Autonomous Nanosatellite Swarming using Radio-Frequency and Optical Navigation (ANS)

Kaitlin Dennison (kdenn@stanford.edu), Nathan Stacey, Corinne Lippe, Tommaso Guffanti

PI: Prof. Simone D'Amico (damicos@stanford.edu)

Stanford's Space Rendezvous Laboratory (SLAB)

NASA POC: Dr. Howard Cannon

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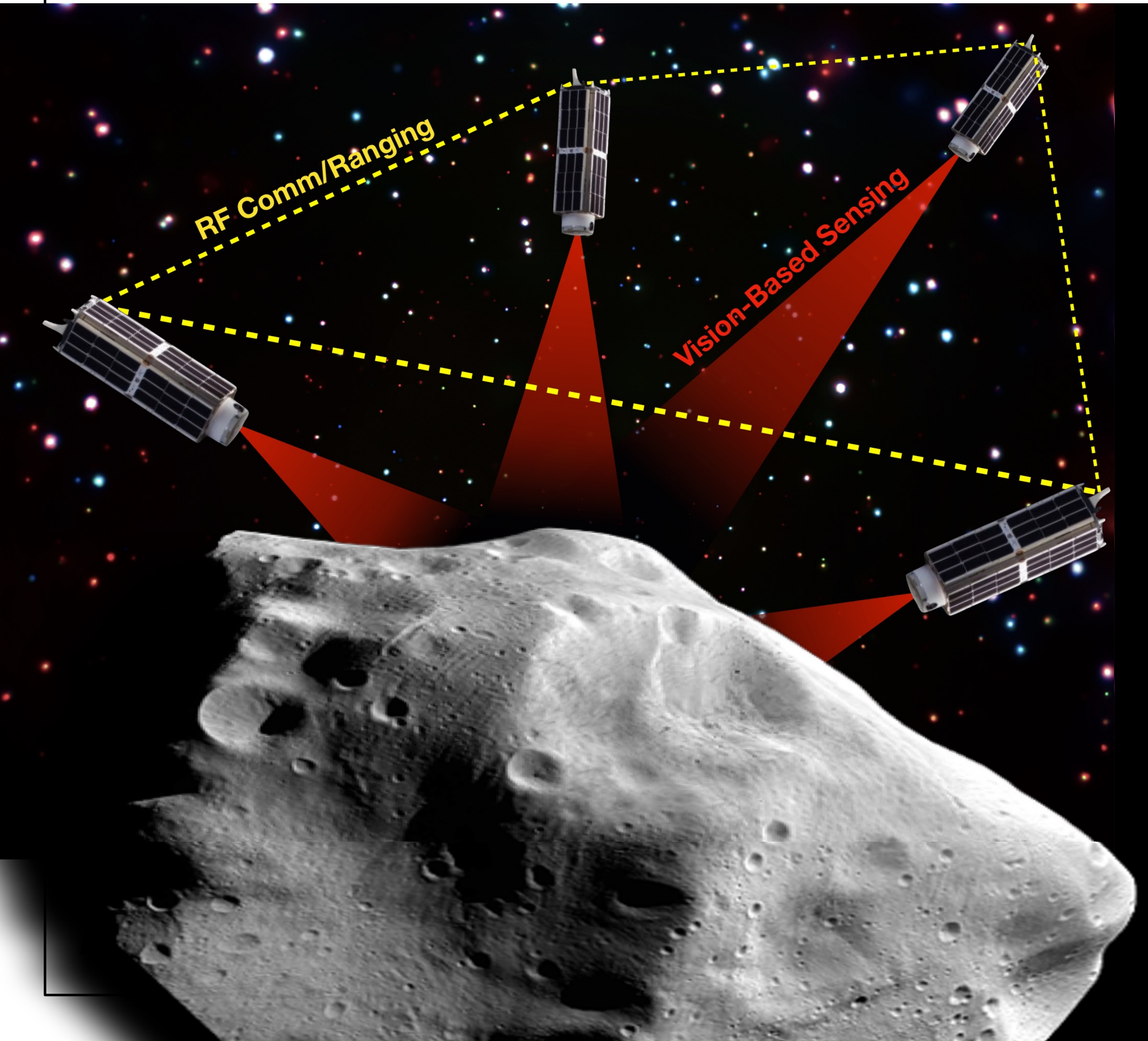
Autonomous **N**anosatellite **S**warming using Radio Frequency and Optical Navigation



Online Operations:

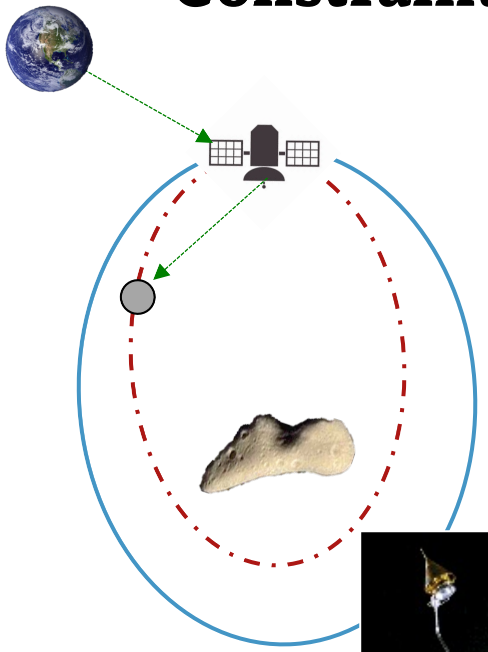
- ✓ Shape Modelling
- ✓ Gravity Recovery
- ✓ Navigation
- ✓ Orbit Guidance
- ✓ Optimal Control

System Improvements:

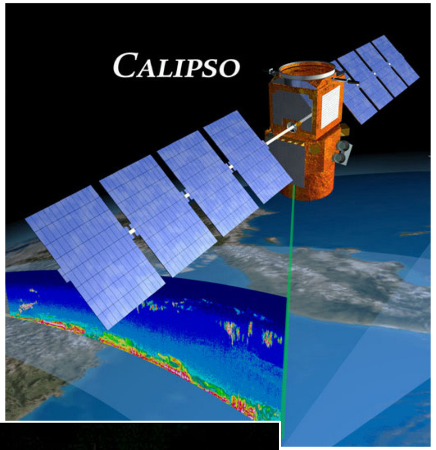
- ✓ Reduced Sensors
- ✓ Low SWaP-C Avionics
- ✓ Multi-Agent

ANS Mission to a Small Body

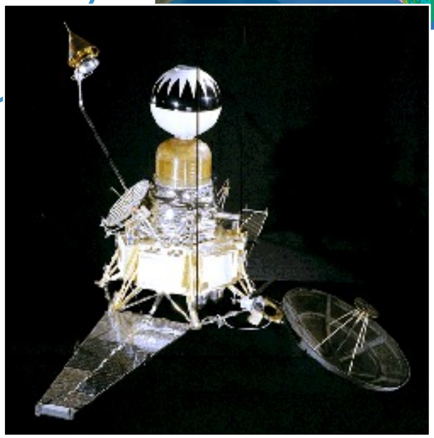
Constraints to Eliminate



Constant GIL



Extraneous, power-intensive sensors



High cost and lack of redundancy

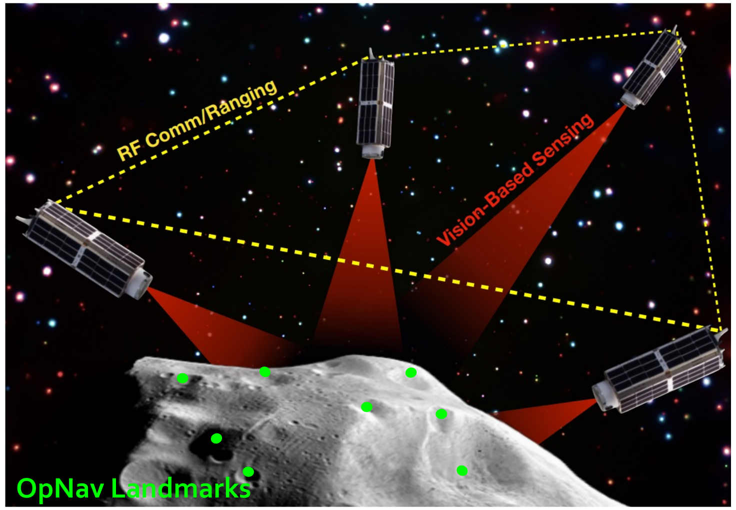
Proposed ANS System

Online Operations:

- Shape Modelling
- Gravity Recovery
- Navigation
- Orbit Guidance
- Optimal Control

System Improvements:

- Reduced Sensors
- Low SWaP-C Avionics
- Multi-Agent



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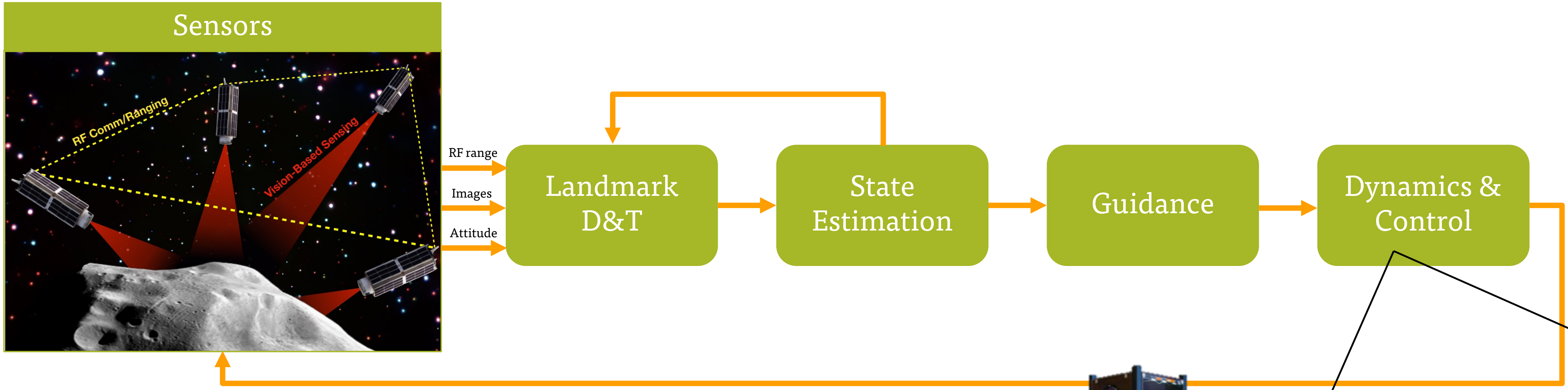
ANS GN&C Pipeline and Tech Advancements

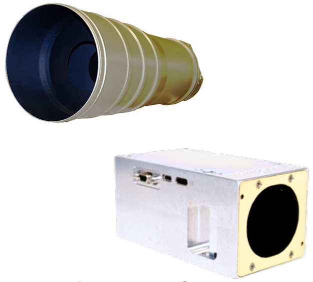
GN&C Pipeline

GN&C Pipeline

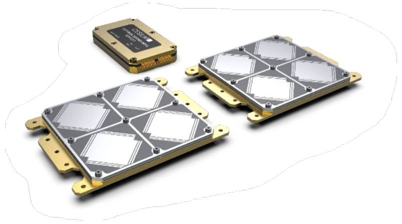


Measurements from the true spacecraft and asteroid dynamics

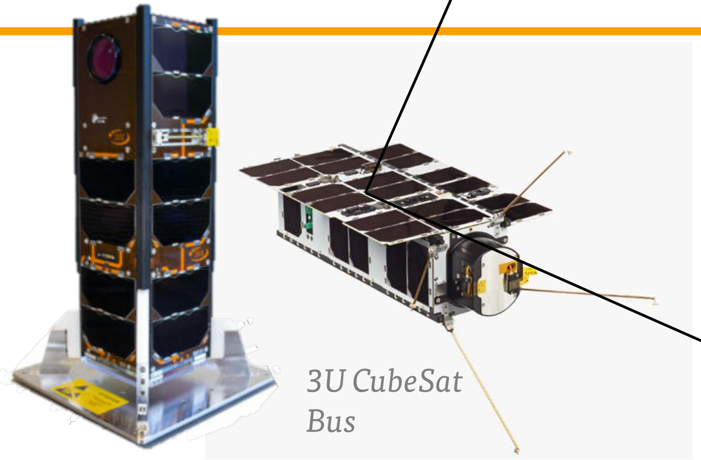
Short-Range Camera



Star Tackers

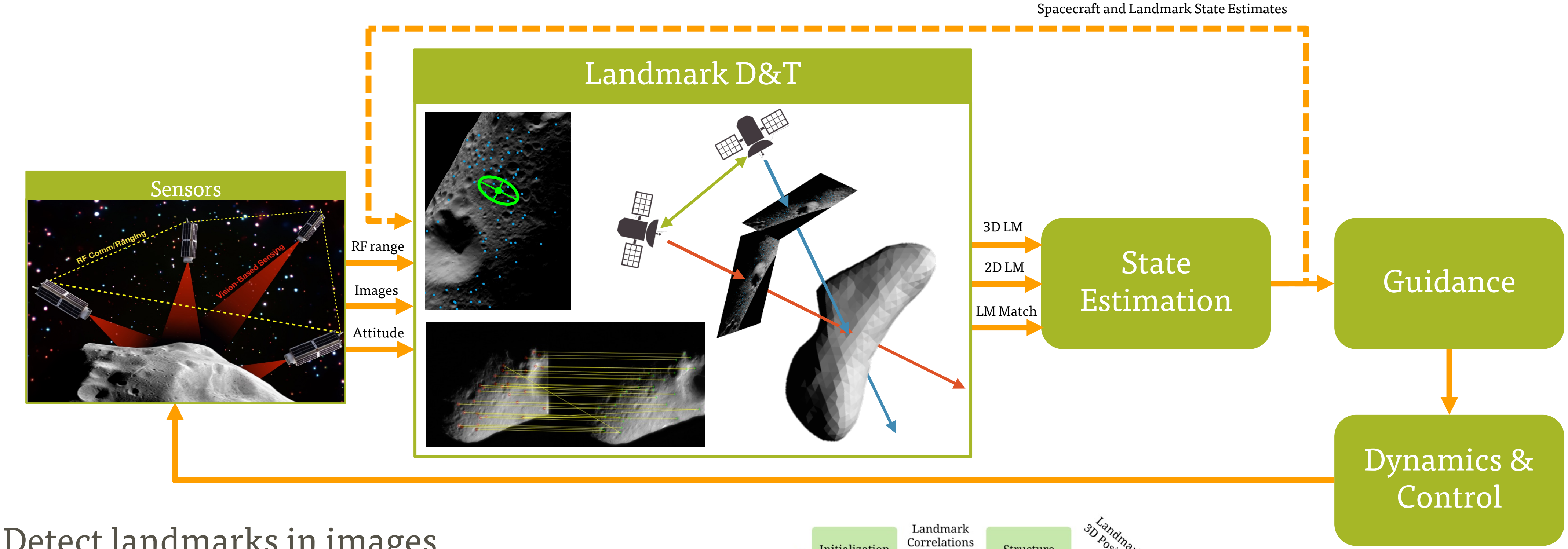


RF Cross-Link

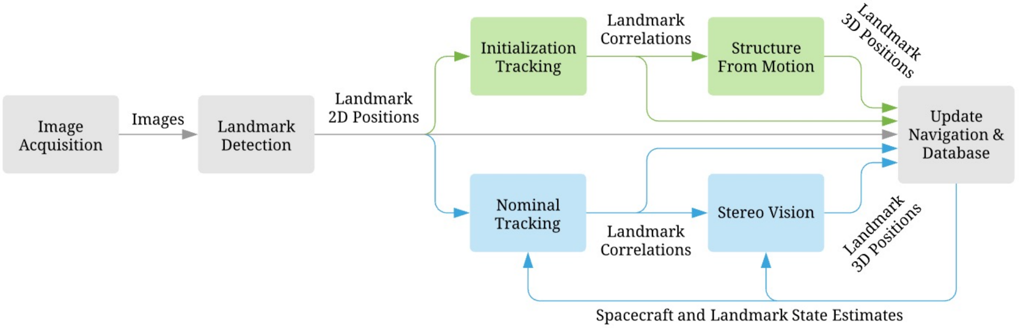


3U CubeSat Bus

GN&C Pipeline



Detect landmarks in images and either track them between images or with respect to a database.



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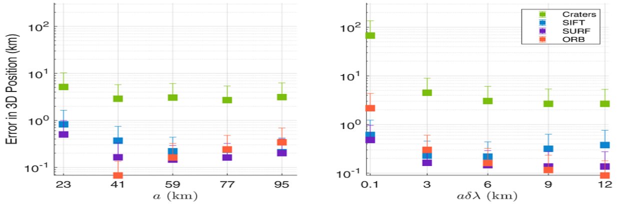
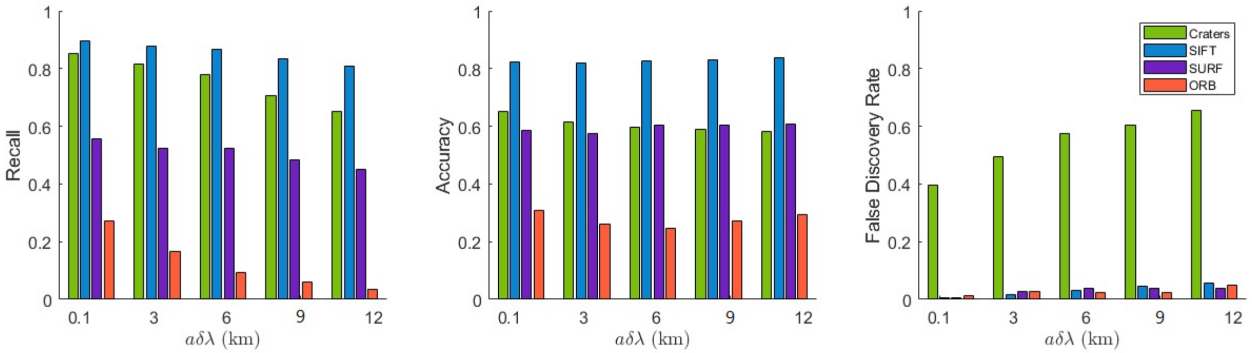
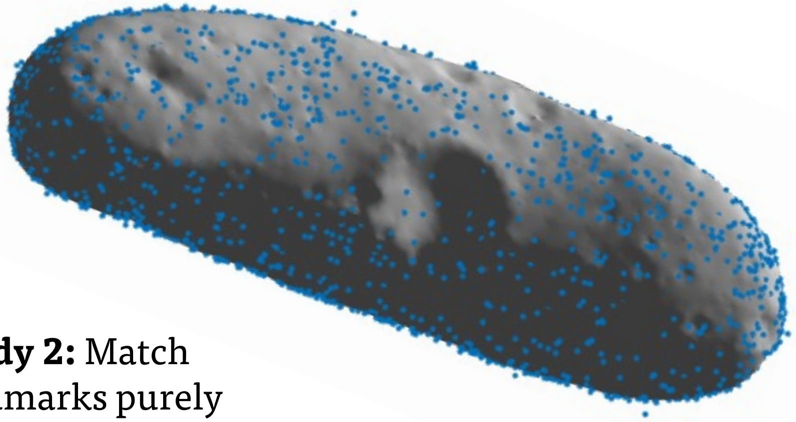
K. Dennison and S. D'Amico, "Comparing Optical Tracking Techniques in Distributed Asteroid Orbiter Missions Using Ray-Tracing," Charlotte, NC, Feb. 2021.

Landmark D&T

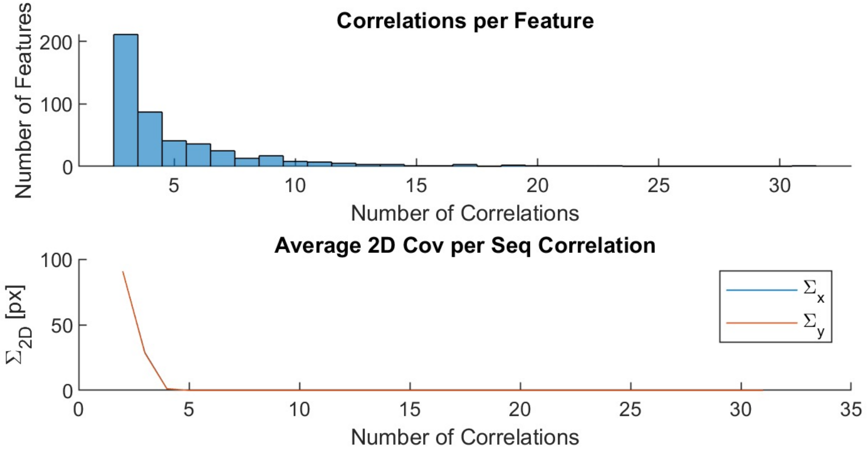
Study 1: Compare performance of landmark detection methods and multi-agent stereo vision



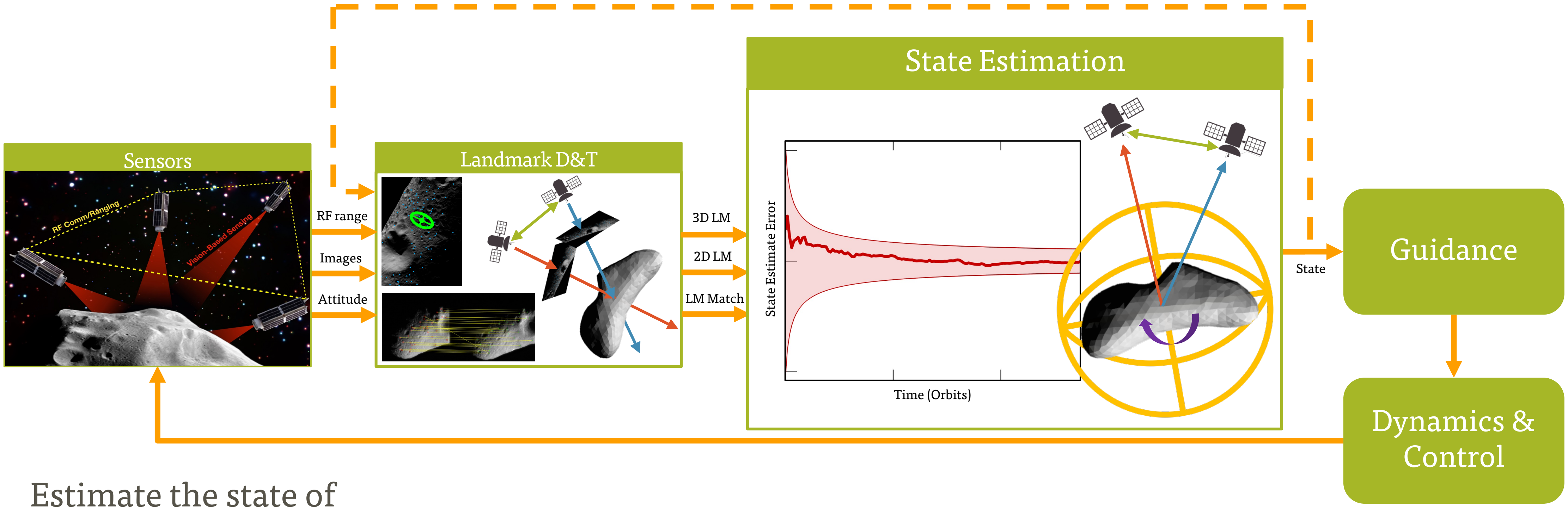




Study 2: Match landmarks purely by Mahalanobis distance.



GN&C Pipeline



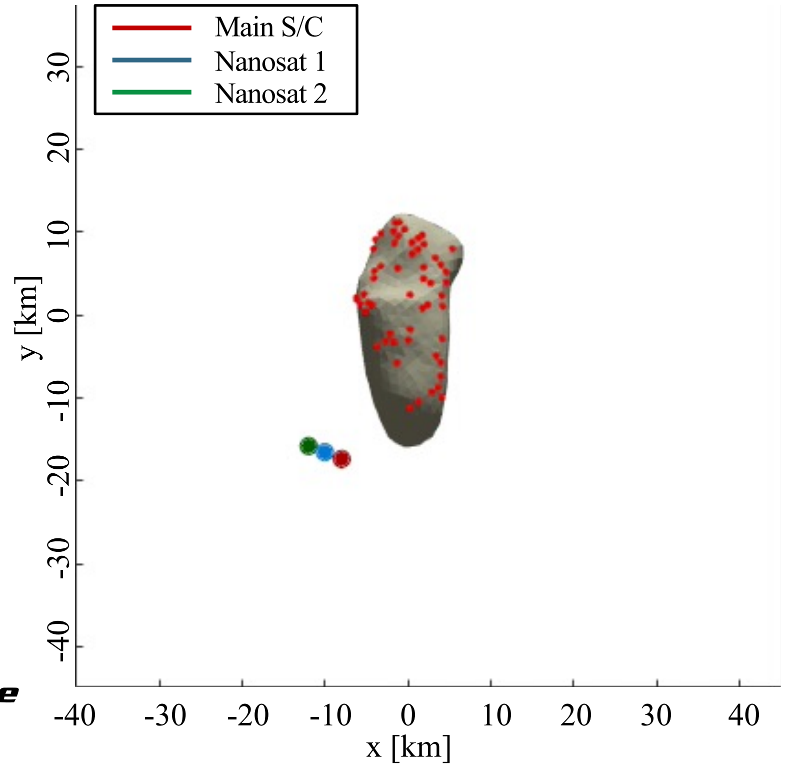
Estimate the state of the spacecraft and the asteroid.

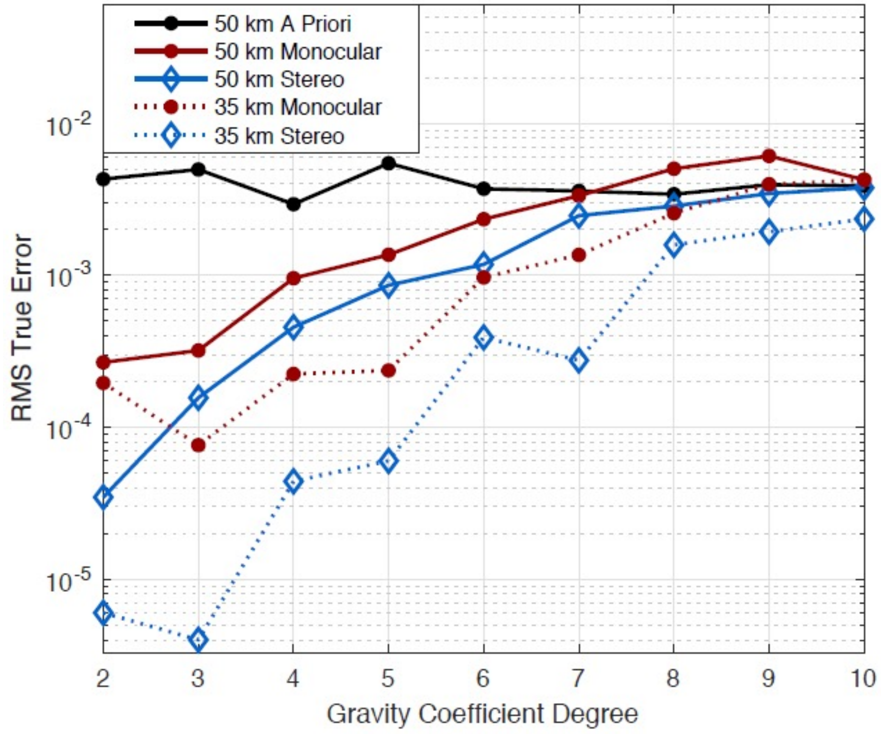
Estimated parameters			
X_k	Spacecraft states	G	Gravitational parameters
C_{rk}	Radiation pressure coefficients	α, δ, w	Asteroid rotational parameters
b	RF measurement biases	L_ℓ	Landmark positions

N. Stacey and S. D'Amico, "Adaptive and Dynamically Constrained Process Noise Estimation for Orbit Determination," IEEE Trans. Aerosp. Electron. Syst., 2021.

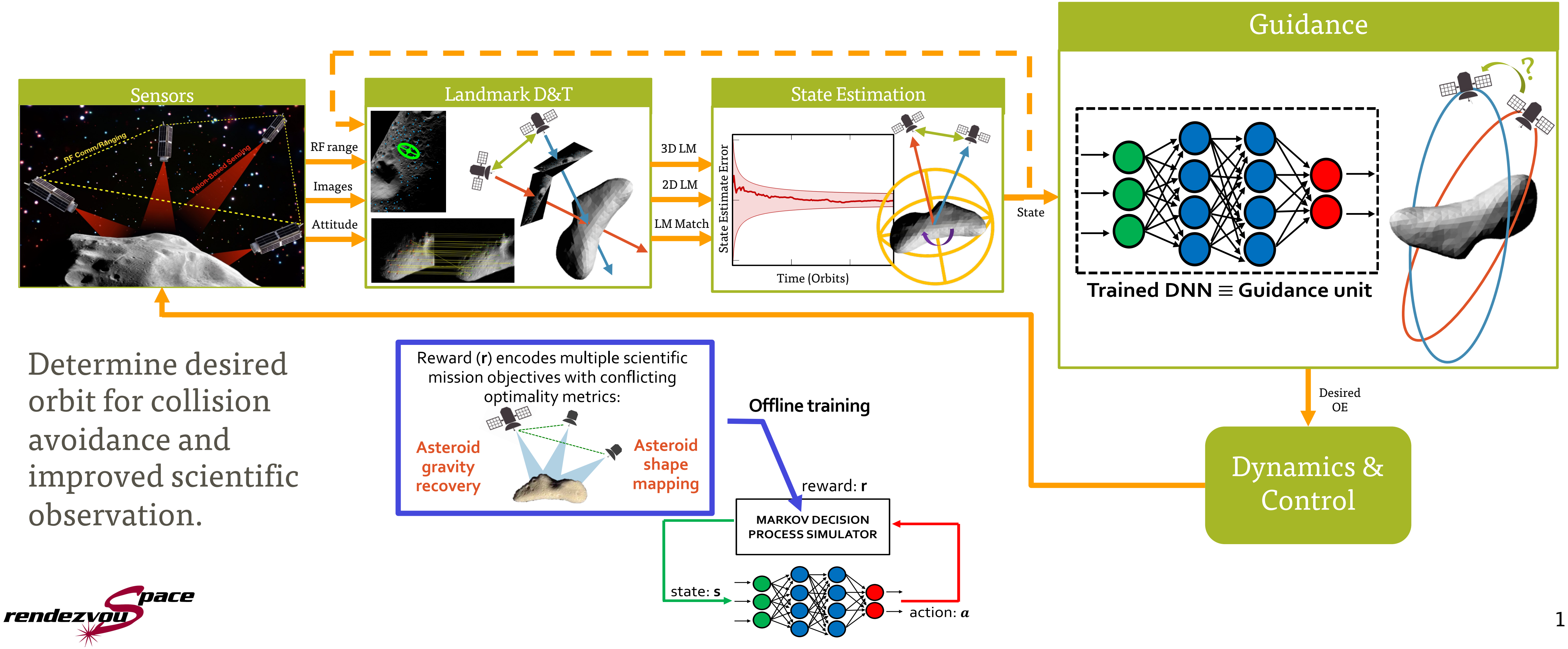
State Estimation

Estimated parameters			
$\boldsymbol{X_k}$	Spacecraft states	$\boldsymbol{G}$	Gravitational parameters
$\boldsymbol{C_{rk}}$	Radiation pressure coefficients	α, δ, w	Asteroid rotational parameters
$\boldsymbol{b}$	RF measurement biases	$\boldsymbol{L_\ell}$	Landmark positions





GN&C Pipeline



Determine desired orbit for collision avoidance and improved scientific observation.

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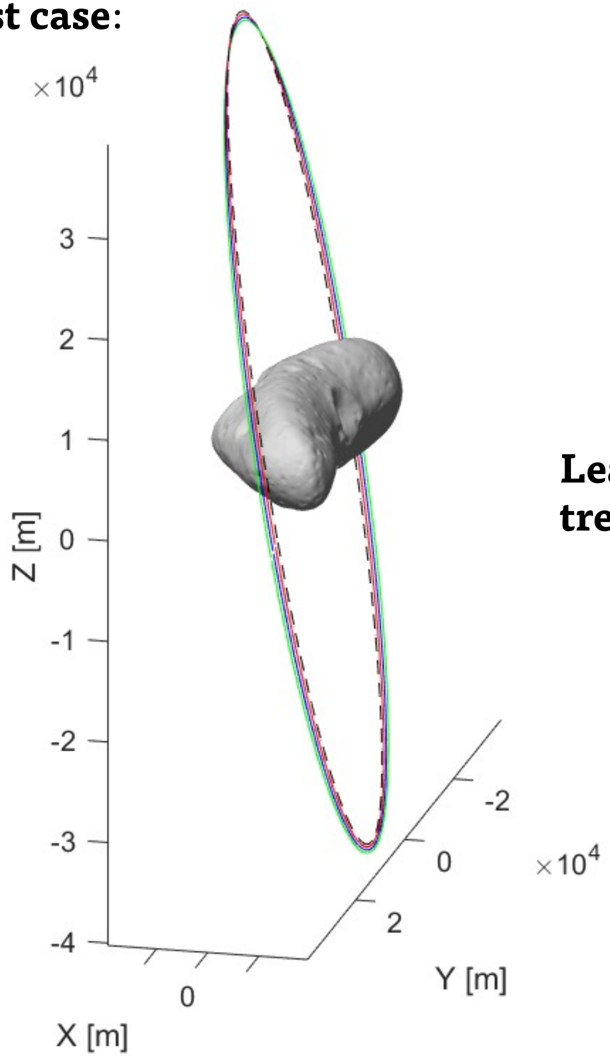
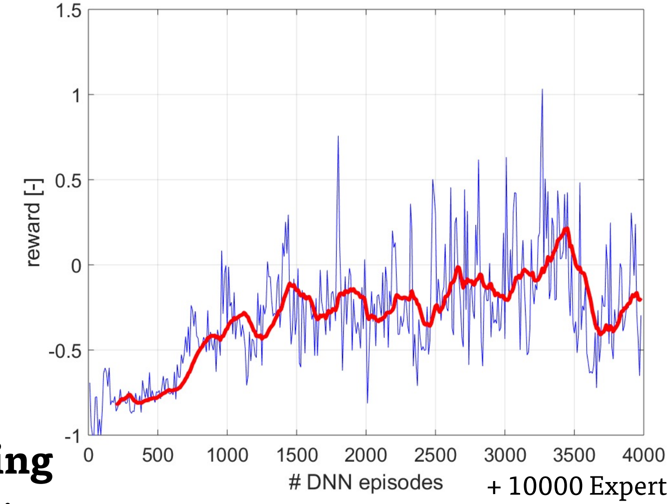
T. Guffanti and S. D’Amico, “Linear Models for Spacecraft Relative Motion Perturbed by Solar Radiation Pressure,” J. Guid. Control Dyn., vol. 42, no. 9, pp. 1962–1981, 2019, doi: 10.2514/1.G002822.

Guidance

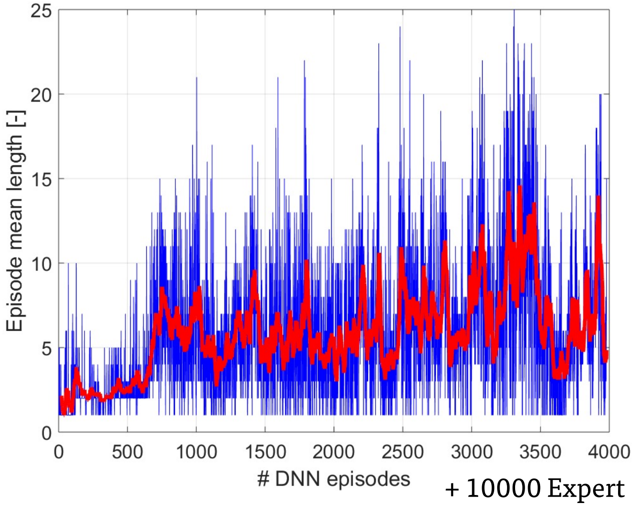
Test case:



Learning trends:

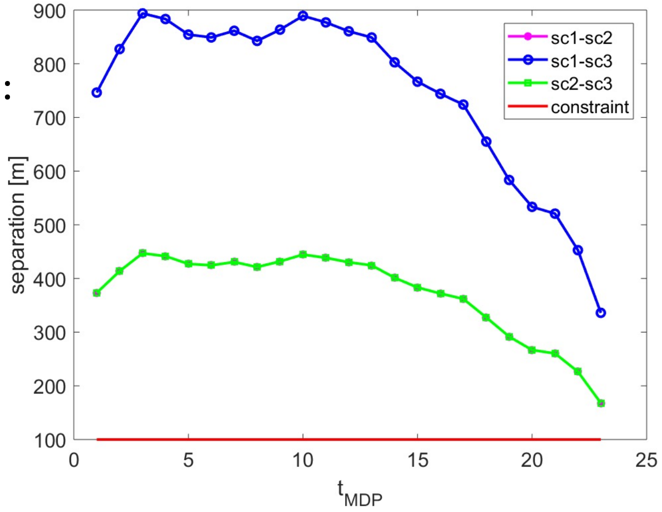


+ 10000 Expert Episodes

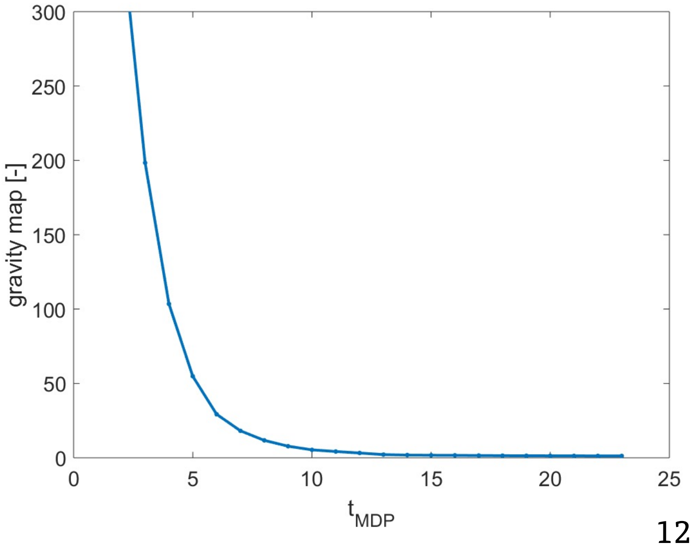


+ 10000 Expert Episodes

Collision avoidance:



Gravity recovery:



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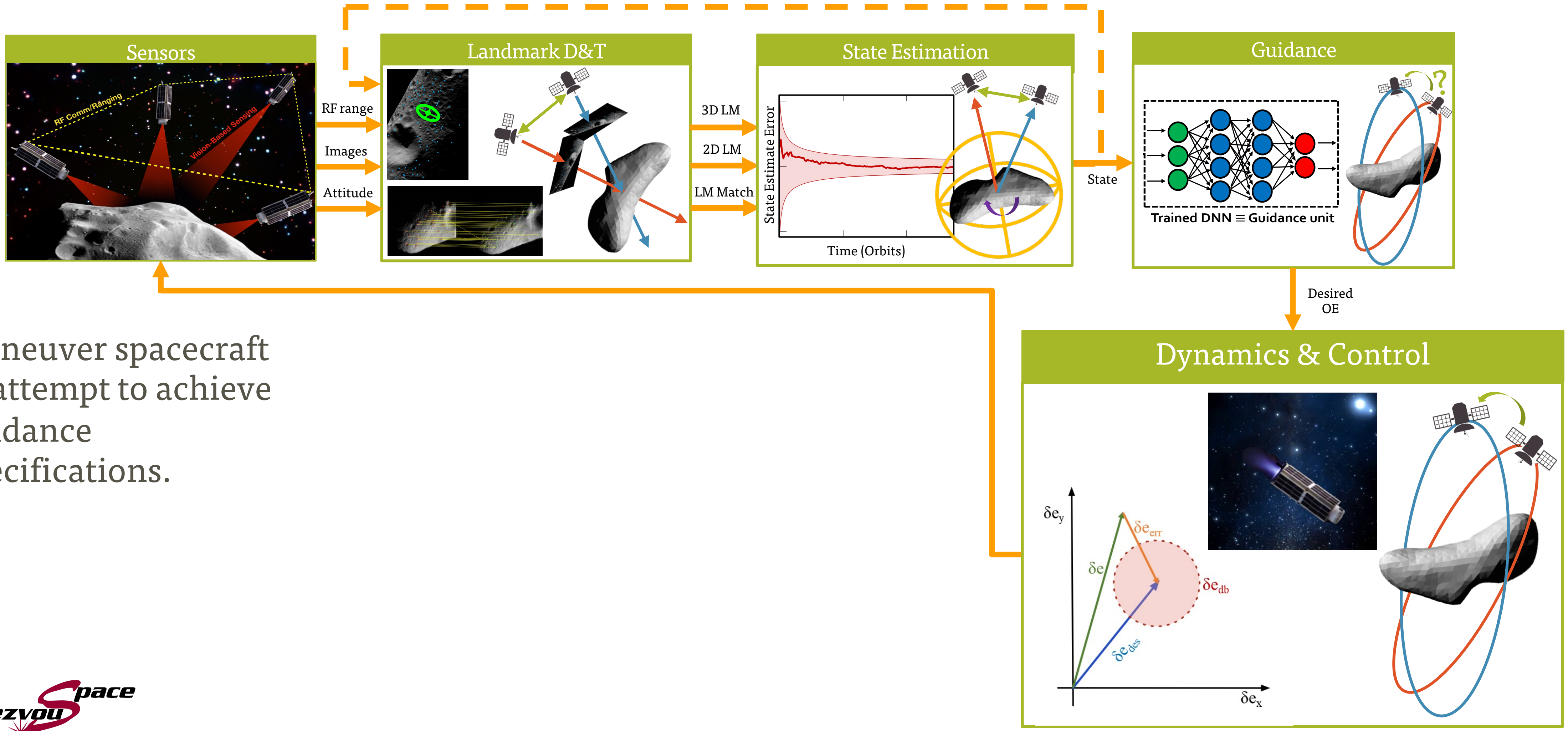
GN&C Pipeline



Maneuver spacecraft to attempt to achieve guidance specifications.

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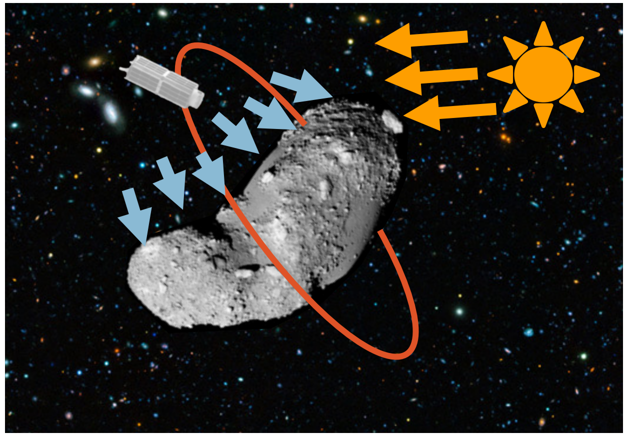
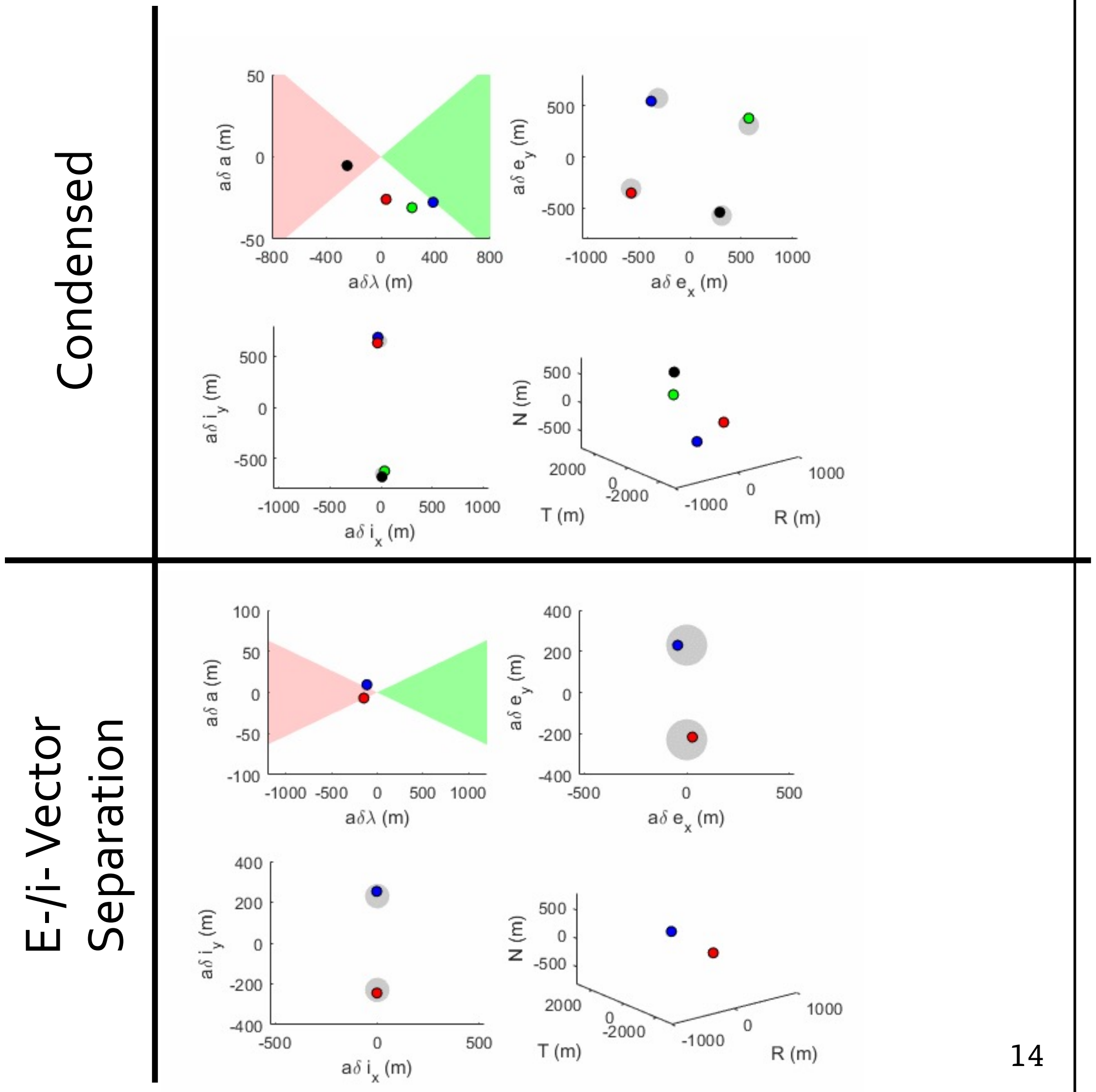
C. Lippe and S. D'Amico, "Spacecraft swarm dynamics and control about asteroids," Adv. Space Res., Jul. 2020, doi: 10.1016/j.asr.2020.06.037.

Dynamics & Control

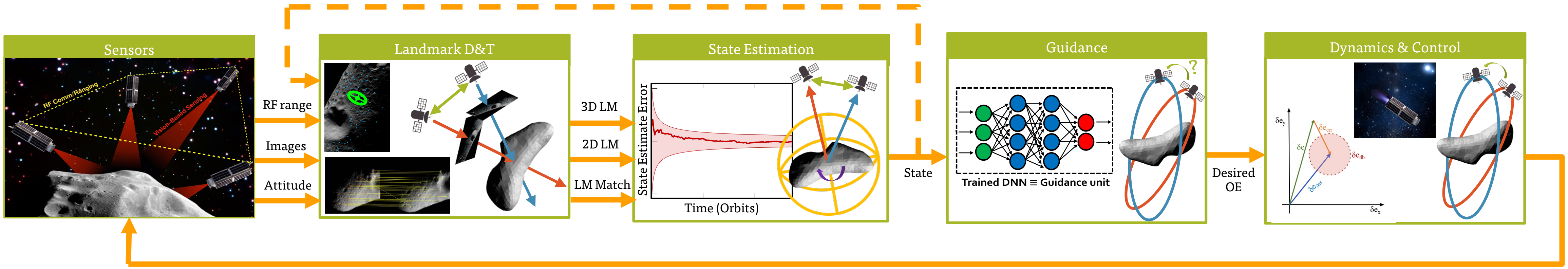
ROE-based control that accommodates:

- Non-spherical gravity perturbations
- Solar radiation pressure



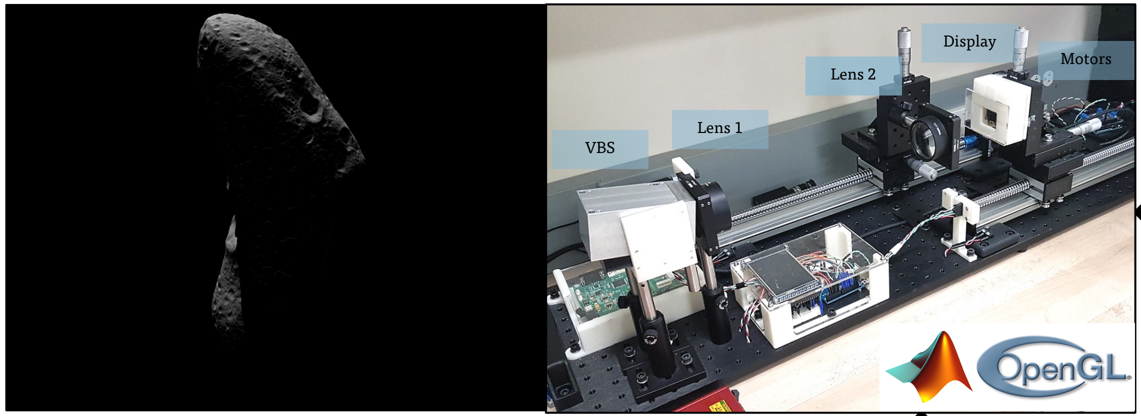


GN&C Pipeline



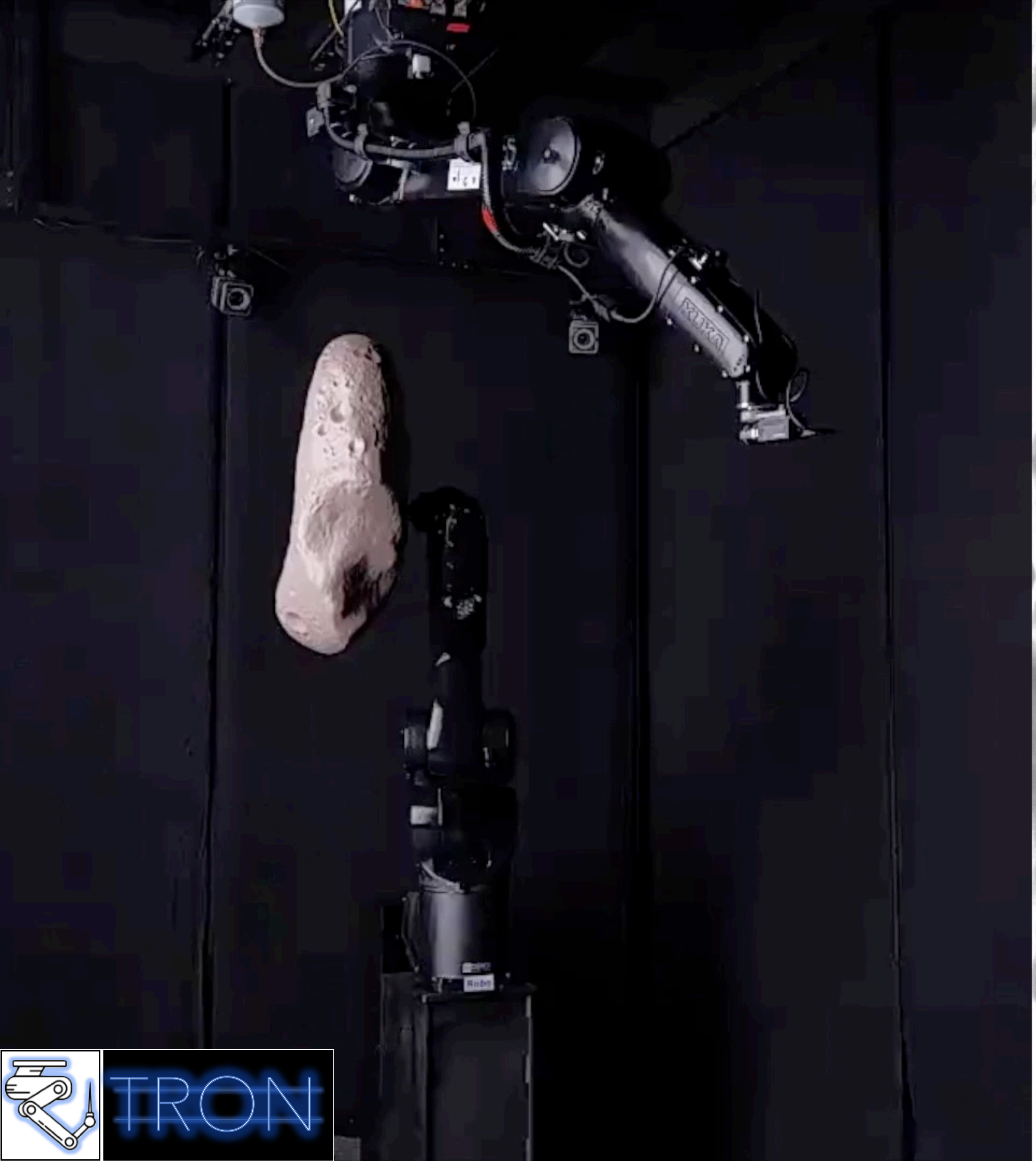
Validation Methods

Software & Hardware Validation



Domain gap

Real-time closed-loop control



Summary & Future Work

Advancements

Online Operations:

- Shape Modelling
- Gravity Recovery
- Navigation
- Orbit Guidance
- Optimal Control

System Improvements:

- Reduced Sensors
- Low SWaP-C Avionics
- Multi-Agent

Planned Validation

- Software: Summer 2021
- OS: Summer 2021
- TRON: Late 2021

TRLs

- Current ANS: 5
- Post-Validation: 6

Flight Opportunities:

- State Estimation (TRL 8) onboard VISORS
- Swarm Guidance (TRL 8) onboard SwarmX

SLAB/ANS Publication List

[1] S. D’Amico, “Autonomous Nanosatellites Swarming (ANS) Using Radio-Frequency and Optical Navigation; NASA Fact Sheet, Stanford Space Rendezvous Laboratory (SLAB).” 2018, [Online]. Available: https://damicos.people.stanford.edu/sites/g/files/sbiybj2226/f/ans_factsheet_6-21-18.pdf.

[2] N. Stacey and S. D’Amico, “Autonomous Swarming for Simultaneous Navigation and Asteroid Characterization,” presented at the AAS/AIAA Astrodynamics Specialist Conference, Snowbird, UT, Aug. 2018.

[3] C. Lippe and S. D’Amico, “Spacecraft swarm dynamics and control about asteroids,” *Adv. Space Res.*, Jul. 2020, doi: 10.1016/j.asr.2020.06.037.

[4] C. Lippe and S. D’Amico, “Adaptive Filter for Osculating-to-Mean Relative Orbital Elements (ROE) Conversion,” South Lake Tahoe, CA, Aug. 2020, p. 28.

[5] K. Dennison and S. D’Amico, “Comparing Optical Tracking Techniques in Distributed Asteroid Orbiter Missions Using Ray-Tracing,” Charlotte, NC, Feb. 2021, p. 20.

[6] N. Stacey and S. D’Amico, “Adaptive and Dynamically Constrained Process Noise Estimation for Orbit Determination,” *IEEE Trans. Aerosp. Electron. Syst.*, 2021.

[7] N. Stacey and S. D'Amico, “Analytical Process Noise Covariance Modeling for Absolute and Relative Orbits,” *Acta Astronautica*, 2021, Submitted. ArXiv: 2105.06516.

[8] T. Guffanti and S. D’Amico, “Multi-Agent Passive Safe Optimal Control using Integration Constants as State Variables,” Nashville, TN, Jan. 2021, p. 20, doi: 10.2514/6.2021-1101.

[9] T. Guffanti and S. D’Amico, “Linear Models for Spacecraft Relative Motion Perturbed by Solar Radiation Pressure,” *J. Guid. Control Dyn.*, vol. 42, no. 9, pp. 1962–1981, 2019, doi: 10.2514/1.G002822.

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Why go to asteroids and what makes such missions difficult?

Resource Mining

Solar System Formation

Collision Avoidance

Mission High-Level Overview

1. An asteroid is studied via ground-based telescopes: rotation, size, orbit.
2. Spacecraft refine rotation and size upon approach to asteroid.
3. Spacecraft enter orbit and use optical tracking to initialize a map and state estimates.
4. Once initialized, map and state estimates are refined, gravity recovery and maneuvers begin.

Most missions to date use GIL or expensive equipment to aid these

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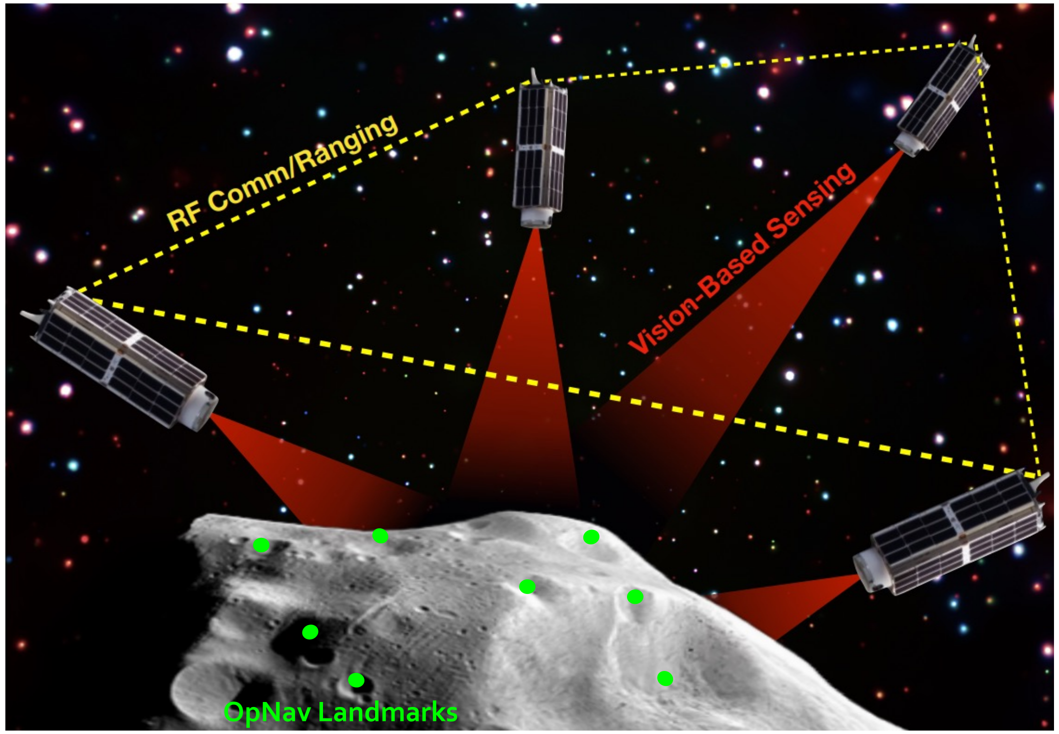
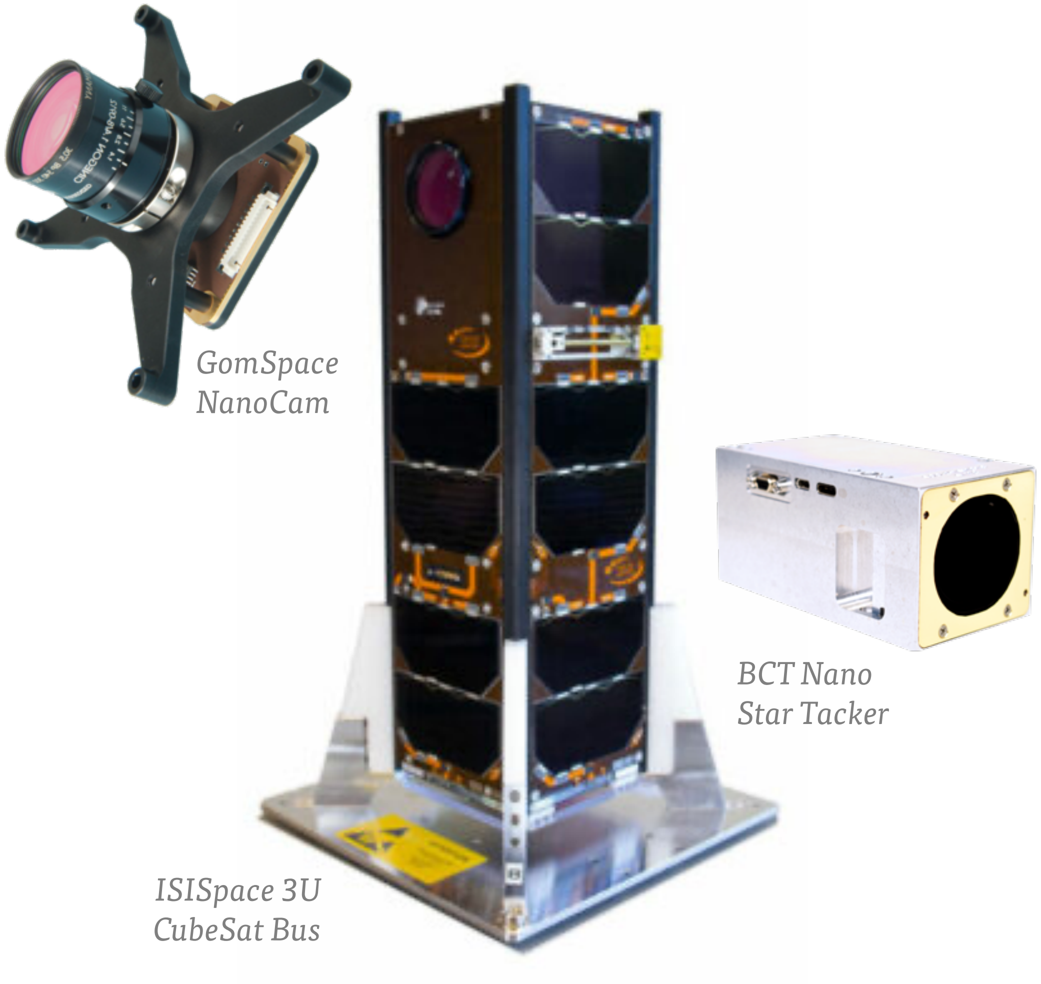
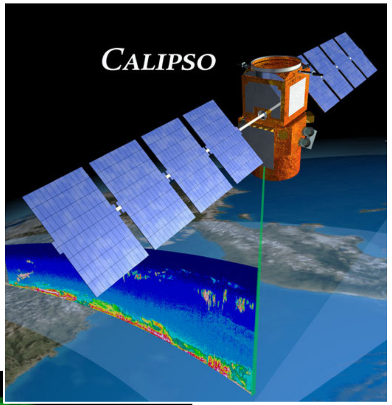
Sensors


Sensors
Landmark D&T
State Estimation
Guidance
Dynamics & Control

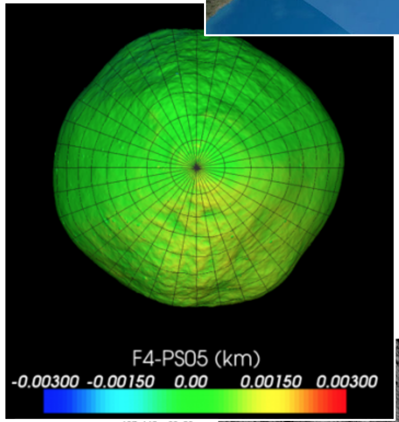

RF Comm/Ranging
Vision-Based Sensing
OpNav Landmarks


GomSpace NanoCam
BCT Nano Star Tacker
ISISpace 3U CubeSat Bus

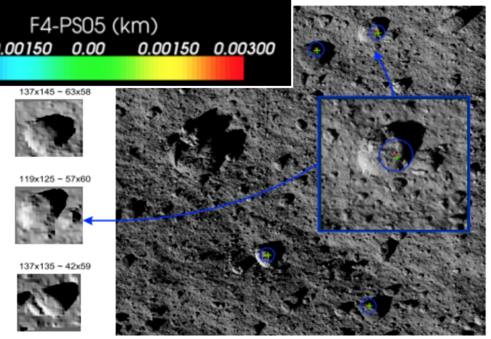
Landmark D&T

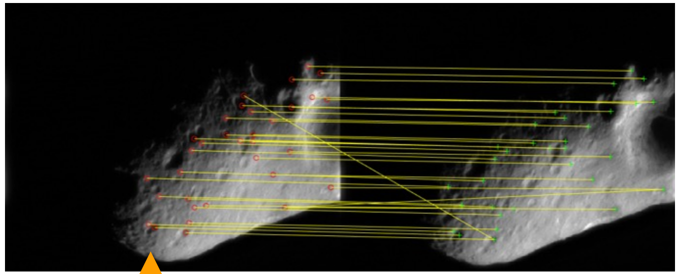


LIDAR Depth Measurements

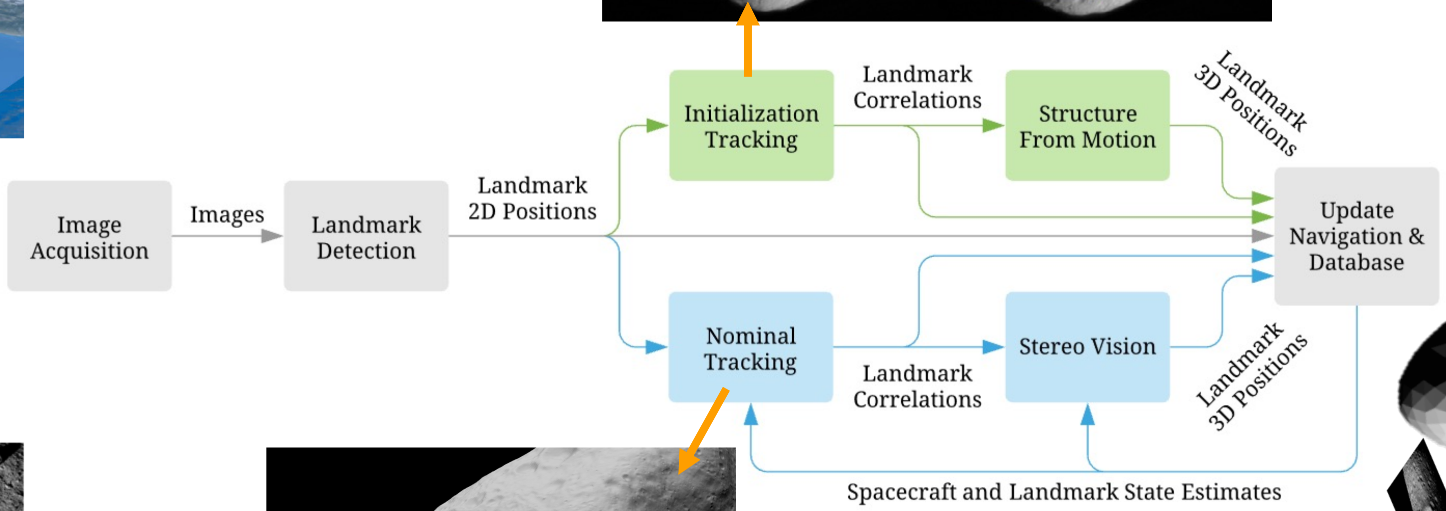


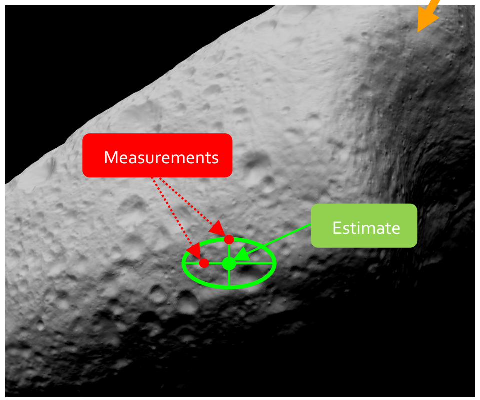
SPC + Cross Correlation



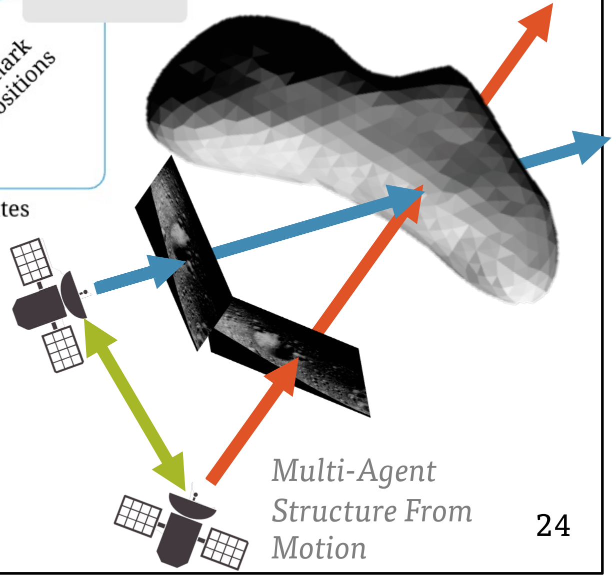


SIFT Feature Matching





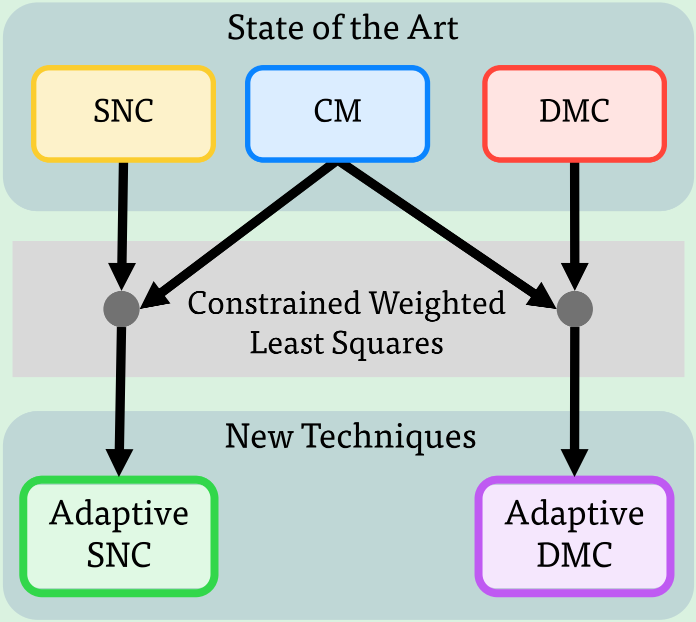
Mahalanobis Distance



Multi-Agent Structure From Motion

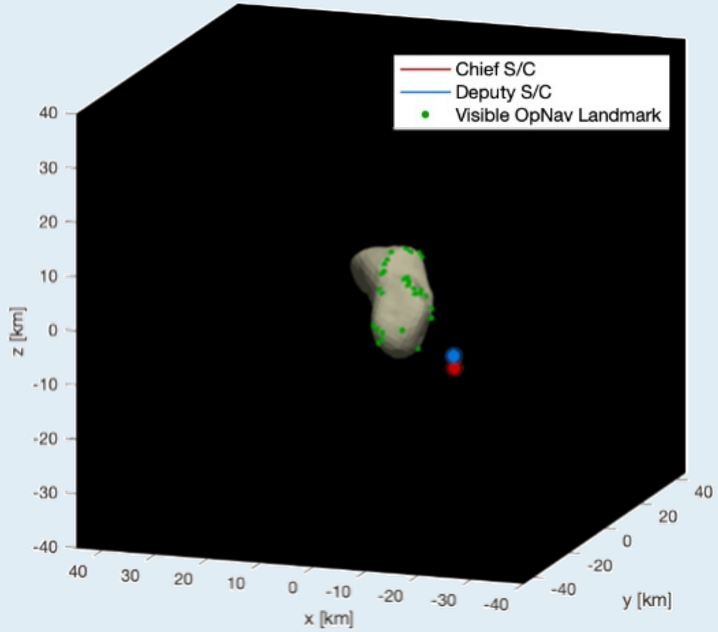
State Estimation

Adaptive Filtering



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

Simultaneous Navigation and Characterization



Exploiting Triangular Structure UKF

$$\boldsymbol{\Gamma}\boldsymbol{\Gamma}^T = \boldsymbol{\Sigma}$$

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

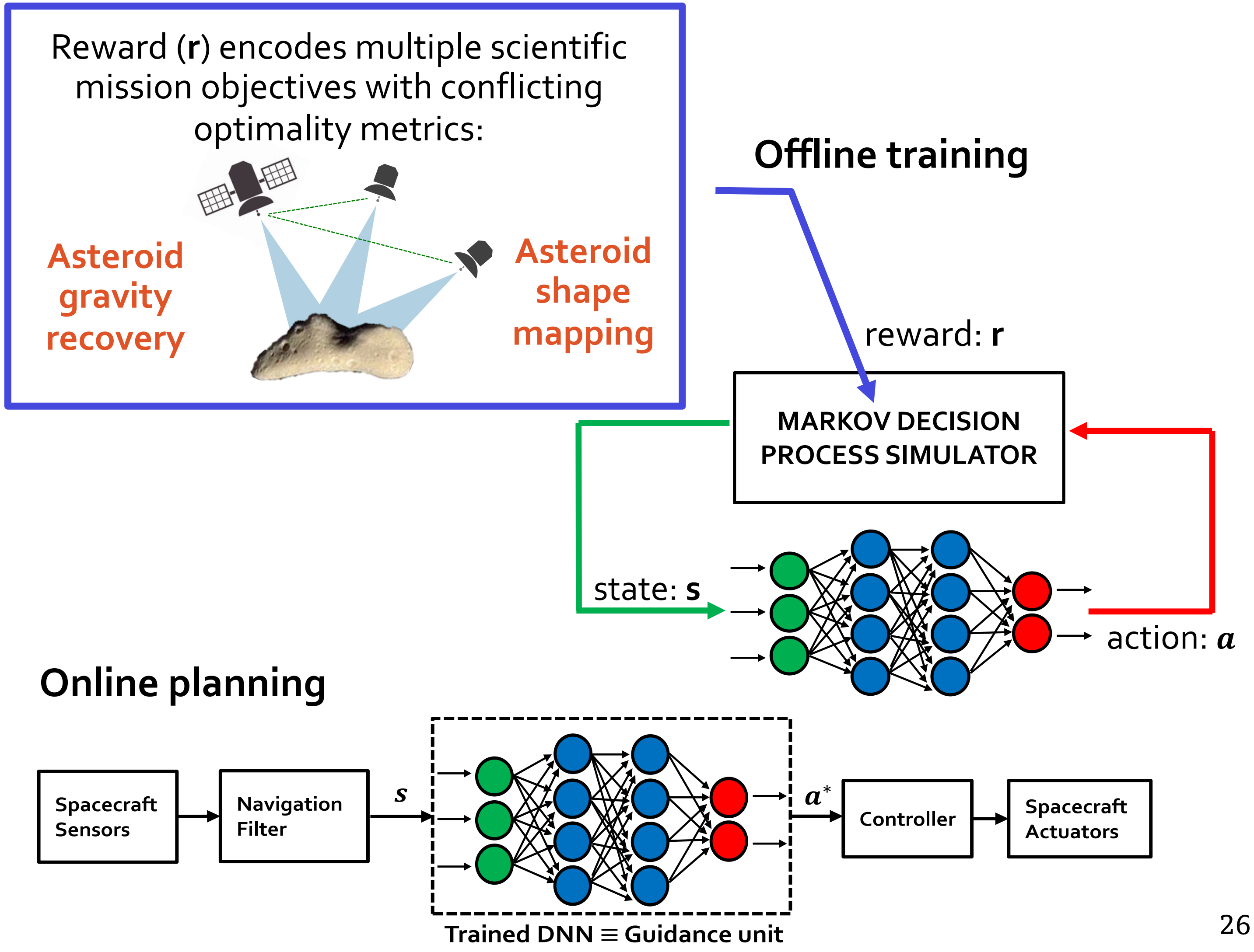
$$\mathbf{A} = \begin{bmatrix} a_{11} & 0 & \dots & 0 \\ a_{21} & a_{22} & \ddots & \vdots \\ \vdots & & \ddots & 0 \\ a_{n1} & \dots & \dots & a_{nn} \end{bmatrix}$$

Stacey and D'Amico, "Autonomous Swarming for Simultaneous Navigation and Asteroid Characterization," AIAA/AAS Astrodynamics Specialist Conference, 2018.

rendezvous Space

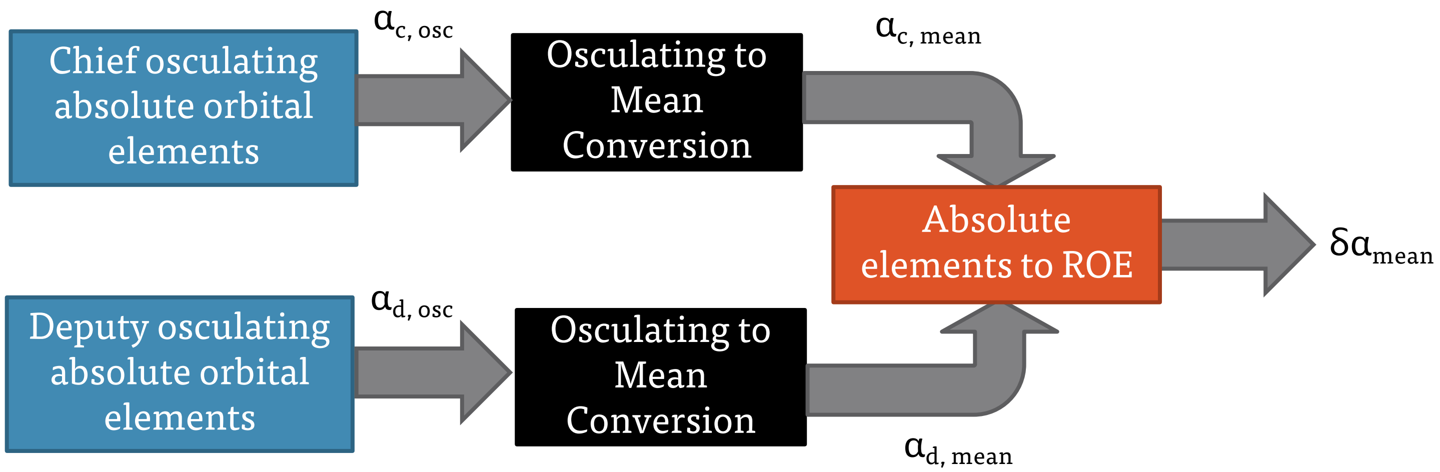
Guidance

- State-of-the art guidance techniques for asteroid characterization are ground-in-the-loop.
- We propose an autonomous guidance unit that optimizes science while enforcing passive collision safety.
- Deep RL enables…
  - training a guidance-deep-neural-net ***offline***
  - learn an optimal policy of swarm orbital reconfigurations ***online***

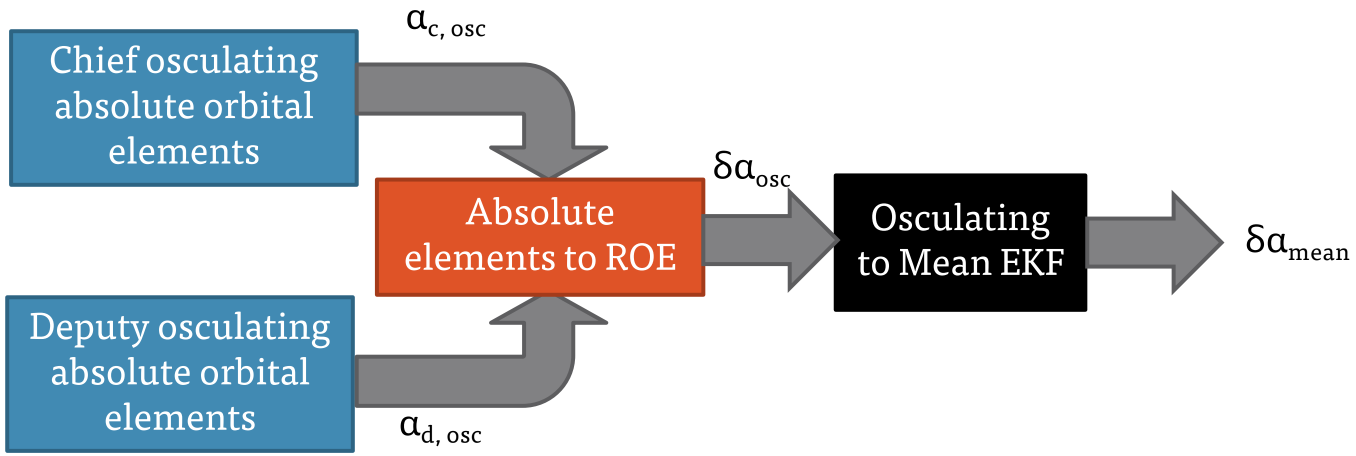


Dynamics & Control

State of the Art

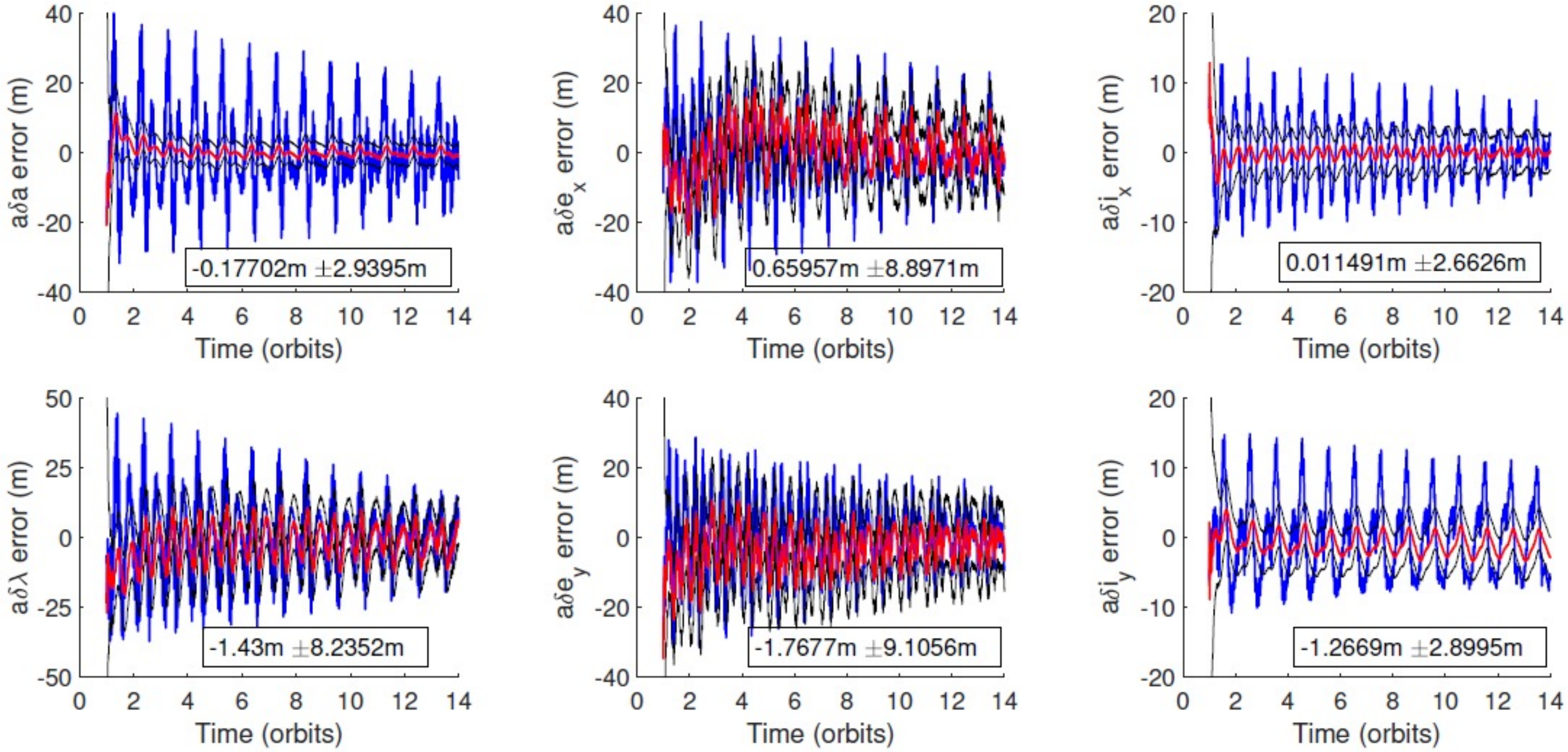


Our Approach



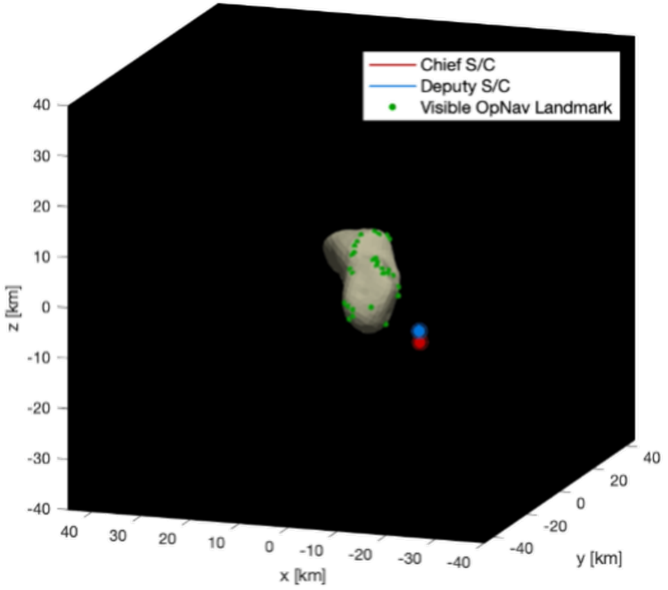
Dynamics & Control

Our Approach

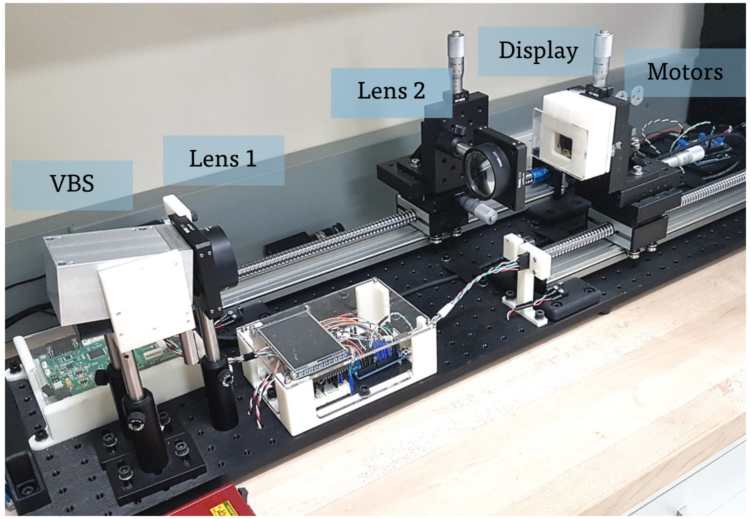


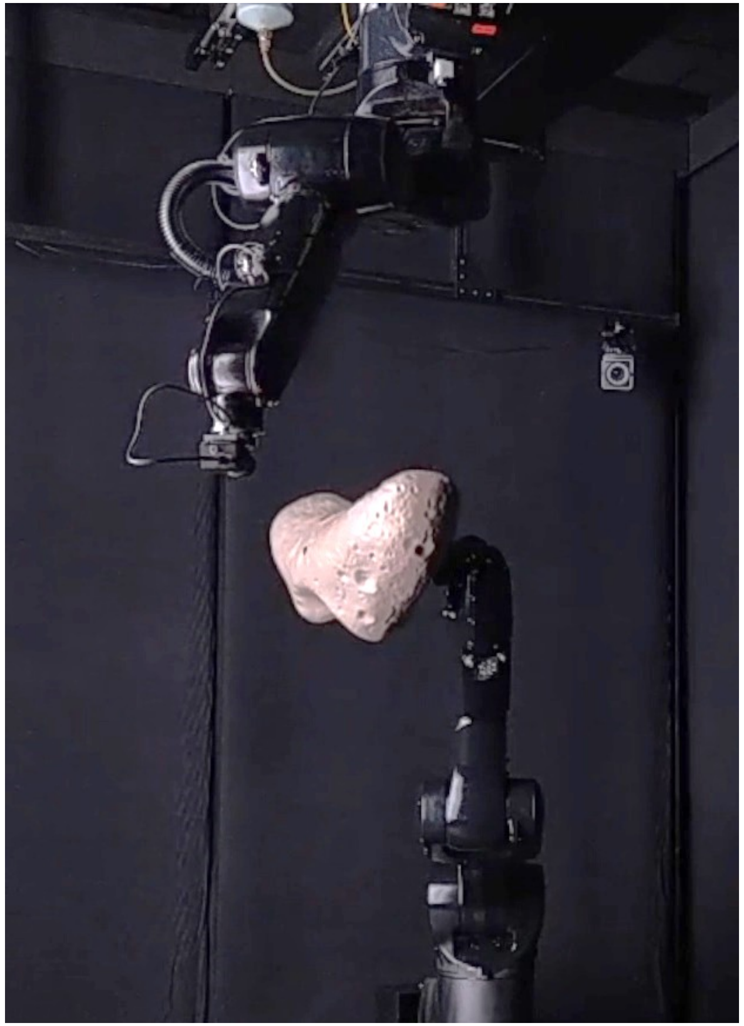
Software & Hardware Validation

MATLAB simulated space environment: Synthetic image generation, perturbed spacecraft propagation, full GN&C pipeline.



Optical Stimulator (OS): variable-magnification platform for stimulating a vision-based sensor (VBS) using synthetic images rendered to an OLED display.

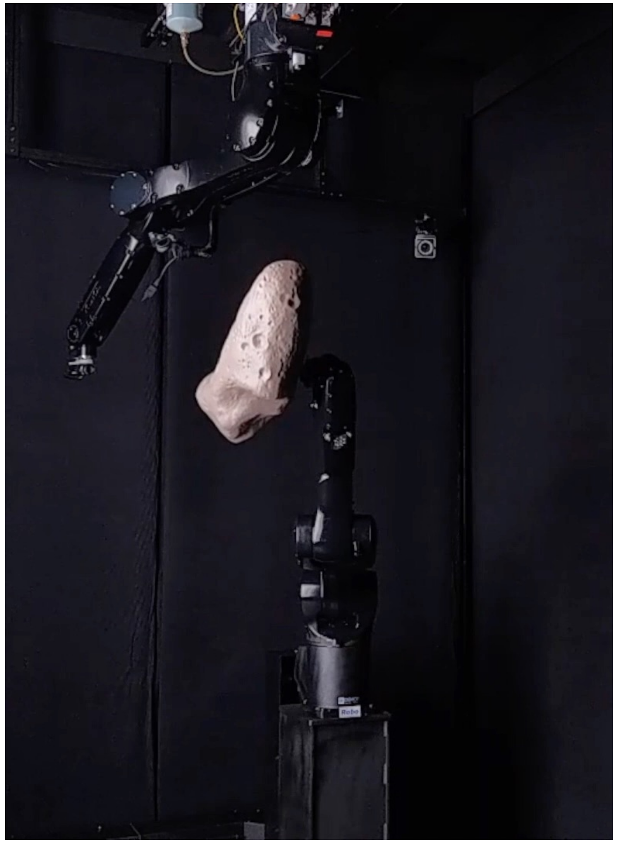


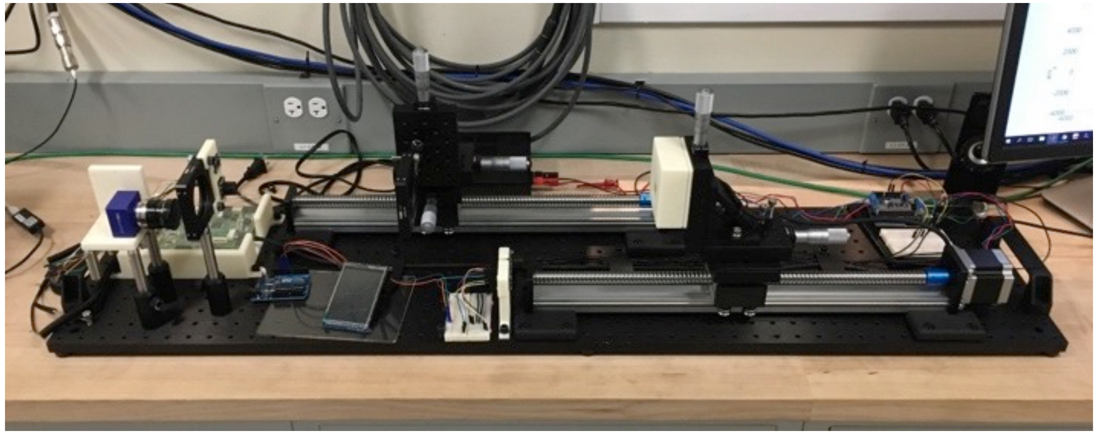


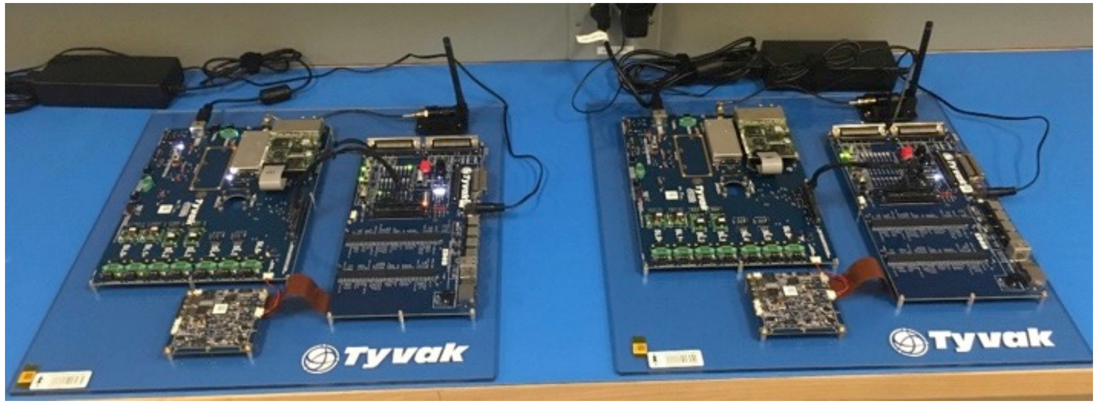
Testbed for Rendezvous and Optical Navigation (TRON): stationary and translating 6-DOF robotic arms enable physical simulation of a space scene for image capture by a VBS.

rendezvous Space

Hardware Validation







High-fidelity verification testbed at Stanford's Space Rendezvous Laboratory (SLAB).
***Left:** high-performance Kuka Agilus robotic arms with additively manufactured model of asteroid 433 Eros in space environment simulator room. Photometrically-calibrated illumination panels provide lighting.*
***Top right:** virtual reality optical stimulator.*
***Bottom right:** Tyvak flatsat microcomputers and satellite-to-satellite cross-link.*

Software & Hardware Validation

Case	Primary Objectives
1	Demonstrate feature tracking and satellite navigation
2	Demonstrate feature tracking, satellite navigation, and gravity recovery
3	Demonstrate feature tracking, satellite navigation, and gravity recovery with closed-loop formation keeping
4	Demonstrate feature tracking, satellite navigation, and gravity recovery with closed-loop formation keeping and guidance to improve characterization in highly-perturbed environment