Robust Autonomous Spacecraft Navigation and Environment Characterization

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Abstract

The characterization of properties of a celestial body (e.g., the gravity field, rotational motion, and 3D shape) is often coupled to some extent with the navigation of an orbiting spacecraft. This task belongs to a class of estimation problem defined in this work as simultaneous navigation and characterization (SNAC). Currently, SNAC is completed almost exclusively offline and on the ground for missions in Earth orbit and deep space. However, autonomous SNAC can reduce mission costs and the burden on ground-based resources. This work enables autonomous SNAC through the development of new algorithms that are robust enough to operate dependably without significant human oversight and that are computationally efficient enough for onboard execution. First, new algorithms are presented to increase the robustness of spacecraft navigation to dynamics modeling deficiencies and system nonlinearities in a computationally efficient manner. Then a novel approach is described for 3D shape reconstruction of celestial bodies using spherical harmonics. Regularization based on empirical knowledge of the shape characteristics of celestial bodies is used to significantly increase the accuracy and robustness of the reconstructed shape. These contributions are leveraged in the development of a new multi-spacecraft mission concept that uses intersatellite radio-frequency measurements and optical landmark tracking to autonomously characterize an asteroid including its gravity field, 3D shape, and rotational motion. This mission concept is called Autonomous Nanosatellite Swarming (ANS). A high-fidelity numerical simulation of three spacecraft orbiting the asteroid 433 Eros demonstrates that ANS provides accurate navigation and asteroid characterization without any a priori shape model. After just 10 orbits, the spacecraft position uncertainty is less than 10m, and the asteroid shape is reconstructed with a root mean square error that is 3.7% of the true average asteroid radius. Additionally, the asteroid gravity spherical harmonic coefficients are estimated to an uncertainty approximately equal to or less than the magnitude of the true coefficients up through degree and order six. From the shape and gravity recovery, the bulk density is estimated with an error that is 0.16% of the true value.

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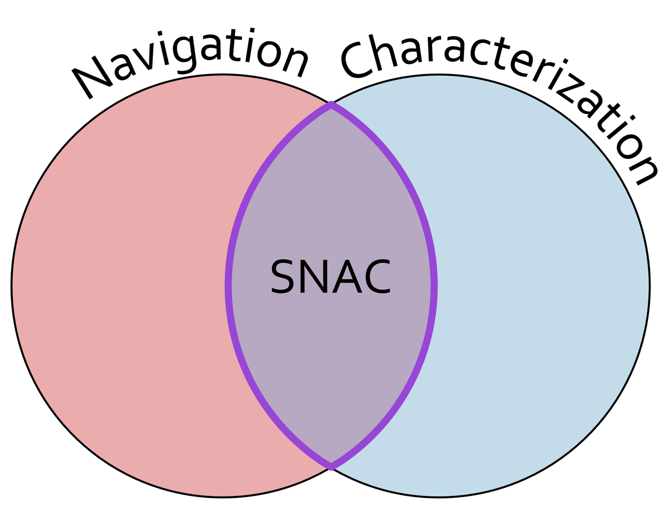
Motivation and Objectives

Improved algorithms for spacecraft navigation and environment characterization are developed to expand autonomy in Earth orbit and deep space

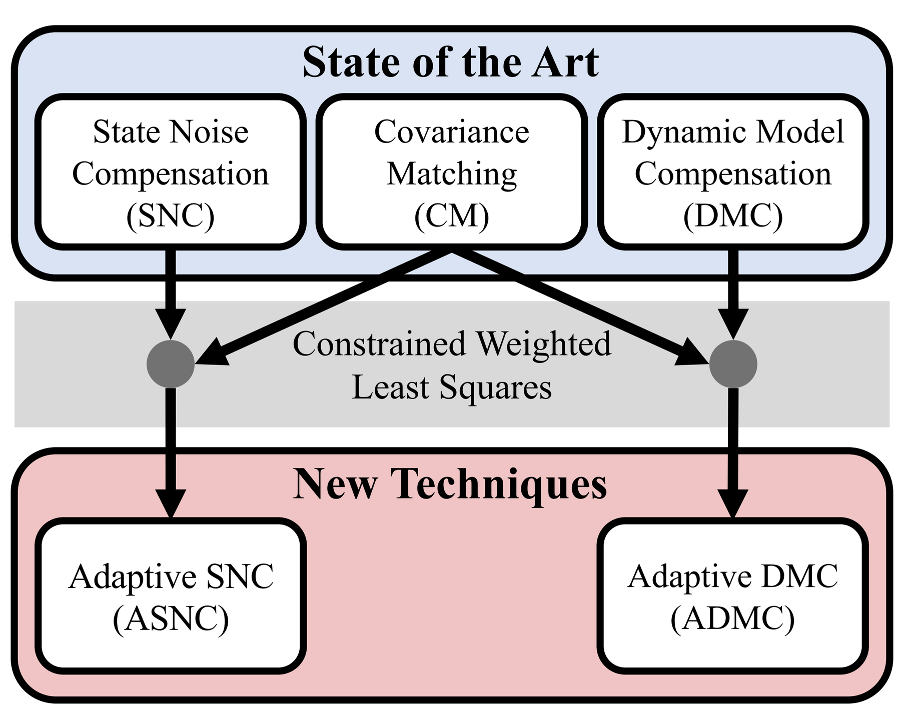
- Navigation and environment characterization (e.g., estimation of body gravity field, shape, or rotational motion) are often coupled, which is defined here as simultaneous navigation and characterization (SNAC)
- Autonomy reduces cost and may be required when the spacecraft must react quickly or communication delays are significant
- Autonomous algorithms must be computationally efficient and robust enough for onboard execution without human oversight
- Computationally efficient and robust algorithms for navigation and characterization are presented to expand autonomy

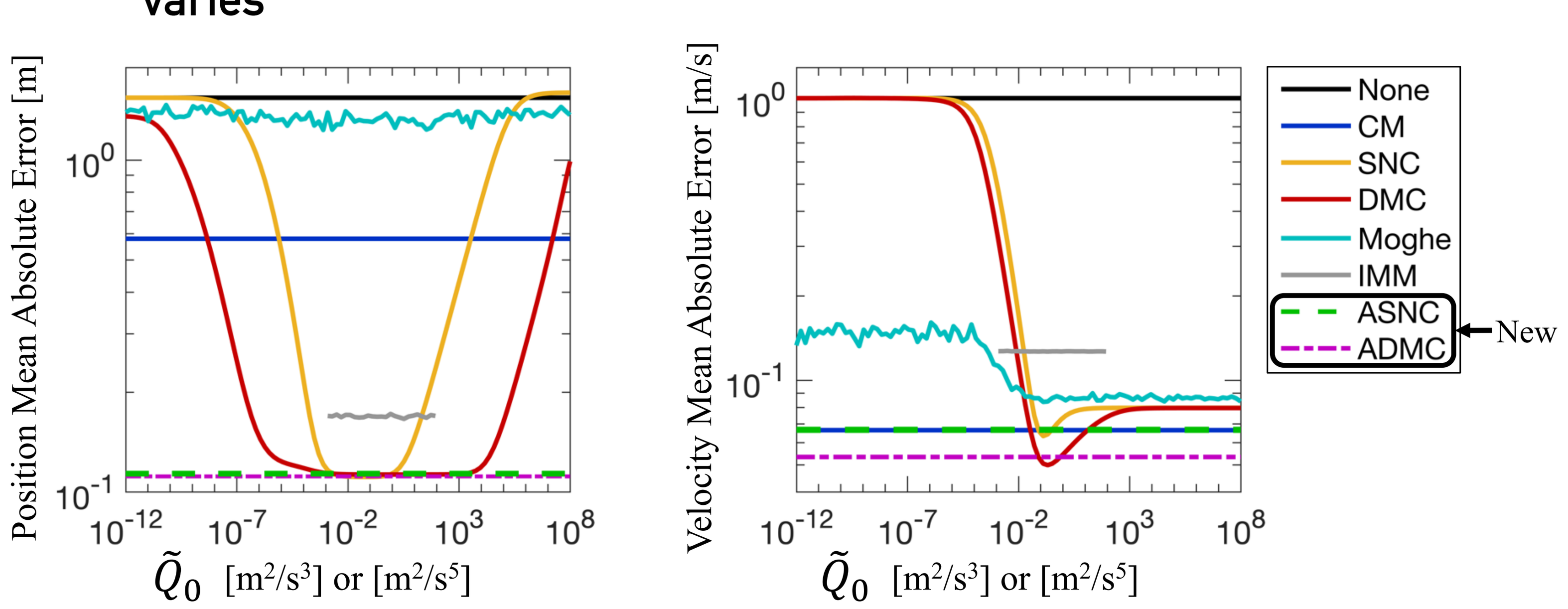


Process Noise Modeling and Estimation

New computationally efficient algorithms developed for robust navigation in presence of dynamics modeling uncertainties

- Analytical models of the process noise covariance, Q, are derived for absolute and relative spacecraft states
  - Models provide accurate Q, which is essential for navigation through Kalman filtering
  - Considers Cartesian and orbital element state parameterizations
- Approach proposed to adaptively estimate Q
  - Existing algorithms are fused to overcome their limitations
  - Beneficial when Q is poorly known a priori or varies





Computationally Efficient Estimation Filter

Novel method for more computationally efficient navigation with no loss of accuracy

- The unscented Kalman filter (UKF) is accurate but can be computationally expensive
- New technique is derived to reduce UKF run time with no loss of accuracy
- Method leverages matrix triangular structure to avoid redundant computations

$$\Gamma\Gamma^T = \mathbf{P}$$

$$\mathbf{A} = \sqrt{n+\psi}\,\Gamma$$

$$\mathbf{A} = \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ a_{21} & a_{22} & \ddots & \vdots \\ \vdots & & \ddots & 0 \\ a_{n1} & \cdots & \cdots & a_{nn} \end{bmatrix}$$

$$\chi_{[0]} = \boldsymbol{\mu}$$

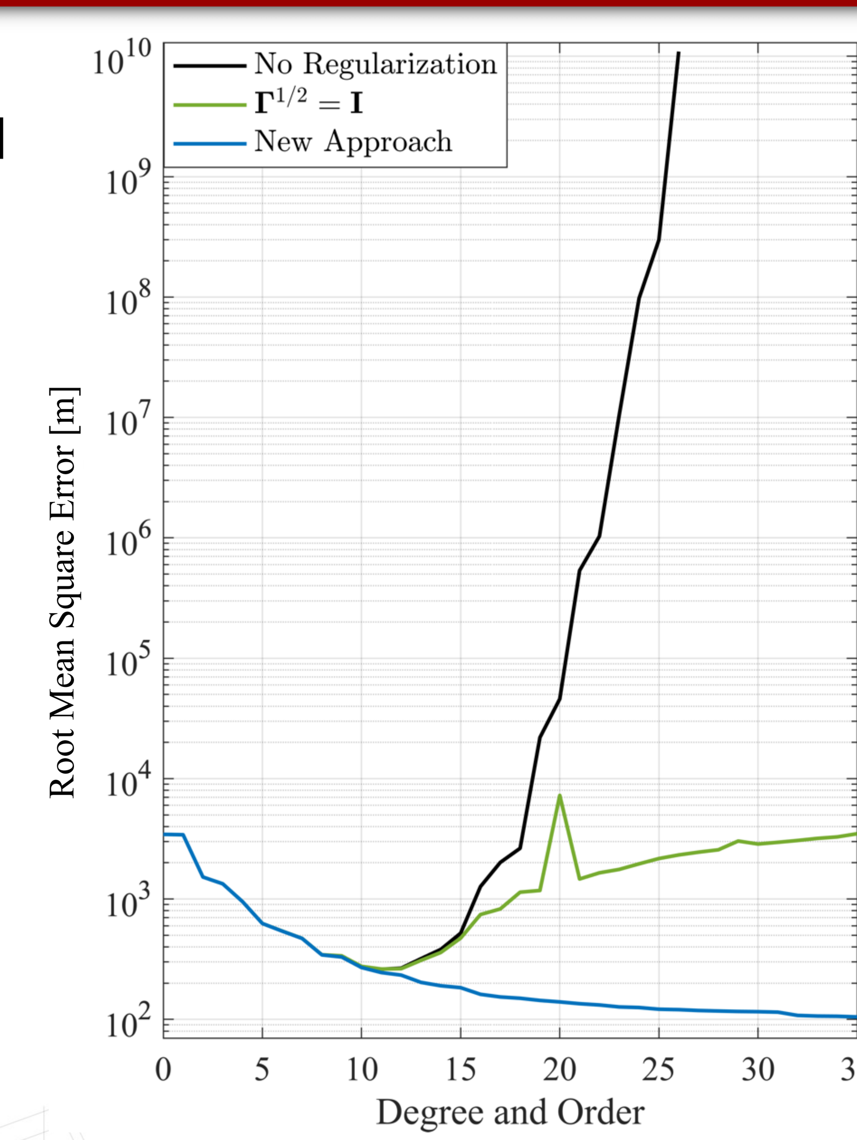
$$\chi_{[i]} = \boldsymbol{\mu} + \boldsymbol{A}_{[i]} \quad \text{for } i = 1,\ldots,n$$

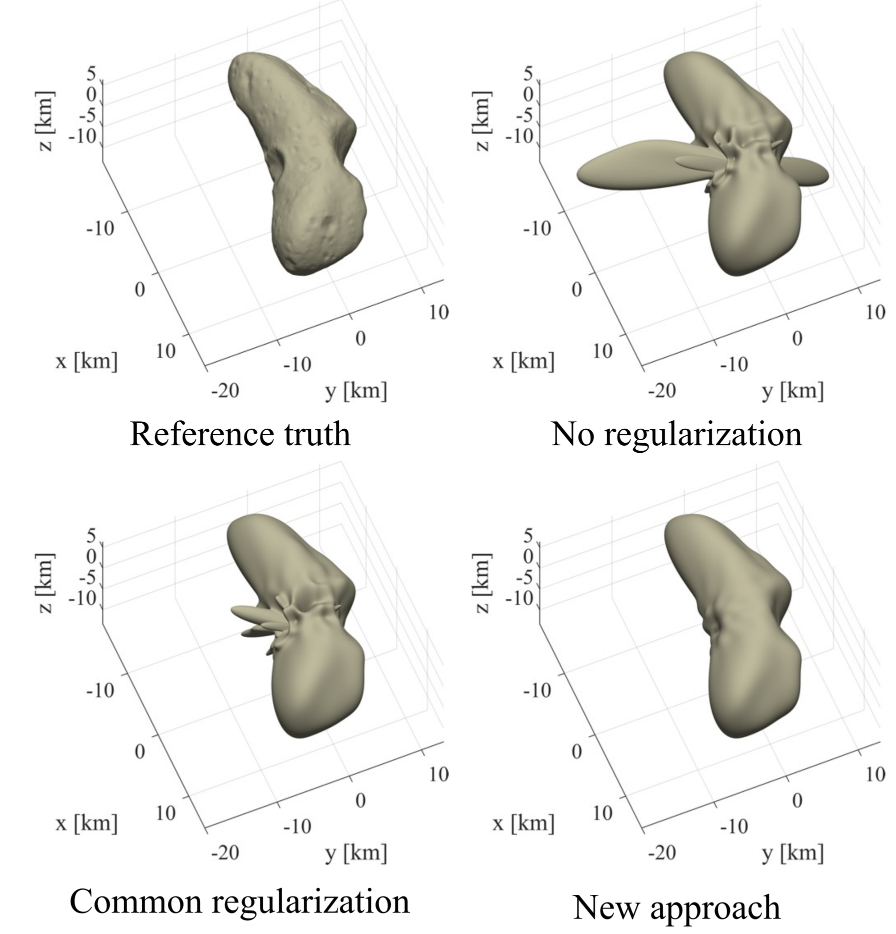
$$\chi_{[i]} = \boldsymbol{\mu} - \boldsymbol{A}_{[i-n]} \quad \text{for } i = n+1,\ldots,2n$$

Shape Reconstruction of Celestial Bodies

New algorithm for computationally efficient and robust shape reconstruction

- Algorithm leverages empirical knowledge of shape characteristics of celestial bodies
  - Spherical harmonic coefficients are fit to 3D point cloud
  - Regularization based on empirical data prevents over fitting
  - Robust and efficient enough for autonomy



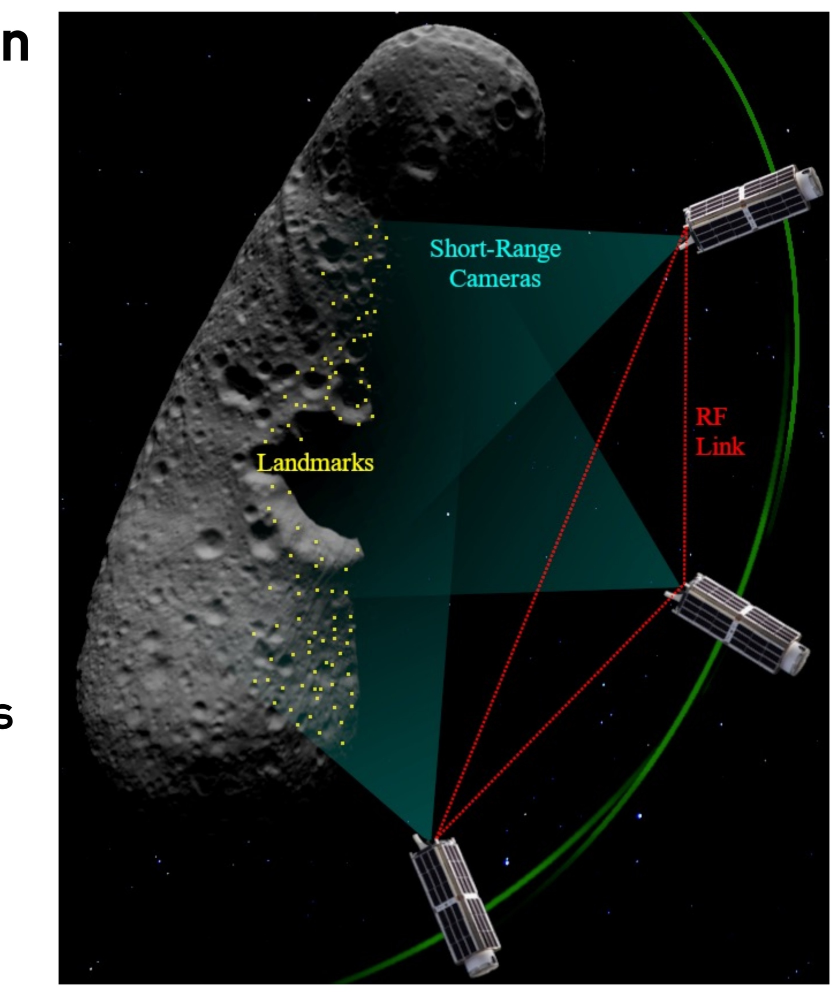


- New approach outperforms state of the art techniques
  - 750 points sampled on surface of truth shape model of Eros
  - Models of varying degree constructed using different approaches (see left for degree 16 models)
  - Benefits more pronounced for higher degrees

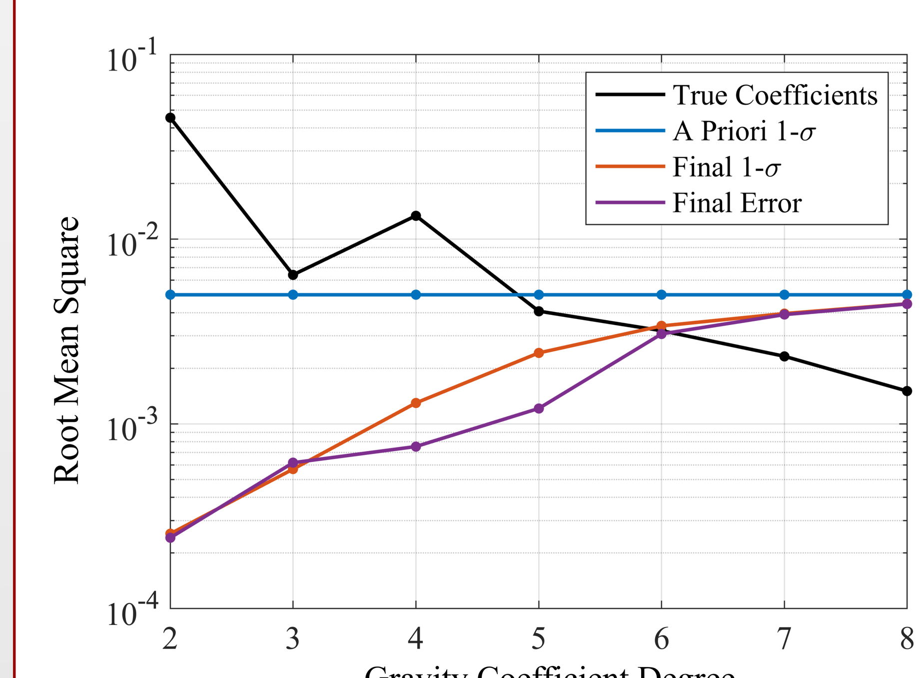
Autonomous Asteroid Characterization

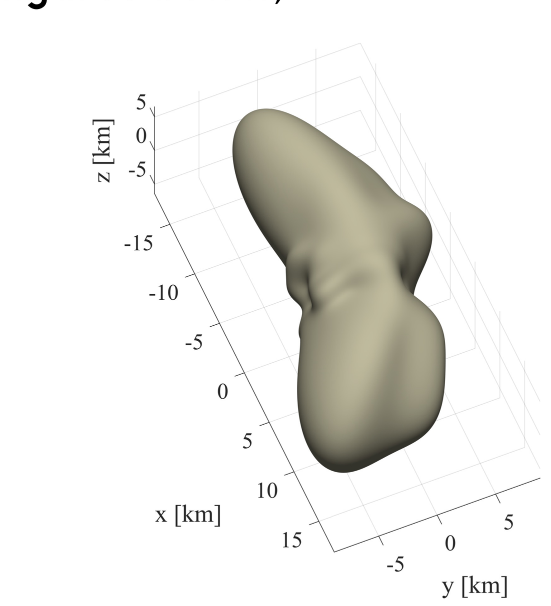
Novel multi-spacecraft mission architecture for autonomous asteroid characterization

- Mission called Autonomous Nanosatellite Swarming (ANS)
  - Satellites cooperate to autonomously achieve SNAC using asteroid images and intersatellite radio-frequency measurements
  - Algorithmic pipeline leverages algorithmic contributions described earlier
  - ANS reduces cost and burden on ground through autonomy



- Computer simulation shows ANS achieves accurate autonomous SNAC
  - Three spacecraft, ten orbits about asteroid Eros
  - Spacecraft positioning and clock synchronization uncertainties of 8 m and 11 ns respectively (1-σ)
  - Rotational motion uncertainty of 0.02° (1-σ)
  - Accurate gravity and shape recovery (see figures below)





Degree 10 shape reconstruction
RMS Error is 3.7% of average radius
Density error = 0.16%

Publications

N. Stacey, "Robust Autonomous Spacecraft Navigation and Environment Characterization," *Stanford University*, PhD Thesis, (2022).

N. Stacey, K. Dennison, and S. D'Amico, "Autonomous Asteroid Characterization through Nanosatellite Swarming," *IEEE Aerospace Conference*, Big Sky, MT, Mar. 5-12 (2022). Submitted to *IEEE TAES*, (2022).

N. Stacey and S. D'Amico, "Analytical Process Noise Covariance Modeling for Absolute and Relative Orbits," *Acta Astronautica*, (2022).

N. Stacey and S. D'Amico, "Adaptive and Dynamically Constrained Process Noise Estimation for Orbit Determination," *IEEE TAES*, (2021).