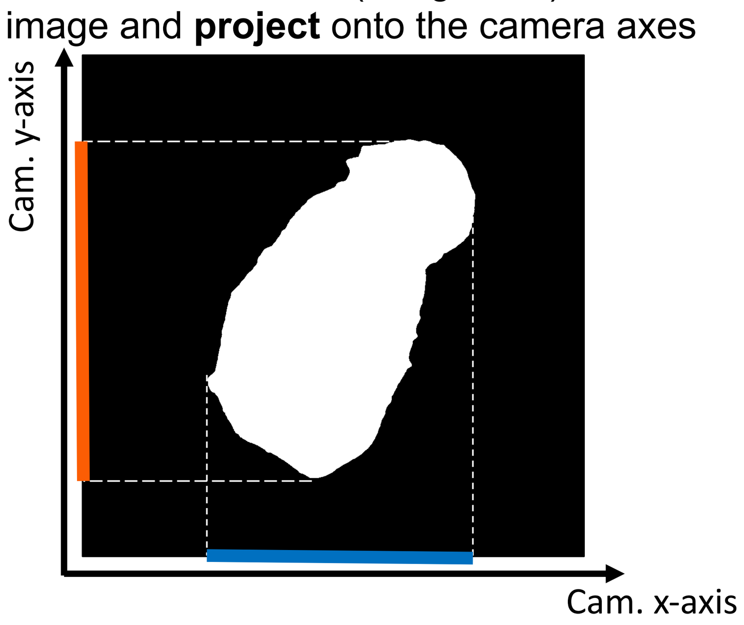
Mission Phase

Approach/Target Characterization → ***Proximity Operations/Landing***

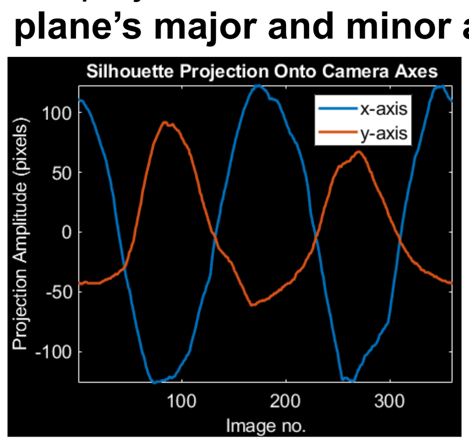
Fast Pole-from-Silhouette (Fast-PfS)

- *Estimates the **3D pole orientation**, given a sequence of low-resolution images and computationally-efficient techniques*
- *Pole estimation **errors below 1 degree***

1. Extract **silhouette** (foreground) from the image and **project** onto the camera axes

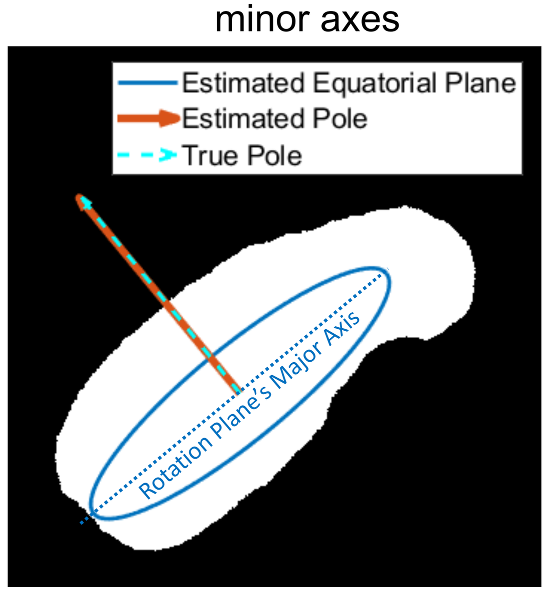


2. Track silhouette projections over multiple frames; compute the **principal component** in the X and Y projections to estimate the **rotation plane's major and minor axis**



3a. Estimate the **in-plane pole** component using the **orientation** of the plane's major axis

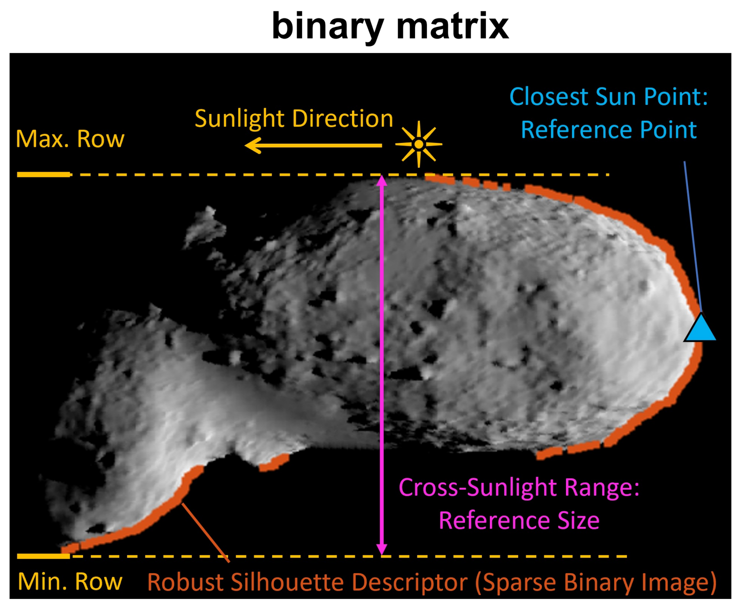
3b. Estimate the **out-of-plane pole** component using the **ratio** between the plane's major and minor axes



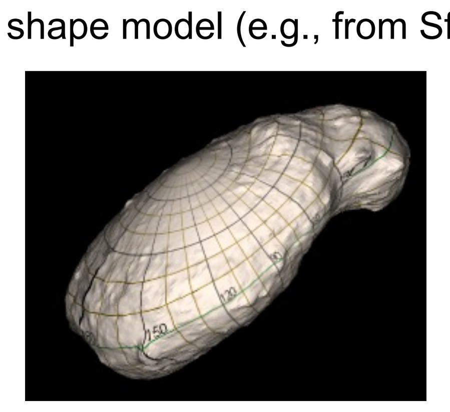
Localization-from-Silhouette (LfS)

- *Estimates the **camera position**, given a low-resolution image, a reference 3D shape model, and the inertial sunlight direction*
- *Localization errors **below grid resolution** of 10 degrees. Can be enhanced using QuadTrees*

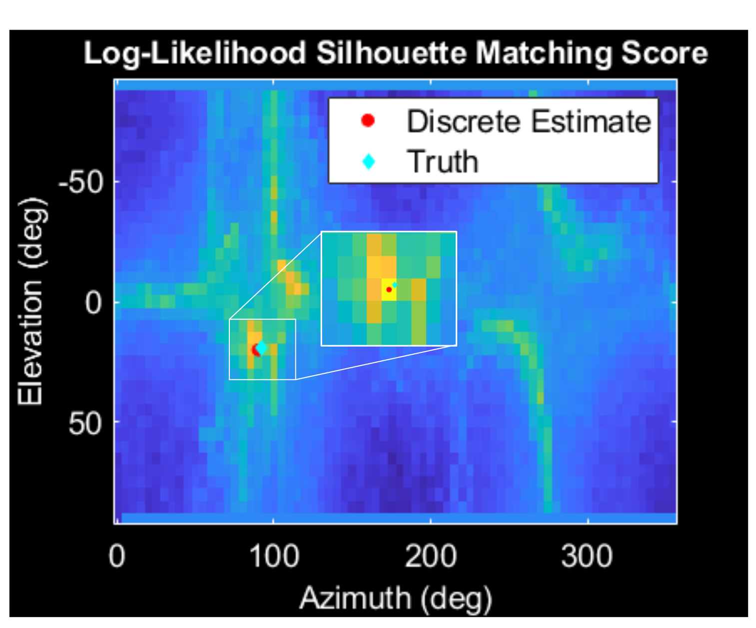
1. Extract **light-robust silhouette descriptor** by only keeping pixels upstream w.r.t. sunlight direction. The descriptor is **scale-and-rotation invariant**, and is stored as an efficient **sparse binary matrix**



2. **Predict silhouette** observations using the 3D shape model (e.g., from SfS)



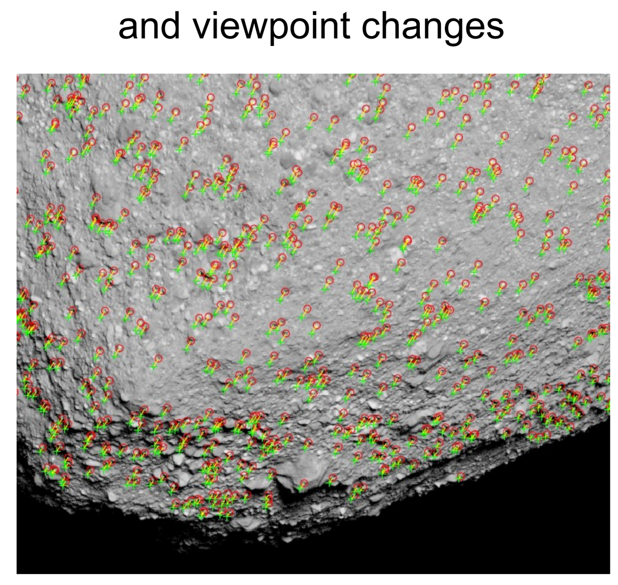
3. **Match observed and predicted** descriptors. The best match corresponds with the expected camera position



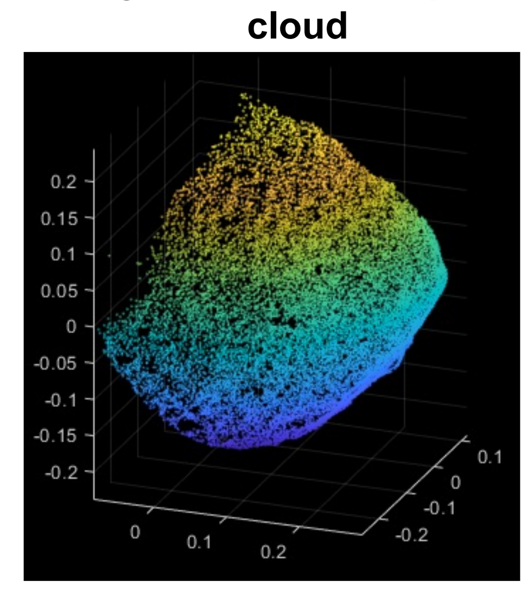
Visual Point Cloud-based Navigation and Mapping (CloudNav)

- *End-to-end navigation and mapping pipeline **without using landmarks**, using opportunistic surface points. Robust to challenging lighting and viewpoint changes.*
- *Positioning **errors** are **below 1% of the radial distance** from the target object.*

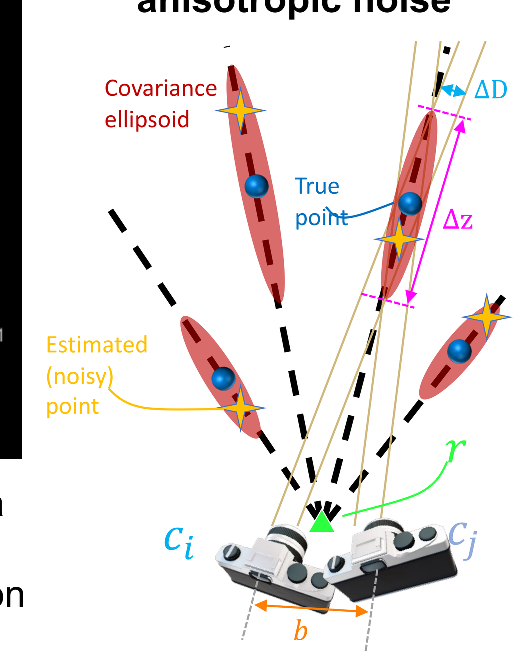
1. **Track** features over a **small stereo baseline** to minimize drift from lighting and viewpoint changes



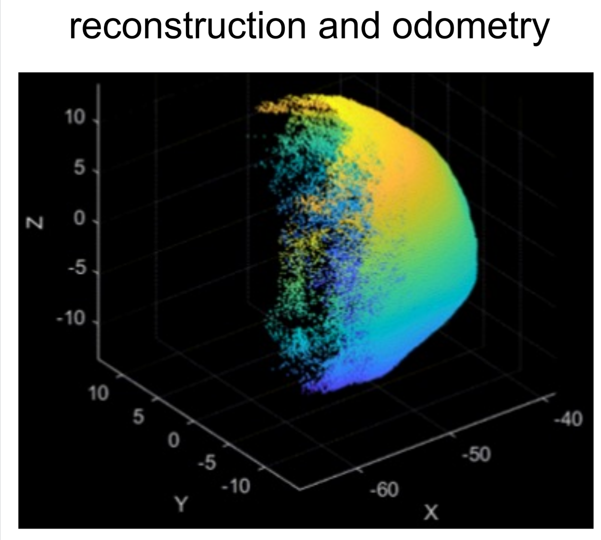
2. Triangulate tracked points to generate a **visual point cloud**



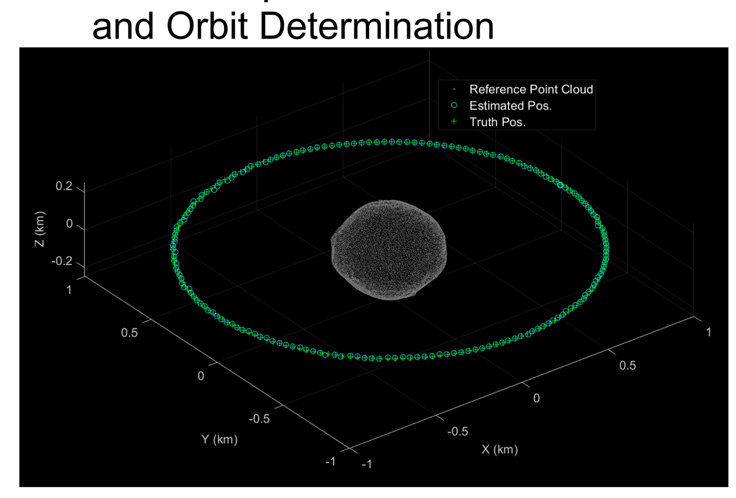
3. Register point cloud with a reference using our **Perspective ICP (P-ICP)** algorithm designed for **anisotropic noise**



Mapping Mode: match consecutive point clouds for shape reconstruction and odometry



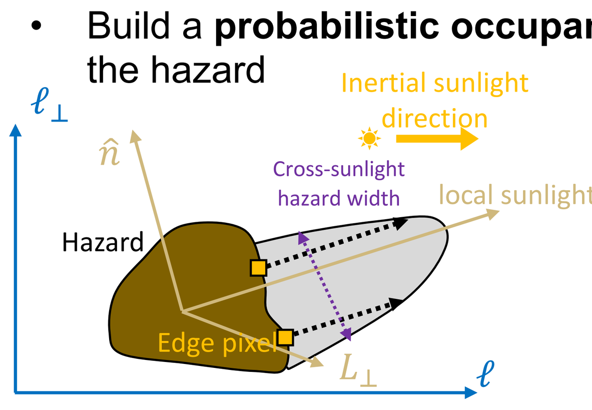
Localization Mode: match a measured point cloud with a reference shape for localization and Orbit Determination

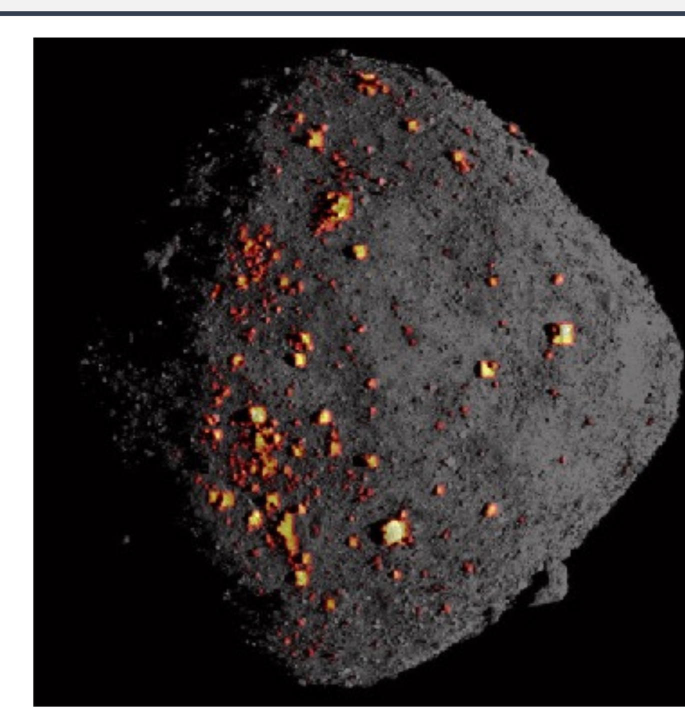


Shadow-Based Hazard Detection

Estimate a probabilistic hazard map using shadow-casting objects

1. Detect **shadow-hazard edge**
2. Estimate the hazard size using a **sample-based approach**
   - For each pixel, scan the cross-sunlight hazard width
   - Build a **probabilistic occupancy grid** for the hazard





Probabilistic hazard maps based on shadow morphology, asteroid Bennu (OSIRIS-REx image)

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.nasa.gov

Clearance Number: CL# 23-xxxx
Poster Number: RPC# xxx
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Publications:

1. J. Villa, J. McMahon, and I. Nesnas, "Image Rendering and Terrain Generation of Planetary Surfaces Using Source-Available Tools", AAS Guidance, Navigation, and Control Conference, Breckenridge, 2023
2. J. Villa, K. Kuppa, J. McMahon, A. Dietrich, and I. Nesnas, "Fast Target-Relative Navigation and Pole Estimation Using Silhouettes in Imagery", AAS Astrodynamics Specialist Conference, Big Sky, 2023
3. M. Givens, J. Villa, J. McMahon, and I. Nesnas, "Visual Point Cloud SLAM for Spacecraft Rendezvous and Proximity Operations", AAS Astrodynamics Specialist Conference, Big Sky, 2023
4. J. Villa, J. McMahon, I. Nesnas, "PICP: Leveraging Sensor Perspective for Accurate Point Set Registration with Radial Anisotropic Noise", IEEE Transactions on Pattern Analysis and Machine Intelligence (in preparation)
5. J. Villa, J. McMahon, I. Nesnas, "CloudNav: Landmark-Free Terrain Relative Navigation at Planetary Bodies Using Visual Point Clouds", Journal of Guidance, Control, and Dynamics (in preparation)

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