Autonomous Optical Navigation at Jupiter

Nathan B. Stastny
Dr. David K. Geller

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Outline

• Conventional vs. Autonomous Optical Interplanetary Navigation
• AutoNav at Jupiter
• Dynamic Models for Simulations
• Position and Velocity Estimation
• Analysis Tools
• Future Research
Conventional Interplanetary Navigation

**Encounter**
Ground-based approach
optical navigation is limited in accuracy and time, reducing scientific return

**Radio-metric data**
requires costly tracking

**Doppler and Range**

**Images downlinked,**
Nav commands developed,
sequenced and uplinked

Deep Space Network - DSN

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Autonomous Optical Navigation (AutoNav)

**Encounter**
Increased accuracy with onboard navigation closed-loop target tracking, increasing scientific return

Images processed onboard

Spacecraft position and velocity estimated onboard from optical data

Deep Space 1 Spacecraft
Autonomous Optical Navigation at Jupiter

• Can an AutoNav system be used for orbit insertion and orbit determination around Jupiter?

• What are the key parameters that affect system accuracy?

• Research:
  – Baseline: NASA’s proposed Juno mission
  – Navigation: Line-of-sight optical measurements of Jupiter’s moons
  – Performance Analysis: Linear Covariance
• Dynamic models required for simulation and analysis:
  
  – Spacecraft Trajectory
  
  – Jovian System Model
• Two general trajectory segments:
  – Hyperbolic approach
  – Polar orbit ($e \approx 0.97$)

• Point-mass plus J2 Gravitational Model

• Additional perturbations (n-body, J3, J4, etc) are not included, but are accounted for as random disturbances
Jupiter, with 63 known moons, is a very complex system to model.

Utilize “SPICE” to obtain accurate ephemerides.

SPICE is provided by NASA’s Navigation and Ancillary Information Facility (NAIF) at JPL.

High-accuracy data similar to that flown on DS1 and Stardust AutoNav systems.
Truth Models – SPICE Ephemeris Data Files

• SPICE
  – Spacecraft, Planet, Instrument, C-Matrix (Attitude), Events

• Used at JPL for
  – Pre-flight evaluations
  – Modeling
  – Analysis
  – Planning
  – Visualization
Jovian Satellite Orbits (17 of 63) from SPICE Data File

Metis  Adrastea  Ganymede
Kalman filter is an optimal, recursive data processing algorithm.

Estimate spacecraft’s position and velocity.

Continuous-discrete extended Kalman filter would allow for the time-critical operations like orbit insertions maneuvers and flybys.

\[
\begin{align*}
P_{k-1}^- &= \Phi_{k-1}^T P_{k-1}^+ \Phi_{k-1}^T + Q_{k-1} \\
\hat{x}_{k-1}^- &= \Phi_{k-1}^T \hat{x}_{k-1}^+
\end{align*}
\]

\[
\begin{align*}
K_k &= P_k^- H_k^T [H_k P_k^- H_k^T + R_k]^{-1} \\
\hat{x}_k^+ &= \hat{x}_k^- + K_k [\tilde{z}_k - \tilde{\hat{z}}_k] \\
P_k^+ &= (I - K_k H_k) P_k^- (I - K_k H_k)^T + K_k R_k K_k^T
\end{align*}
\]
• Monte-Carlo Analysis:
  – Uses model simulation and Kalman filter (with random processes) to obtain results
  – May require hundreds of runs

• Linear Covariance (LinCov) Analysis:
  – Propagates the model using Gaussian distributions rather than random numbers
  – Results can be obtained in a single run
  – Can save lots of time in pre-flight analysis
What are the key parameters affecting the system accuracy?

Parameters analyzed:
- *A-Priori* Covariance
- Accuracy of estimated moon positions
- Un-modeled accelerations
- Number of moons imaged & imaging frequency
- Image Processing Accuracy
- Noise
Results (Anticipated) – B-Plane Targeting

B-Plane Target Error Ellipse

Jupiter B-Plane

Target Point

Error Ellipse

Jupiter

Target Error Ellipse

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Results (Anticipated) – Problem Parameters

1-σ Semi-Major Axis of B-Plane Error Ellipse Mapped to Encounter

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Possible Future Work

• Expand the model from 3-DOF to 6-DOF

• Include correction maneuvers and controls

• Include background stars in optical measurements

• Use simulated images and image processing algorithms
Summary

• AutoNav Systems
• Truth Models
  – Spacecraft Trajectory
  – SPICE
• Kalman Filter
• LinCov Analysis
• Problem Parameters
• Anticipated Results
Questions?