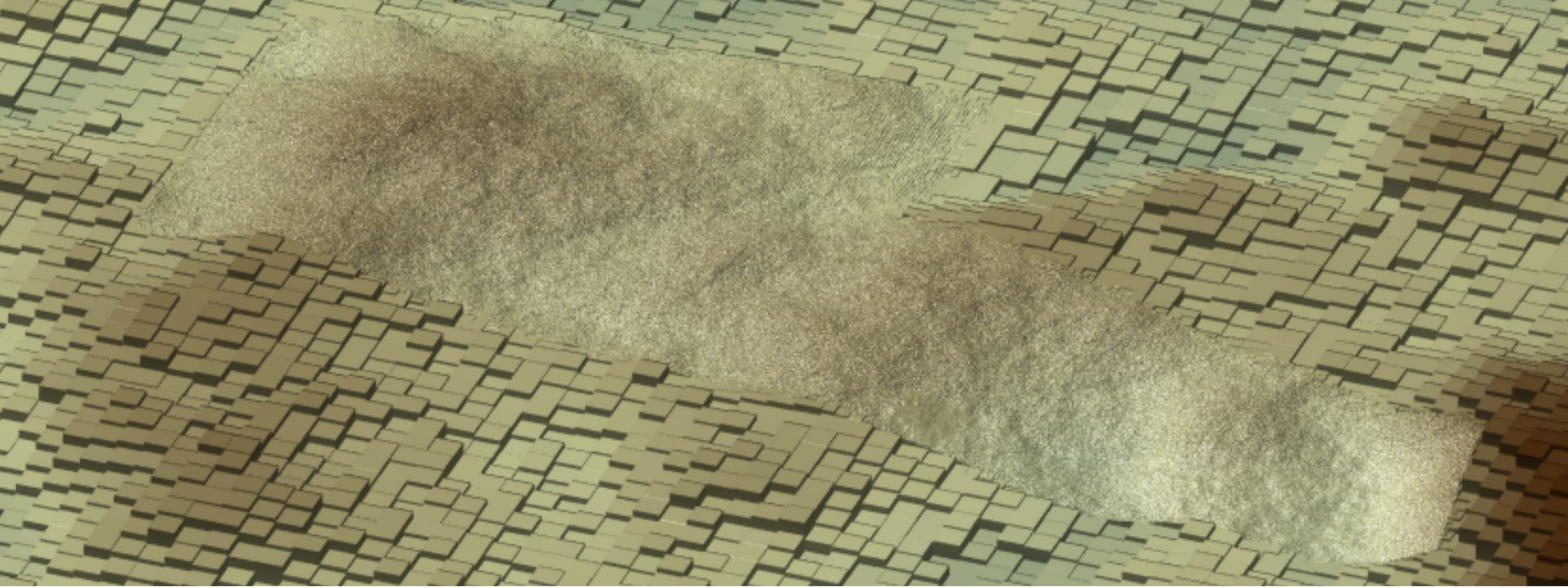

Virtual Research Presentation Conference

LiDAR-Inertial Based Navigation and Mapping for Precision Landing

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Program: Topical R&TD

Assigned Presentation #: RPC-195

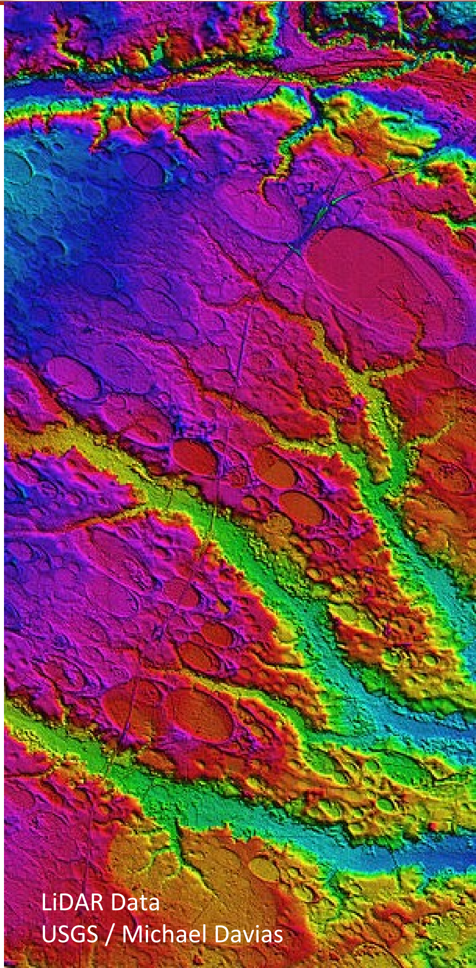
Tutorial Introduction

Abstract

When exploring planetary bodies throughout the solar system, the most scientifically interesting regions – the craters, the canyons, the mountains, the deltas, and the lava tubes – are also the most dangerous, being home to rugged hazardous terrain. The existing solution for landing in hazardous terrain, visual terrain relative navigation (TRN), is not widely applicable throughout the solar system since lander-scale hazard maps are generally unavailable for destinations other than Mars and the Moon. Additionally, to ensure consistent lighting, visual TRN requires that the landing time of day be similar to that when orbital reconnaissance was acquired. These challenges can be mitigated or solved with the LiDAR-inertial navigation and mapping system developed in this R&TD.

A LiDAR instrument is used to measure the distance to a surface by recording the time of flight of a pulsed laser beam. Often, the intensity of the reflected laser beam, which is a function of range, laser power, surface albedo, and surface normal, is also measured.

An inertial measurement unit (IMU) is used to measure the spacecraft's angular velocity and acceleration. Integration of IMU measurements over time can be used to estimate the spacecraft's attitude and position.


LiDAR Data
USGS / Michael Davias

Problem Description

Context

- Future lander missions will travel to destinations without high-resolution orbital reconnaissance (e.g., Europa, Enceladus)
- Safe landing will require terrain relative navigation and onboard generation of lander-scale topographic maps for hazard detection and avoidance
- LiDARs in development for the Europa Lander mission will be capable of operating continuously below 5 km altitude

Advancements Over State of the Art

- Unlike cameras, LiDAR is insensitive to lighting conditions and can be used to map topography
- Smoothing-based technique estimates entire spacecraft trajectory, not just latest state
- Navigation algorithm does not require dedicated phases, and can operate throughout descent, building a topographic map of increasing fidelity

Relevance to NASA and JPL

- Enables safe and precise landing throughout the solar system, in any lighting conditions, when only low-resolution orbital reconnaissance is available

Europa Clipper topographic map pixel size (32 m/px)

○ Approximate Europa Lander footprint (2 m diameter)

□ Estimated map pixel size in this R&TD (0.5m/px)

Methodology

LiDAR-Inertial Dataset Generation

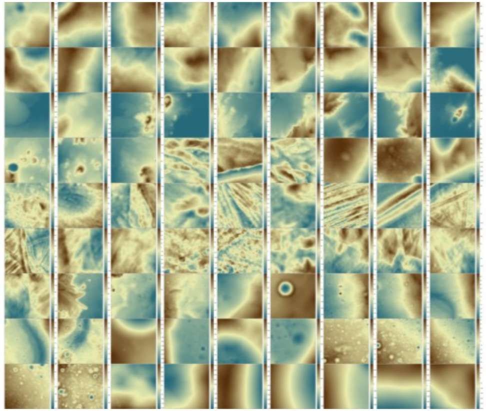
- Obtained data from eight planetary bodies (Ceres, Earth, Enceladus, Eros, Europa, Mars, the Moon, and Vesta)
- Upsampled topographic date to create 81 digital elevation models, each 4×4 km, at 0.5 m/px resolution
- Augmented the Mars 2020 Lander Vision System Simulator (LVSS) for LiDAR simulation during descent

Algorithm Design

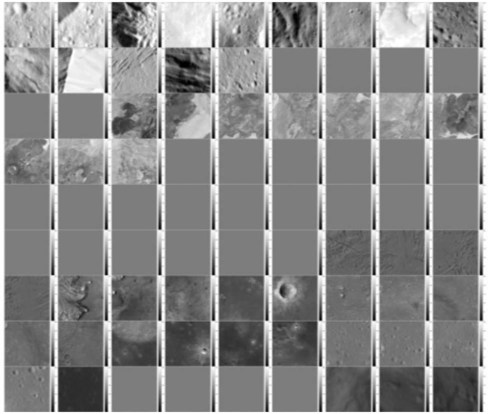
- Factor graph smoothing-based approach to estimate entire spacecraft trajectory (i.e., pose, velocity, and accelerometer and gyroscope biases) at the LiDAR scan frequency
- Includes IMU integration, LiDAR odometry, and topographic map relative localization (MRL), and refinement of a variable resolution quadtree map

Testing

- Tested for descent over all 81 terrains, using two notional simulated trajectories from the Europa Lander mission
- Tested with both flash and scanning LiDAR, with different prior map fidelities



Topographic maps.

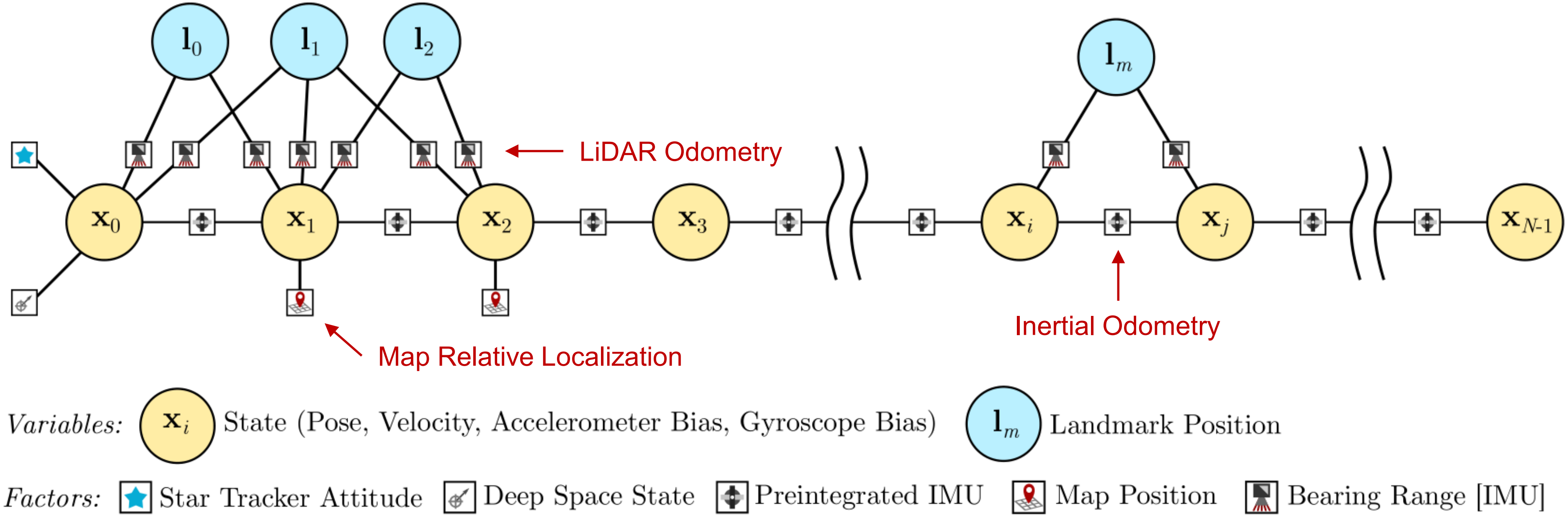


Albedo maps.

Methodology

Factor Graph

- Represents the conditional independence of the problem, with each factor representing a measurement or prior expectation
- Solved incrementally using an augmented version of open source Georgia Tech Smoothing and Mapping (GTSAM) library



LiDAR Odometry

Map Relative Localization

Inertial Odometry

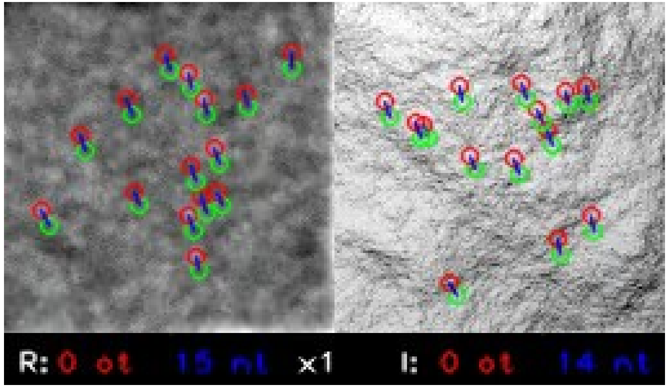
Results

* Videos at 4X speed

LiDAR Odometry

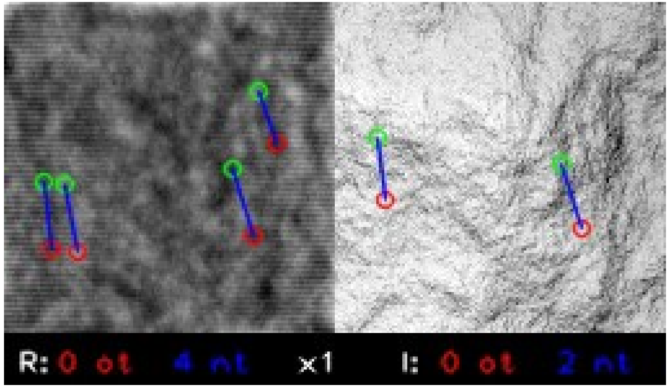
Example case: Europa e-86-1 terrain; trajectory has velocities up to 100 m/s

Flash LiDAR (2 Hz)


High-Passed Range

Intensity

Scanning LiDAR (0.5 Hz)


High-Passed Range

Intensity

━ New feature trails (nt, two features)

━ Old feature trails (ot, more than two features)

🟢 First feature detection

🟡 Intermediate feature detection

🔴 Last feature detection

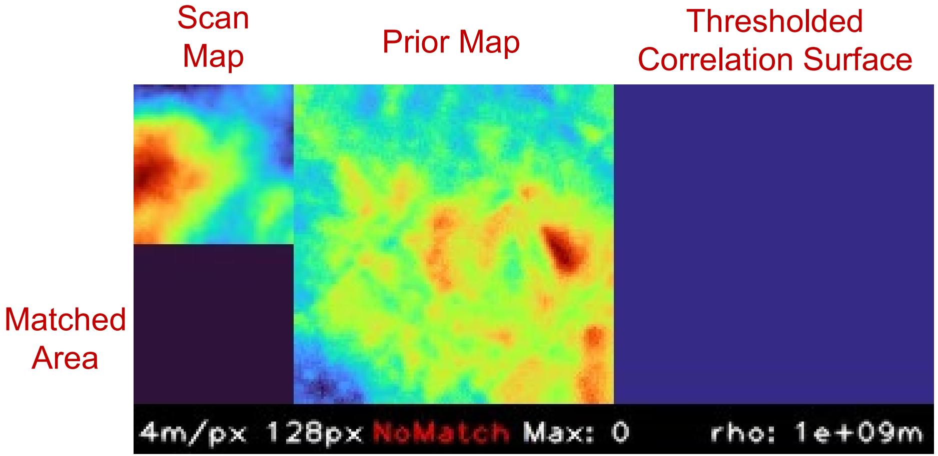
Results

* Videos at 4X speed

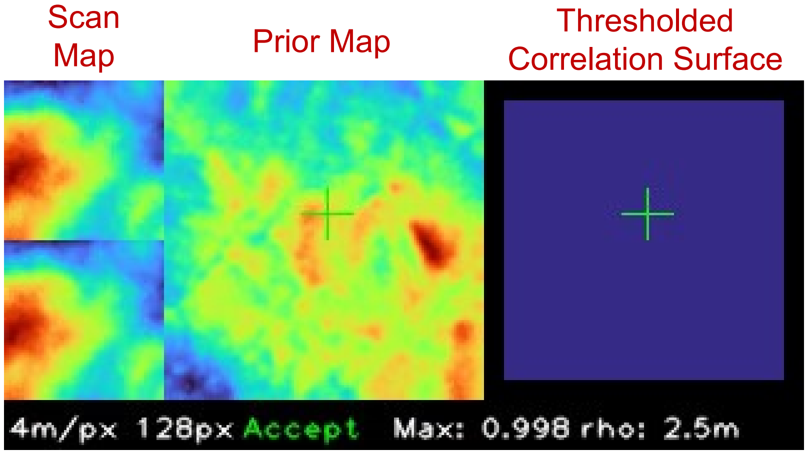
Map Relative Localization

Example case: Europa e-86-1 terrain; trajectory starts at 5 km altitude

Scanning LiDAR, 32 m/px prior map with 4 m 1σ elevation noise



Scanning LiDAR, 4 m/px prior map with 0.5 m 1σ elevation noise



+ Accepted match

+ Rejected match

* Note: MRL is performed by matching a scan map to a topographic map

Results

Estimation Errors

━ · ━ Instantaneous estimate

━━ Smoothed estimate

━ ━ 3σ uncertainty

━━ Inertial odometry with perfect velocity prior (io)

Mean Mag.: Instantaneous (Final)

LiDAR-inertial odometry with MRL, zero velocity prior, and map center position prior

━━ 4 m/px prior orbital map (trad-liom-4mpp)

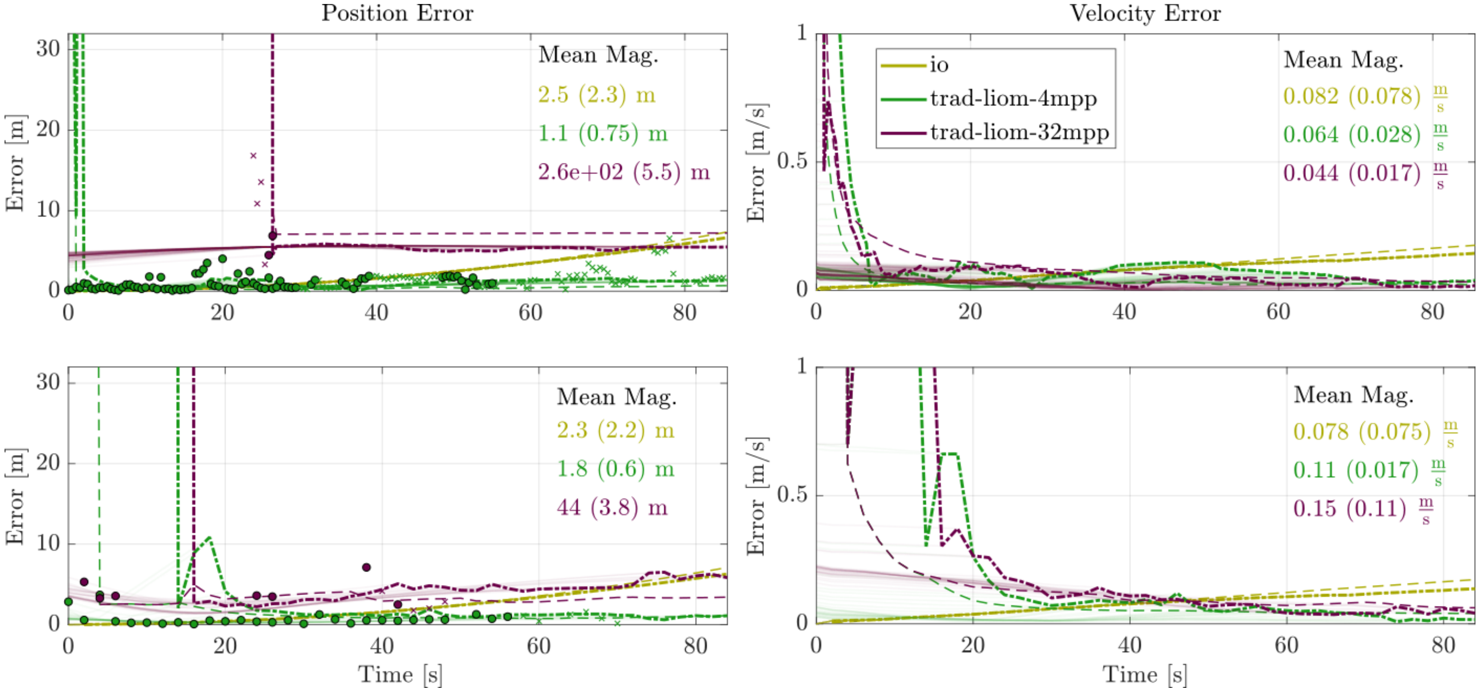
━━ 32 m/px prior orbital map (trad-liom-32mpp)

● Accepted MRL position estimate

× Rejected MRL position estimate

Flash LiDAR

Scanning LiDAR

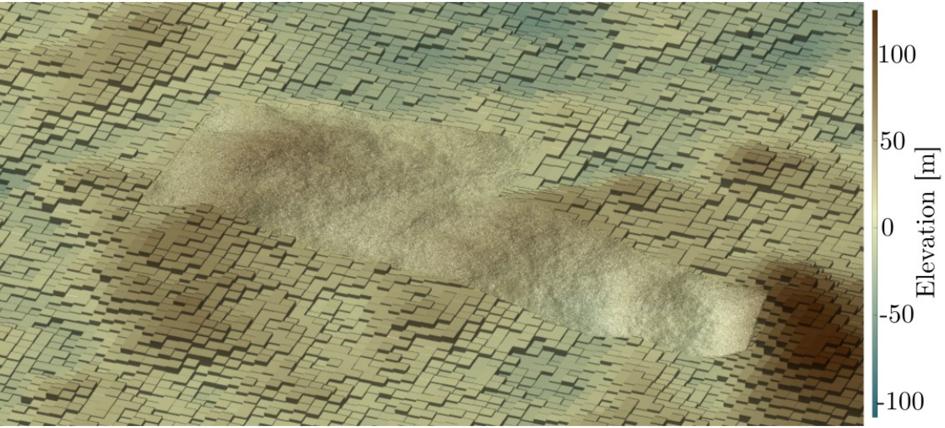


Results

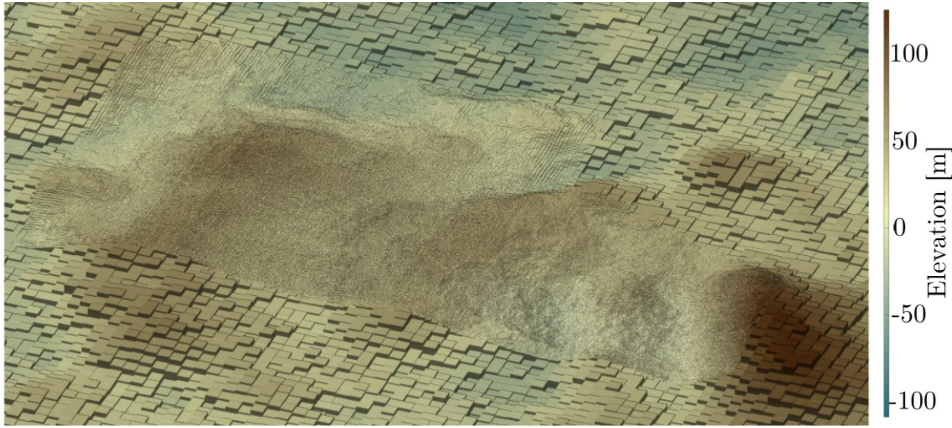
Map Refinement

Example case: Europa e-86-1 terrain with 32 m/px prior map, and 0.5 m/px refined map

Flash LiDAR (6° field of view)



Scanning LiDAR (11.4° field of view)



Results

Accomplishments Versus Goals

- Created a smoothing-based LiDAR-inertial navigation and mapping algorithm
- Tested it on all 81 terrains for two trajectories, with the majority of runs converging on results that met our quantitative objectives
- Performance on par with visual terrain relative navigation in areas where the terrain was sufficiently rough for MRL

Significance

- First smoothing-based landing system at JPL; first landing system to include onboard mapping at all stages of descent
- Demonstrates feasibility of LiDAR-inertial based navigation and mapping for mitigating shortcomings of camera-based systems

Next Steps

- Decouple orientation estimation from the rest of the problem; it is difficult to improve upon star tracker and EDL-class gyroscope
- Adapt software for real-time operation (in JPL FPrime framework)
- Test algorithm with real-world data (either acquired at the JPL Formation Control Testbed, or using existing JPL aerial LiDAR datasets)

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Publications and References

[1] T. P. Setterfield, R. A. Hewitt, P. Chen, A. Teran Espinoza, N. Trawny, A. Katake, LiDAR-Inertial Based Navigation and Mapping for Precision Landing, Abstract Submitted to IEEE Aerospace Conference, 2021