Linear Covariance Analysis for Proximity Operations Around Asteroid 2008 EV5

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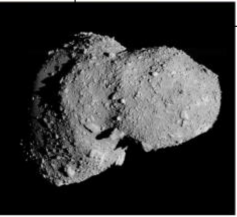


Outline

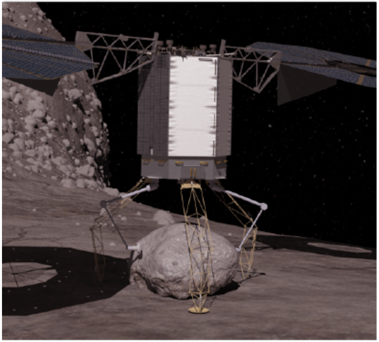
ARRM Mission Overview

Overall goal is to rendezvous with and asteroid and either

1. Option A: Redirect an entire smaller asteroid back to lunar orbit.
2. Option B: Collect a boulder off of a larger asteroid, perform planetary defense demonstration, deliver boulder to lunar orbit.

The objective of this paper is to assess the feasibility of two critical phases of Option B:

1. Descent to surface of asteroid.
2. Planetary Defense Demonstration: Enhanced Gravity Tractor



Option B Boulder Capture [1]

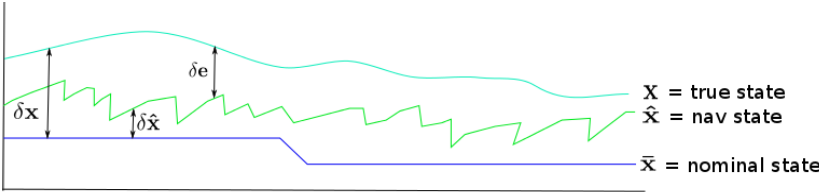
Linear Covariance Analysis (LCA)

- A Linear Covarance Analysis was performed for each phase.
- Linear Covariance Analysis (LCA) provides the capability to characterize the performance of a GNC system in a single run rather than the many runs required for a Monte Carlo simulation.
- An augmented covariance (defined later) is propagated and updated to generate the performance metrics. This covariance represents the "navigation dispersions" as well as the "trajectory dispersions."
- In a LCA only the covariance is propagated and not the state.

State/Covariance Definitions

Overview of States Represented

- True/Environment Dispersions: True State - Nominal State
- Navigation Dispersions: Nav State - Nominal State
- Onboard Navigation Errors: True - Nav State



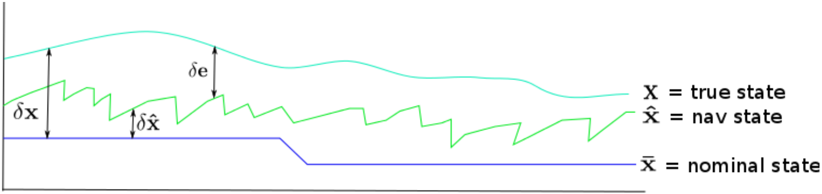
A **dispersion** is defined as a deviation from the nominal state and an **error** is defined as a deviation from the 'truth' state. [3].

State/Covariance Definitions

Covariance Definitions

$$\mathbf{D}_{true} = E[\delta\mathbf{x}\delta\mathbf{x}^T] \qquad \mathbf{D}_{nav} = E[\delta\hat{\mathbf{x}}\delta\hat{\mathbf{x}}^T]$$

$$\mathbf{P}_{onboard} = E[\delta\mathbf{e}\delta\mathbf{e}^T] \quad \mathbf{D}_{aug} = \begin{bmatrix} E[\delta\mathbf{x}\delta\mathbf{x}^T] & E[\delta\mathbf{x}\delta\hat{\mathbf{x}}^T] \\ E[\delta\hat{\mathbf{x}}\delta\mathbf{x}^T] & E[\delta\hat{\mathbf{x}}\delta\hat{\mathbf{x}}^T] \end{bmatrix}$$



Sensors

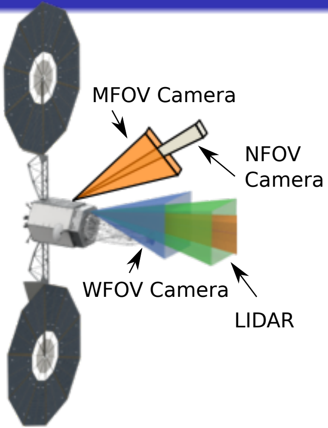
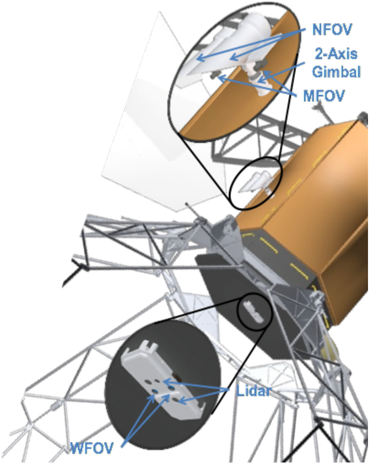
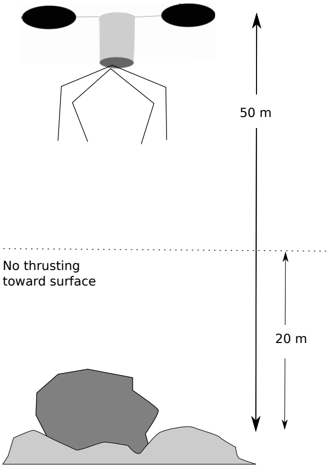


Image Courtesy of [2]



- WFOV Camera, Lidar, and IMU used for Descent
- MFOV Camera and IMU used for Enhanced Gravity Tractor

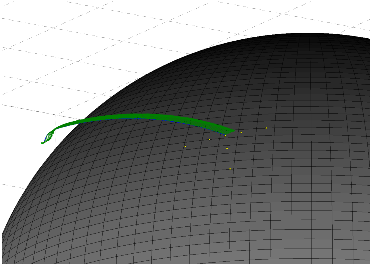
Descent to Surface



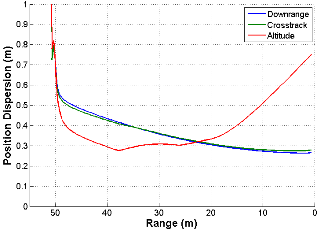
- Asteroid 2008 EV5
- Descent from 50 m to the Surface of the Asteroid
- No thrusting toward the surface below 20 m
- Requirement: Capture arms must be centered over the boulder to within 50 cm
- Using WFOV Camera, Lidar, and IMU
- Continuous PD controller used to track desired trajectory

Results

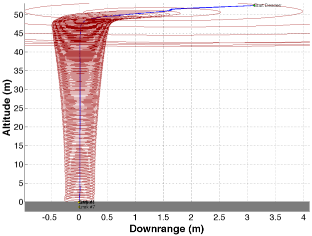
Nominal Trajectory



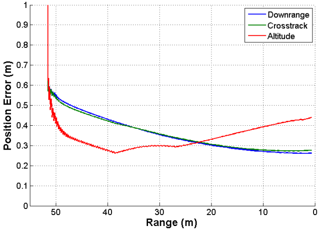
Position Dispersions



Dispersions Along Trajectory



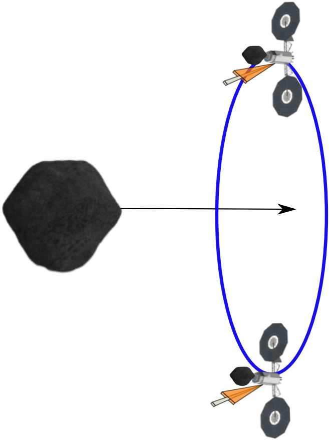
Navigation Errors



Enhanced Gravity Tractor

- Halo Orbit about vbar of Asteroid
- 400 m from center of 2008 EV5
- MFOV Camera used with onboard Stereo Photoclinometry for relative navigation
- Hold halo orbit for 30 days

Enhanced Gravity Tractor



Enhanced Gravity Tractor Control

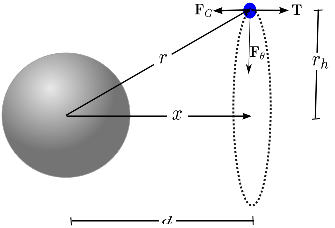
Two types of Control Investigated:

1. Constant Control to Counteract Gravitational Force Along Vbar

$$T = \frac{-GMm}{r^2}\left(\frac{x}{r}\right)$$

2. PD Controller Following Desired Trajectory

Enhanced Gravity Tractor

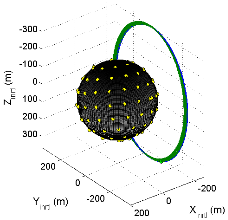


$$\mathbf{r}_{des} = \begin{bmatrix} d \\ r_h \cos(\omega t) \\ r_h \sin(\omega t) \end{bmatrix}$$

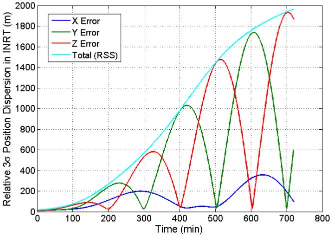
$$\mathbf{v}_{des} = \begin{bmatrix} 0 \\ -r_h \omega t \sin(\omega t) \\ r_h \omega t \cos(\omega t) \end{bmatrix}$$

Constant Thrust

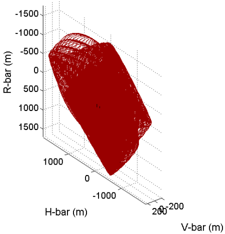
Nominal Trajectory



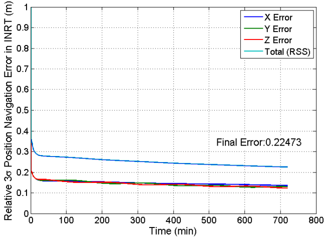
Position Dispersions



Dispersions Along Trajectory

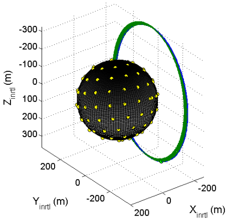


Navigation Errors

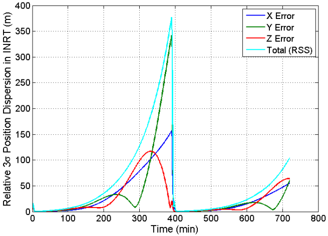


PD Control

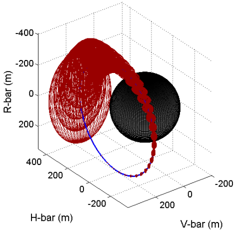
Nominal Trajectory



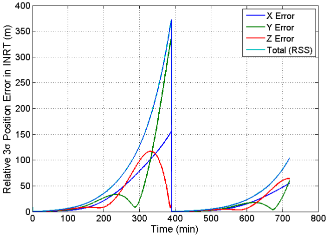
Position Dispersions



Dispersions Along Trajectory

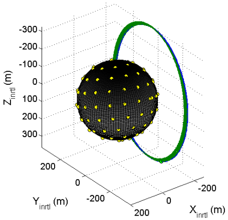


Navigation Errors

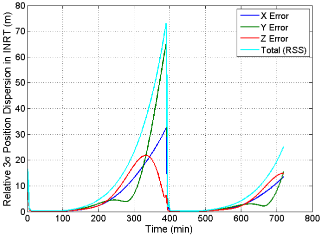


PD Control With 90 Minute Measurement Arc

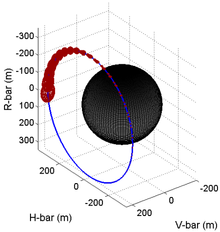
Nominal Trajectory



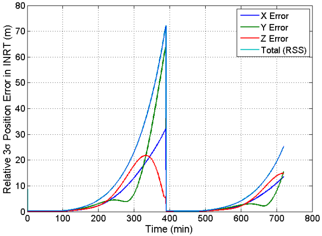
Position Dispersions



Dispersions Along Trajectory

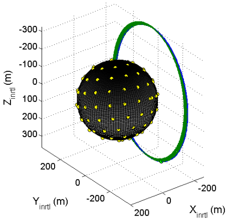


Navigation Errors

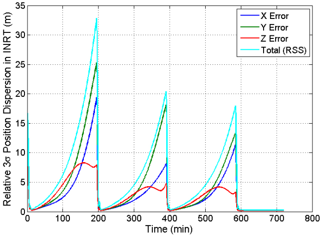


PD Control With Two Measurement Arcs Per Orbit

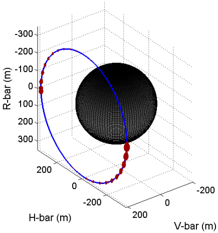
Nominal Trajectory



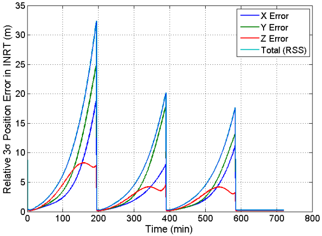
Position Dispersions



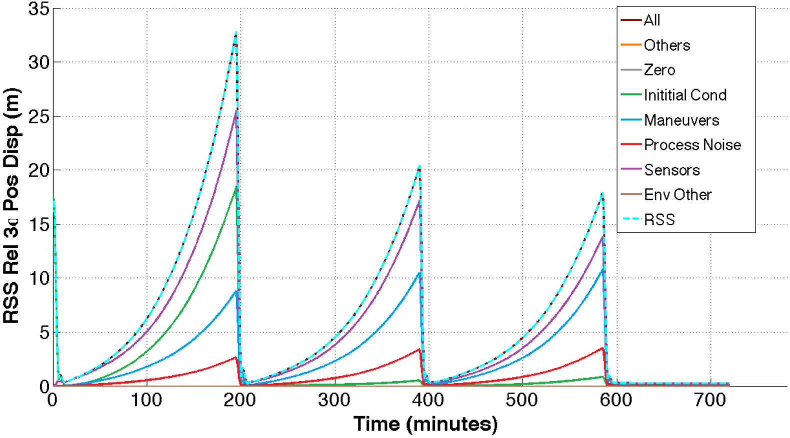
Dispersions Along Trajectory



Navigation Errors



Error Budget



Conclusions

- Position dispersions stay below 50 cm requirement For descent
- Constant thrust to maintain halo orbit is not feasible
- Several measurement arcs may be required to maintain halo orbit

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References I

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https://www.nasa.gov/sites/default/files/files/AsteroidRedirectMissio

[3] David Woffinden, Leonard Epstein, George Stafford, Todd Mosher, John Curry, and Zachary Krevor. Dream chaser on-orbit operations: Preliminary trajectory design and analysis. AIAA 2011-6654, 2011.