Stronger Together -Coordination Among Spacecraft for Novel Exploration Strategies

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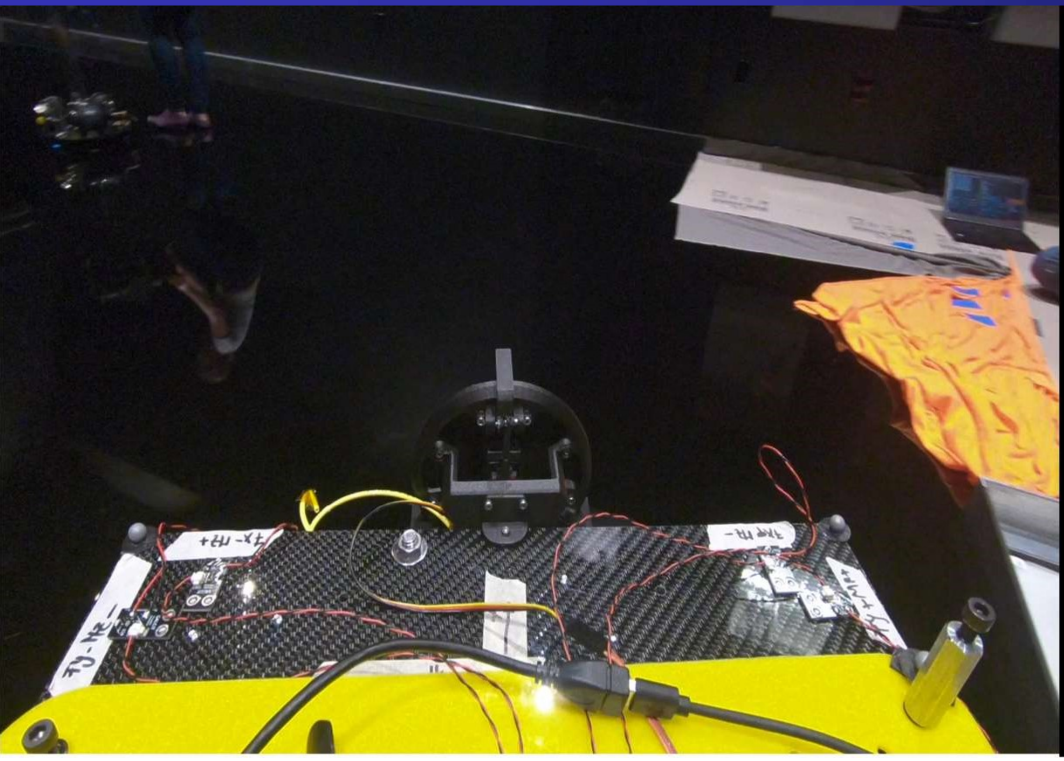
Outline

- Motivation for Spacecraft Swarms, Formation Flying, and Constellation
  - Definitions, Review of Missions, and Advantages
- Swarm/Formation Autonomous Guidance and Control Algorithms
- Autonomous (Relative) Navigation and 3D Comet Shape/Pose Estimation

- Conclusion

Multi-Spacecraft Reconfiguration and Self-Assembly



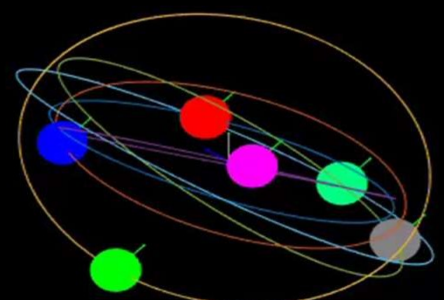
- R. C. Foust, E. S. Lupu, Y. K. Nakka, S.-J. Chung, and F. Y. Hadaegh, "Ultra-Soft Electromagnetic Docking with Applications to In-Orbit Assembly," *Proc. 69th International Astronautical Congress*, Bremen, Germany, 1-5 October 2018.
- Y. K. Nakka, R. C. Foust, E. S. Lupu, D. B. Elliott, I. S. Crowell, S.-J. Chung, and F. Y. Hadaegh, "A Six Degree-Of-Freedom Spacecraft Dynamics Simulator for Formation Control Research," *the 2018 AAS/AIAA Astrodynamics Specialist Conference*, Snowbird, Utah, August 19-23, 2018.

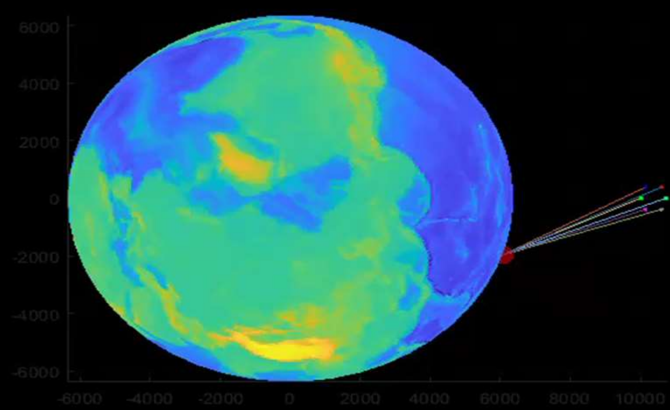
Multi-Agent Transformers

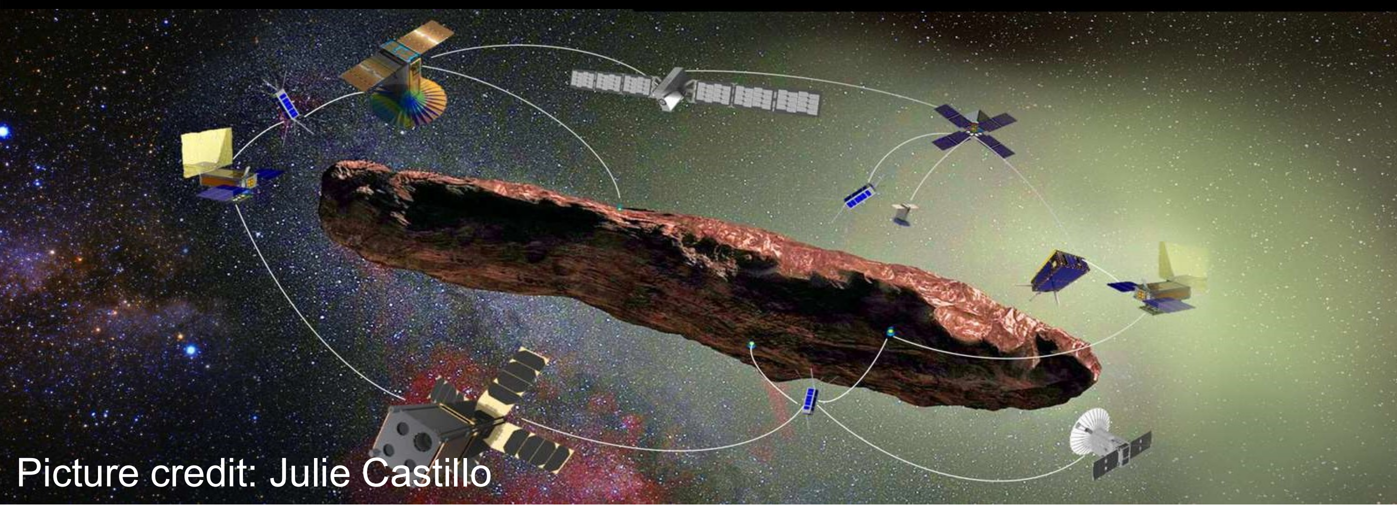
Swarms of Autonomous Robots Transforming Shapes and Functions

- In-space and on-surface deployment, construction, and assembly of complex structures Formation flying, self-assembly, and reconfiguration of autonomous swarms for science, observation, and communication

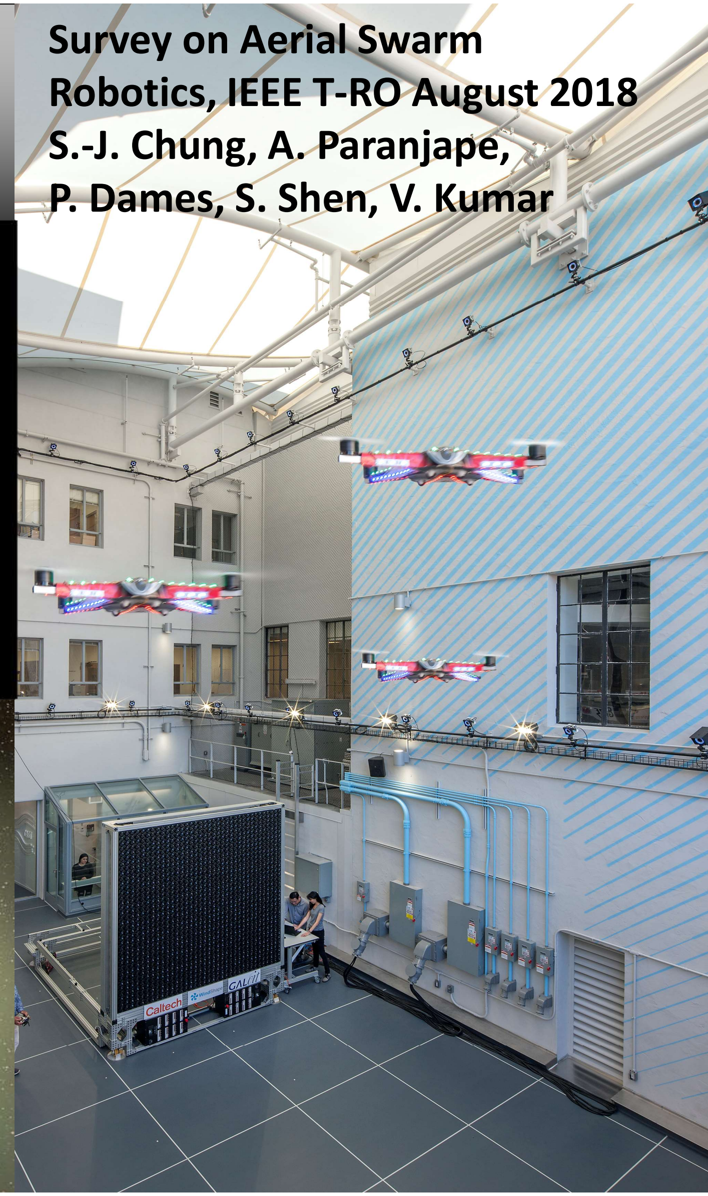
Survey on Aerial Swarm Robotics, IEEE T-RO August 2018
S.-J. Chung, A. Paranjape, P. Dames, S. Shen, V. Kumar



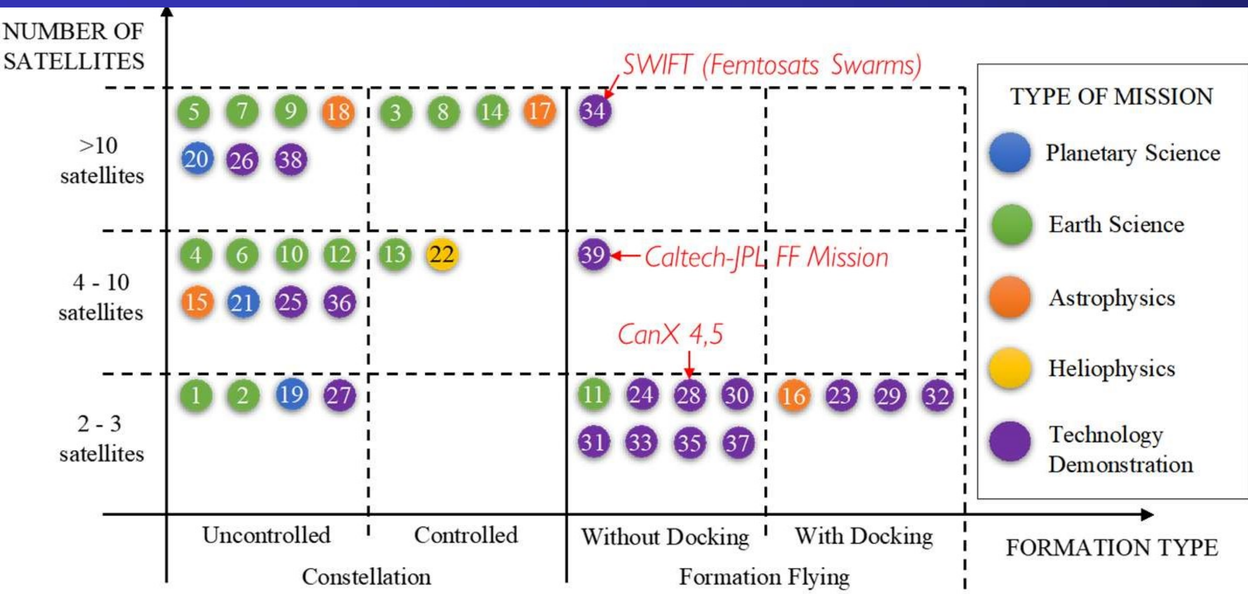




Picture credit: Julie Castillo



Review of Multi-Spacecraft Missions using SmallSats



Formation vs Swarms [2]

Type	Scope	Size
Team	Typically small groups; each agent optimizes individual objectives in a cooperative or competitive manner	typically ≤ 10
Formation	Each agent is typically assigned a specific sub-task, role, or placement	typically ≤ 10s
Swarm	Typically large groups of dispensable agents; global capability arises from emergent behavior	large

Formation Flying: the dynamic states of the satellites are coupled through a common control law via relative sensing or communication. At least one satellite must track a desired state relative to another satellite.

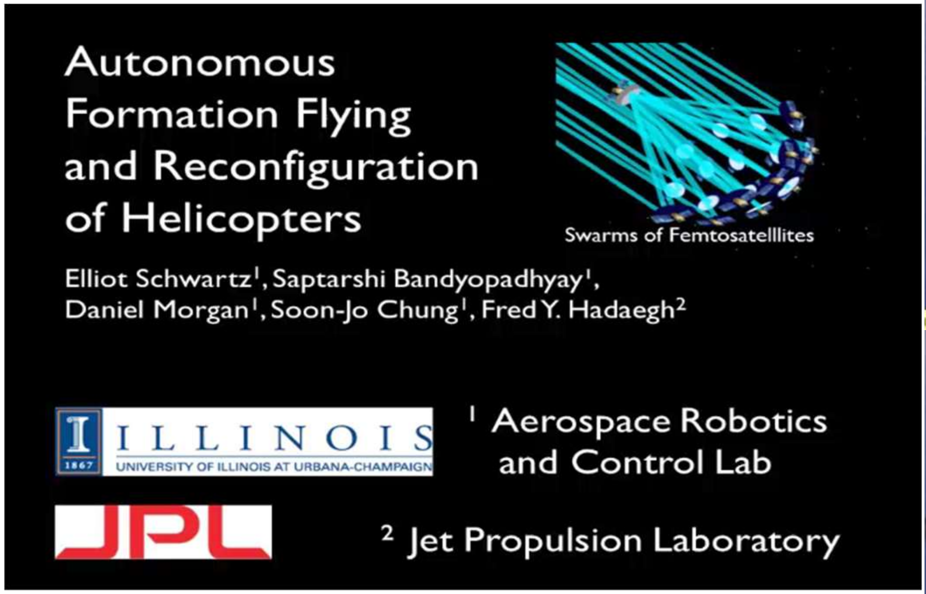
The tracking control law must at the minimum depend upon the states of this other satellite

Constellations: even though specific relative positions are actively maintained, the GPS satellites constitute a constellation since their orbit corrections only require an individual satellite's position and velocity (state).

[1] S. Bandyopadhyay, *et al.*, "Review of Formation Flying and Constellation Missions Using Nanosatellites," **Journal of Spacecraft and Rockets,** 2016.
[2] S.-J. Chung, A. Paranjape, P. Dames, S. Shen, and V. Kumar, "A Survey on Aerial Swarm Robotics," **IEEE Transactions on Robotics**, vol. 34, no. 4, 2018, pp. 837-855.

Why Spacecraft Swarms?- Space LEGO

- Distributed spacecraft systems can deliver a comparable or greater mission capability than monolithic spacecraft, but with significantly enhanced flexibility (reconfigurability, adaptability, scalability, and maintainability) and robustness (reliability, survivability).



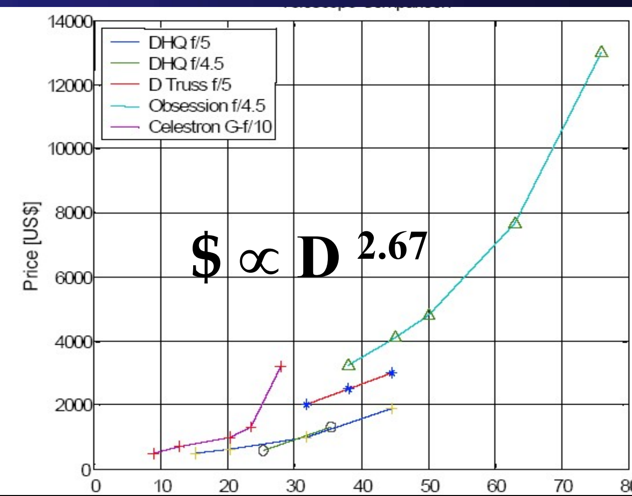
- Dramatically reduced level of risk associated with technical faults of a single spacecraft or a subset of the swarm.
- The reduced spacecraft cost permits anomalous spacecraft to be discarded and replaced gracefully without degrading the overall system performance.

Fred Y. Hadaegh, Soon-Jo Chung, and Harish M. Manohara, "**On Development of 100-Gram-Class Spacecraft for Swarm Applications**" *IEEE Systems Journal*, 2016.

Swarm Application: Sparse Apertures

Delta II 3-m payload fairing

HST- Largest Space-borne monolithic aperture (2.4m)



$$\$ \propto D^{2.67}$$

Finer resolution (large optics) in demand

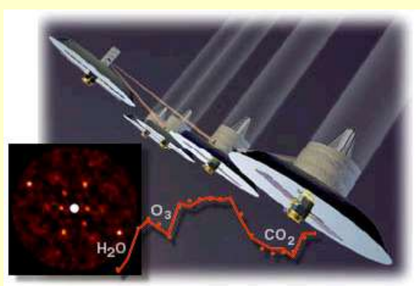
SIM

Michelson Interferometer

Precision Astrometry

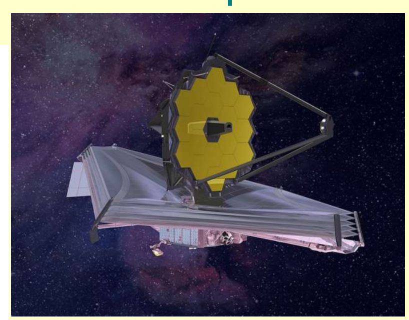
TPF

Michelson Interferometer



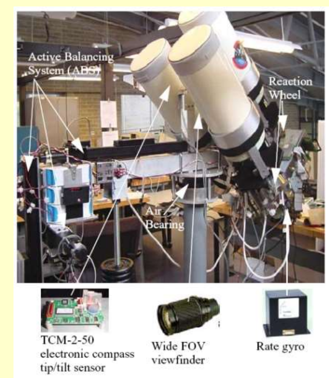
JWST

6.5m Segmented Mirror Telescope



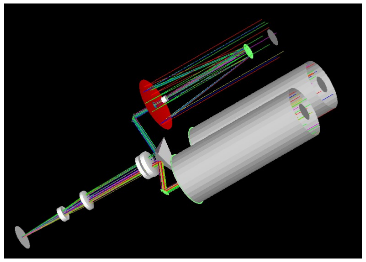
MIT ARGOS 2002

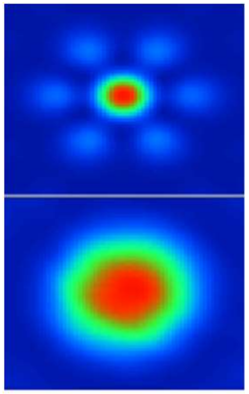
Fizeau Interferometry



Any challenges? Precision formation control (synchronization)

Hierarchical Combination & Synchronization

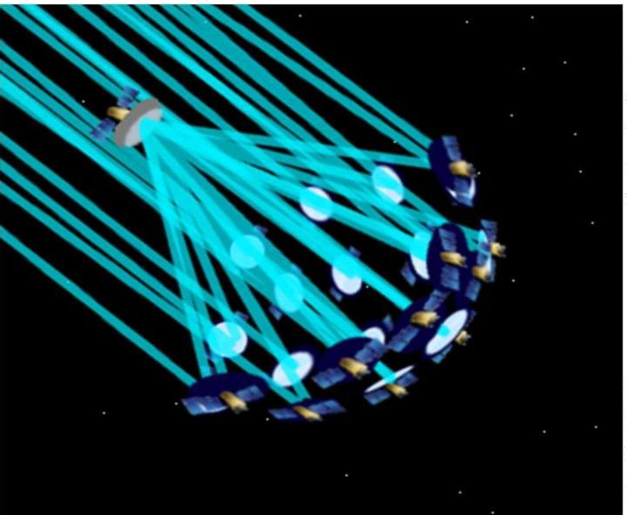


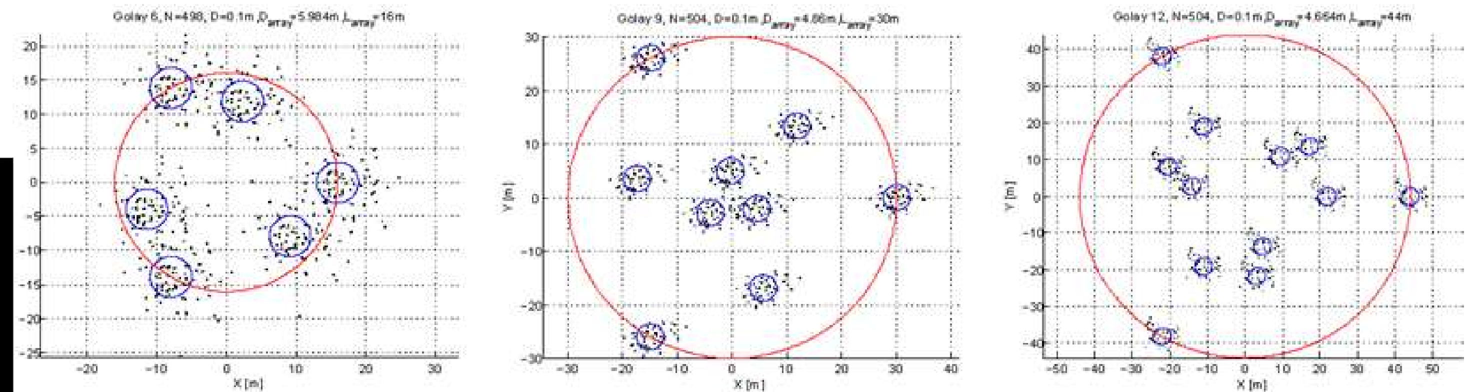


S-J Chung, DW Miller, OL de Weck, Optical Engineering, 2004

S.-J. Chung, Sc.D. Thesis; AIAA JGCD, 2007,2008, 2009

Swarm Golay Arrays

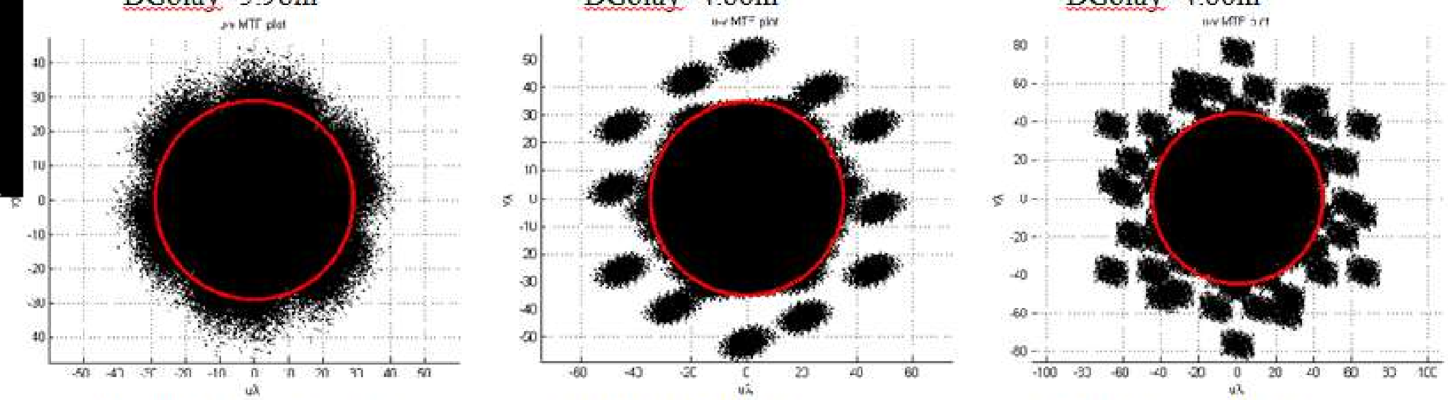




(a) Swarm Golay-6, L=16m, DGolay=5.98m

(b) Swarm Golay-9, L=30m, DGolay=4.86m

(c) Swarm Golay-12, L=44m, DGolay=4.66m



(d) MTF of (a), Deff=29m

(e) MTF of (b), Deff=35m

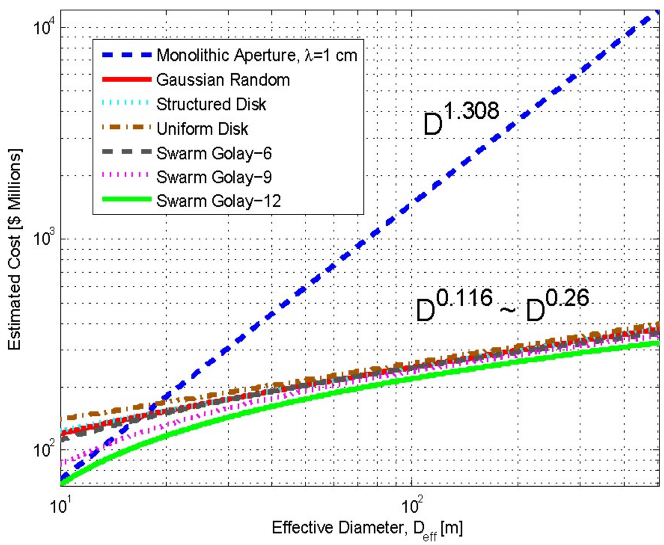
(f) MTF of (c), Deff=44m

Fred Y. Hadaegh, Soon-Jo Chung, and Harish M. Manohara, "**On Development of 100-Gram-Class Spacecraft for Swarm Applications**" *IEEE Systems Journal*, 2016.

Cost Analysis Conclusion

$$\text{cost} = \$2.25\text{billion} \times (\text{mass}/10{,}000\text{kg})^{0.654} \times (1.555^{\text{difficulty level}}) \times (N^{-0.406}) \times 1/\sqrt{\lambda}$$

$1/\sqrt{\lambda}$: impact of Wavelength of Diffraction-Limited Performance (WDLP)

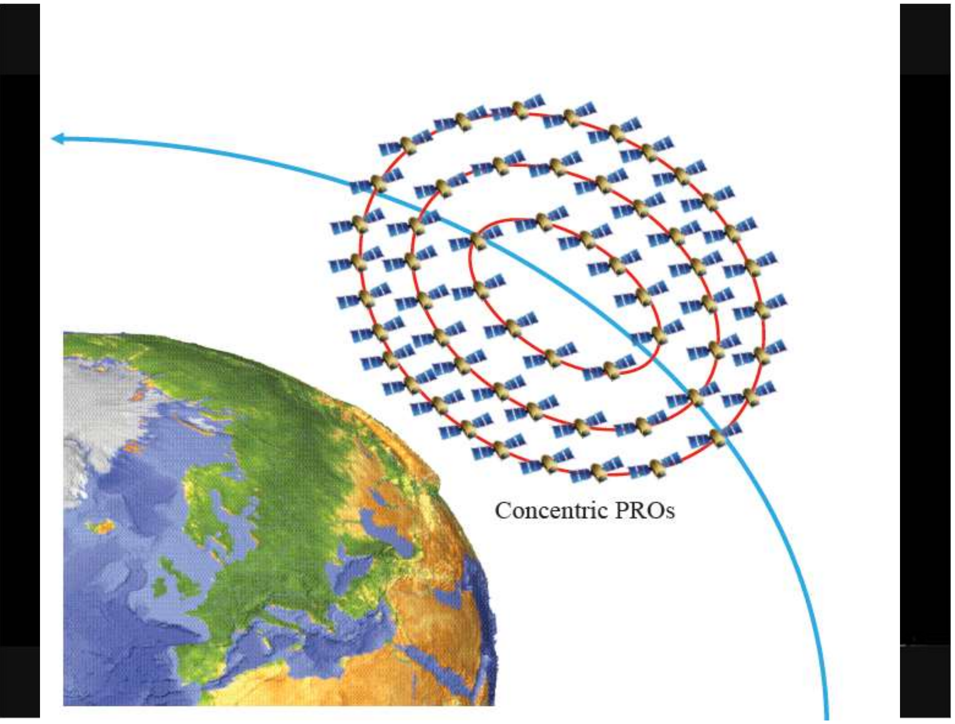


- Assuming that the mass of the telescope is proportional to D^2. Consequently, the cost of a large monolithic space-based radar is proportional to $D^{1.308}$ (in excellent agreement with 1.12 by [Stahl, OPT. ENG, 2010]
- Cost exponent of the monolithic aperture is much steeper than that of the proposed swarm array configurations. we can dramatically save the system cost of launching swarms of much smaller apertures.
- Even if the cost of each femtosat higher, results indicate that there exists a break-even point between a monolithic telescope and a swarm array.

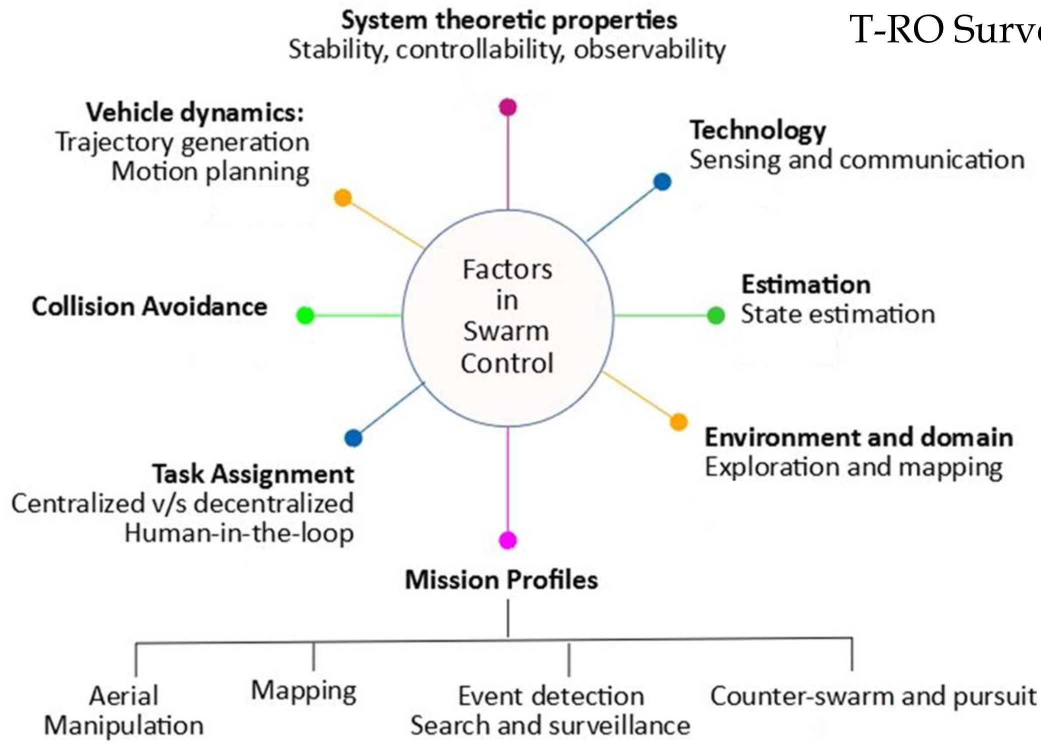
Meinel's law Monolithic	Monolithic Aperture	Gaussian Random	Structured Disk	Uniform Disk	Swarm Golay-6	Swarm Golay-9	Swarm Golay-12
$D^{2.7}$	$D^{1.308}$	$D_{\text{eff}}^{0.217}$	$D_{\text{eff}}^{0.236}$	$D_{\text{eff}}^{0.26}$	$D_{\text{eff}}^{0.157}$	$D_{\text{eff}}^{0.132}$	$D_{\text{eff}}^{0.116}$

Fred Y. Hadaegh, Soon-Jo Chung, and Harish M. Manohara, "**On Development of 100-Gram-Class Spacecraft for Swarm Applications**" *IEEE Systems Journal*, 2016.

Technology Gaps: G&C of Spacecraft Swarms



T-RO Survey

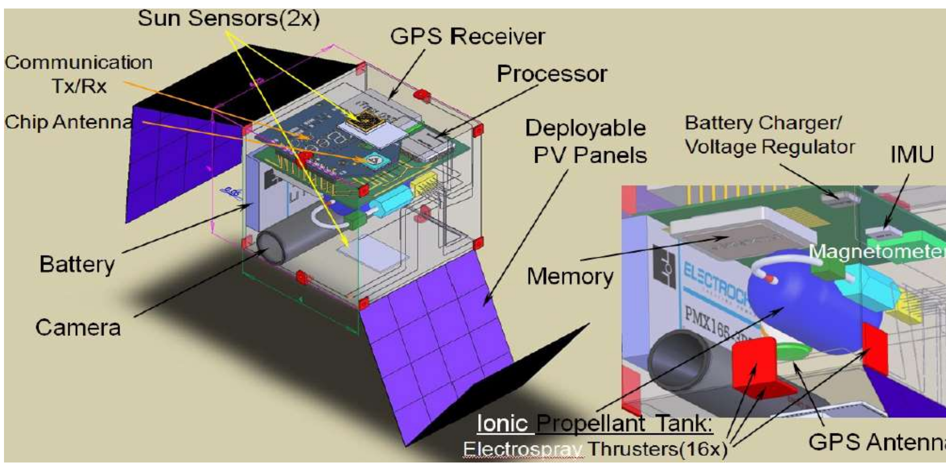


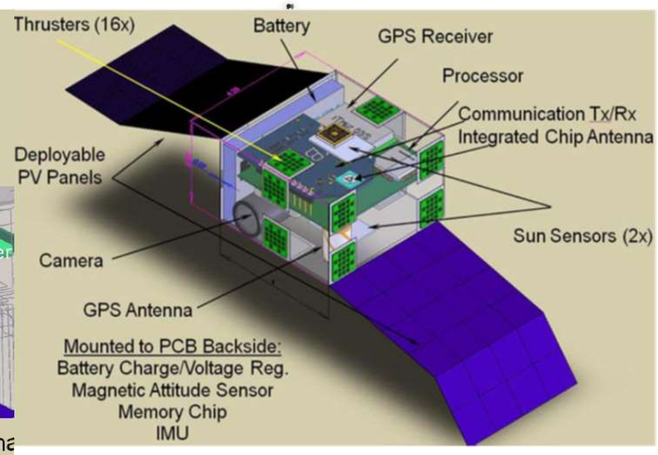
The G&C technologies should simultaneously address 1) such an enormous number of spacecraft in swarms; 2) relatively modest control, sensing, and communication capabilities of smallsats; and 3) the complex 6-DOF motions governed by gravity field and various disturbances and their impact on coupled motions.

Objective: develop a new guidance and control (G&C) and estimation strategy that can reduce the complexity of controlling thousands of small satellites for distributed sensing and autonomous construction in space.

Definition of FemtoSat Swarm

- **Swarm:** a collection of hundreds to thousands of spacecraft
  → maximize the benefit of the massively distributed spacecraft architecture.
- **Femtosat:** a 100-gram-class spacecraft
- In contrast with Cubesats & PCBSat, and the passive silicon-chip spacecraft, ***SWIFT*** represents a “fully functional” 100-gram satellite built on novel 3-D silicon wafer fabrication and integration techniques.





DARPA

Fred Y. Hadaegh, Soon-Jo Chung, and Harish M. Manohara, “**On Development of 100-Gram-Class Spacecraft for Swarm Applications**” *IEEE Systems Journal*, 2016.

JPL

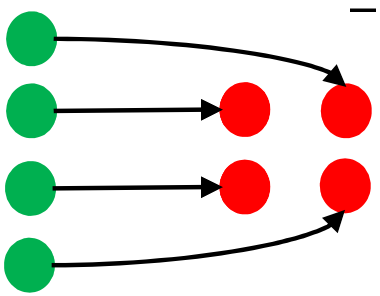
Optimal Swarm Reconfiguration Problem

- Objective: Minimize the total fuel used by all of the spacecraft to create a desired shape

$$\min_{\mathbf{u}_j, j=1,\ldots,N} \sum_{j=1}^{\boxed{N}} \int_0^{t_f} \|\mathbf{u}_j(t)\|_1 dt$$

- Constraints
  - Dynamics (nonlinear with J_2): $\boxed{\dot{\mathbf{x}}_j = \mathbf{f}(\mathbf{x}_j, œ) + B\mathbf{u}_j}$
  - Maximum allowable acceleration: $\|\mathbf{u}_j(t)\|_\infty \leq U_{\max}$
  - Collision avoidance: $\boxed{\|G[\mathbf{x}_j(t) - \mathbf{x}_i(t)]\|_2 \geq R_{\mathrm{col}}}$
  - Initial and terminal states: $\mathbf{x}_j(0) = \mathbf{x}_{j,0}$

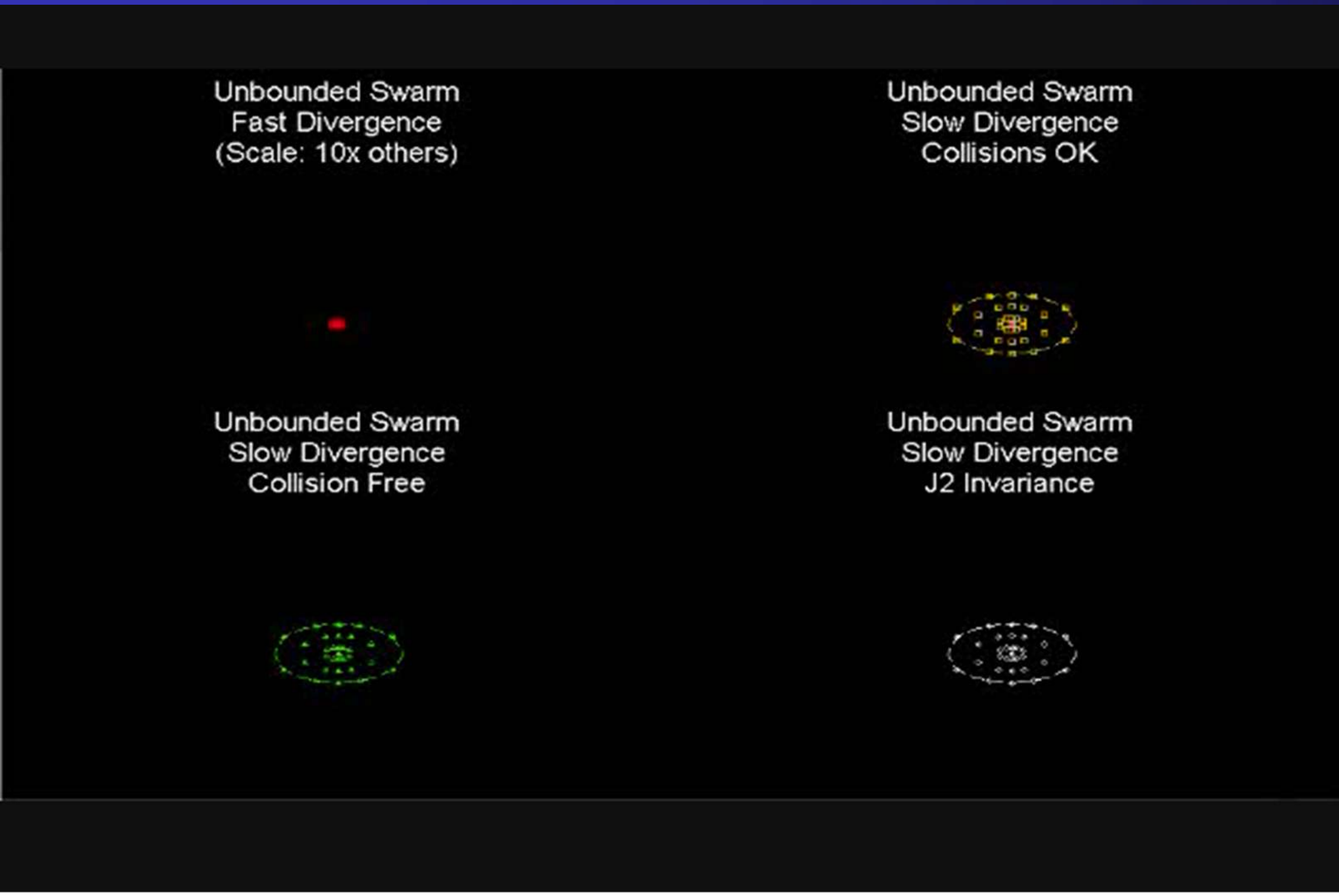
$$\boxed{\mathbf{x}_j(t_f) = \mathbf{x}_{j,f}}$$

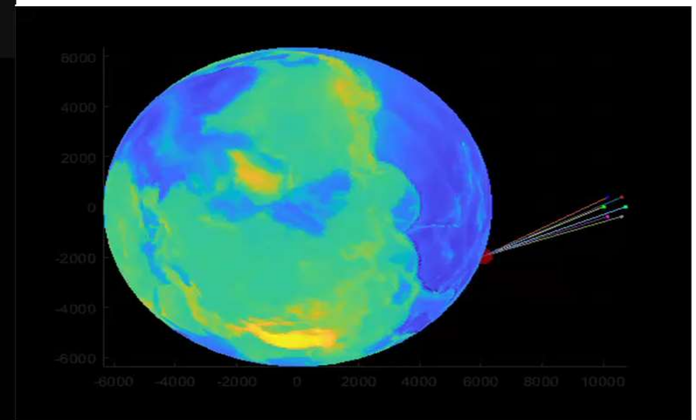


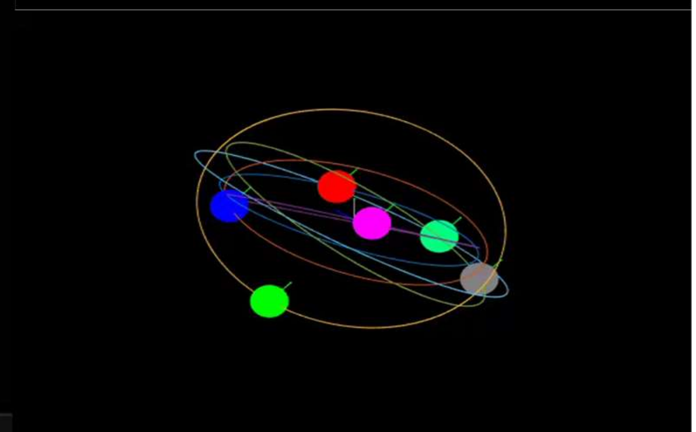
Real-time Algorithm & Decentralized Comm./Comp.

Morgan, Chung, Hadaegh, "Decentralized Model Predictive Control of Swarms of Spacecraft Using Sequential Convex Programming," ***Journal of Guidance, Control, & Dynamics***, 2014

J2-Invariant Concentric Periodic Relative Orbits



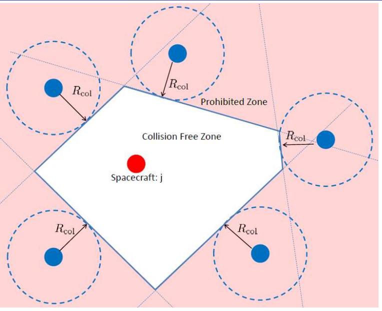




Energy Matched J2 Invariance Drift Rate: 0.0076 m/orbit (3 orders of magnitude better)

D. Morgan, et al. "**Swarm-Keeping Strategies for Spacecraft under J2 and Atmospheric Drag Perturbations**," *J.Guidance, Control, and Dynamics*, 2012

Optimal Swarm Reconfiguration Integrated with Real-Time Optimal Target Assignment



$$\boxed{\min_{\mathbf{u}_j} \sum_{k=k_0}^{k_0+T_H-1} \|\mathbf{u}_j[k]\|_1 \Delta t_1 + \sum_{k=k_0+T_H}^{T-1} \|\mathbf{u}_j[k]\|_1 \Delta t_2}$$

$$\min_{\mathbf{x}_{j,f},j=1,\ldots,N} \sum_{j=1}^{N} C(\mathbf{x}_{j,0}, \mathbf{x}_{j,f})$$

subject to

$$\mathbf{x}_j[k+1] = A_j[k]\mathbf{x}_j[k] + B_j[k]\mathbf{u}_j[k] + s_j[k], \quad k = k_0, \ldots, T-1$$

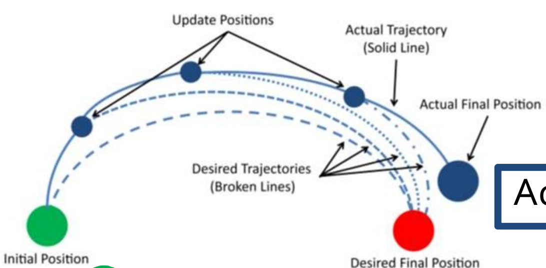
$$(\bar{\mathbf{x}}_j[k] - \bar{\mathbf{x}}_i[k])^T G^T G(\mathbf{x}_j[k] - \bar{\mathbf{x}}_i[k]) \geq R_{i,j}[k] \|G(\bar{\mathbf{x}}_j[k] - \bar{\mathbf{x}}_i[k])\|_2, \quad k = k_0, \ldots, k_0 + T_H$$

$$\{i,j\} : i \in \mathcal{P}_j \cap \mathcal{N}_j, \quad \mathcal{P}_j = \{i | i < j\}, \quad \mathcal{N}_j = \{i | \|\mathbf{x}_j[k_0] - \mathbf{x}_i[k_0]\|_2 \leq R_{\text{comm}}\}$$

$$\boxed{\|D\mathbf{x}_j[k]\|_2 \leq V_{\max}} \quad k = k_0, \ldots, T$$

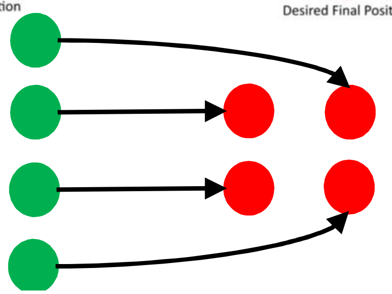
$$\|\mathbf{u}_j[k]\|_\infty \leq U_{\max} \quad k = k_0, \ldots, T-1$$

$$\mathbf{x}_j[k_0] = \mathbf{x}_{j,k_0}$$

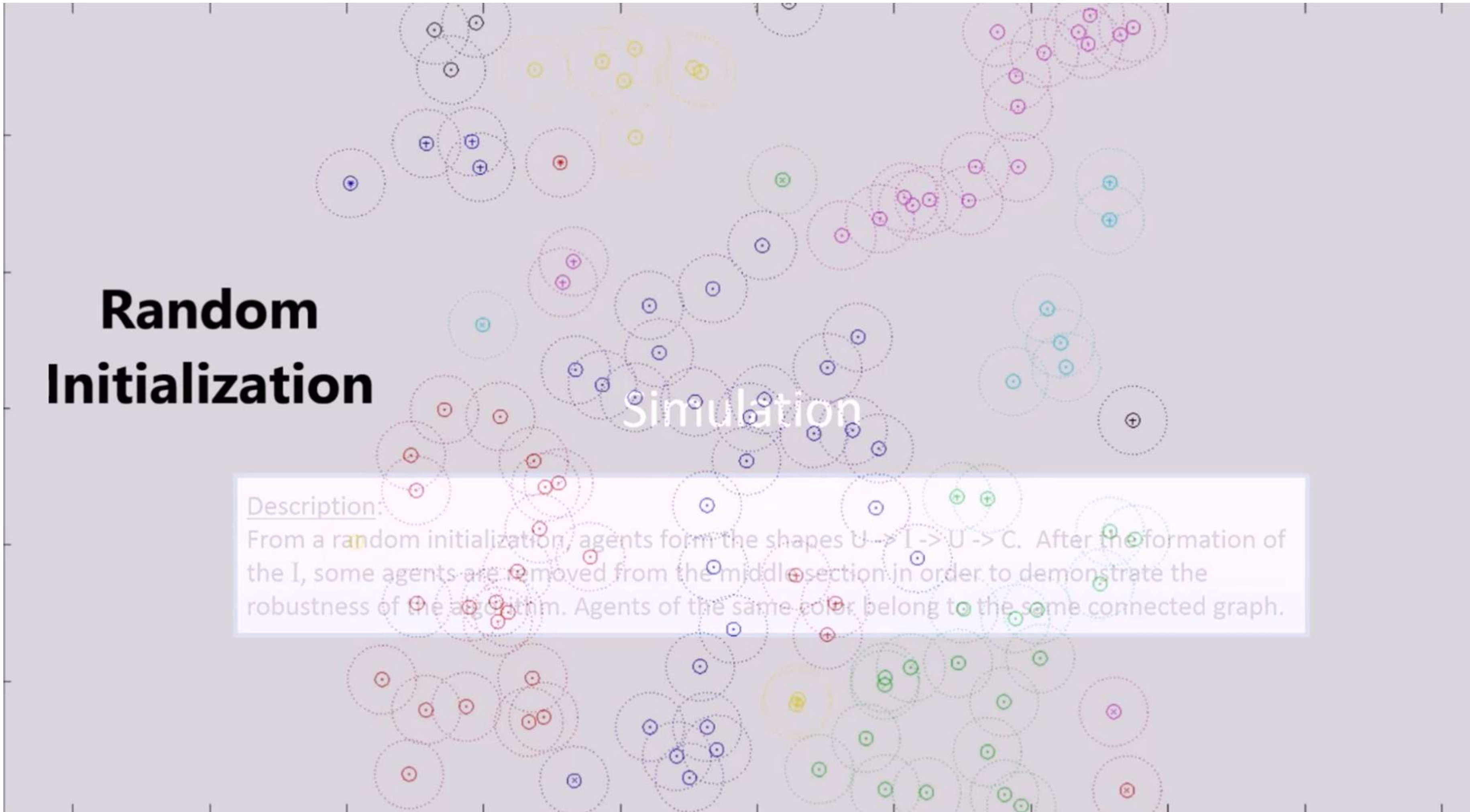


Additional MPC Constraints

Target Assignment Problem:
(Distributed Auction Algorithm)
Given $\mathbf{x}_j(0) = \mathbf{x}_{j,0}$
Find $\boxed{\mathbf{x}_j(t_f) = \mathbf{x}_{j,f} \in \mathcal{X}_f}$



- D. Morgan, G. Subramanian, S.-J. Chung, F. Y. Hadaegh, "Swarm Assignment and Trajectory Optimization Using Variable-Swarm, Distributed Auction Assignment and Model Predictive Control," *International Journal of Robotics Research, 2016. 2015 AIAA Guidance, Navigation, and Control (GNC) Conference* ***Best Paper***.
- J. Yu, S.-J. Chung, P.G. Voulgaris, "**Target Assignment in Robotic Networks: Distance Optimality Guarantees and Hierarchical Strategies**," ***IEEE Trans. on Automatic Control***, 60(2):327-341, 2015.

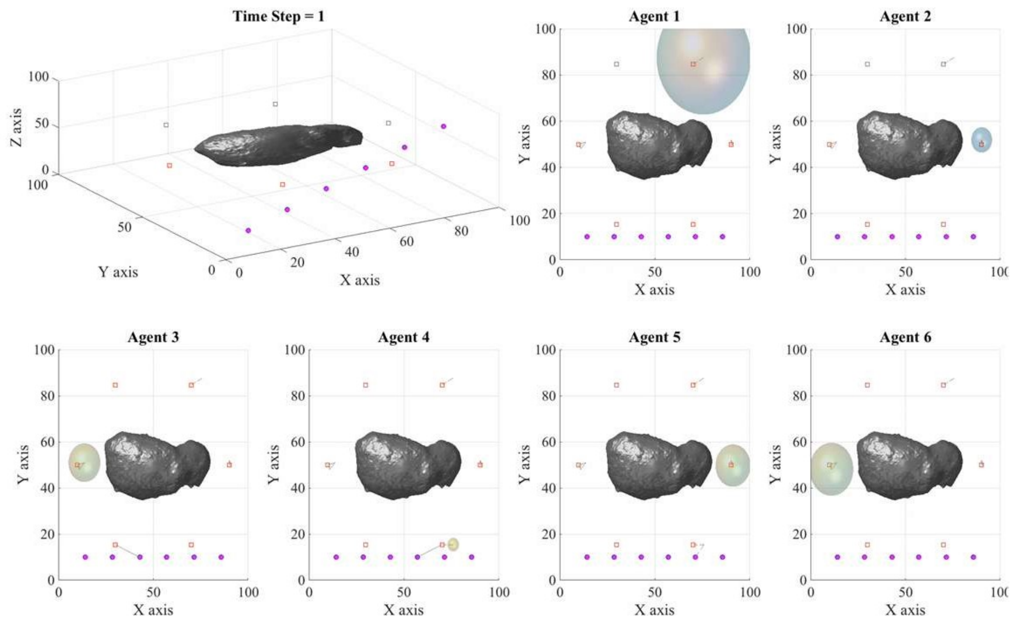


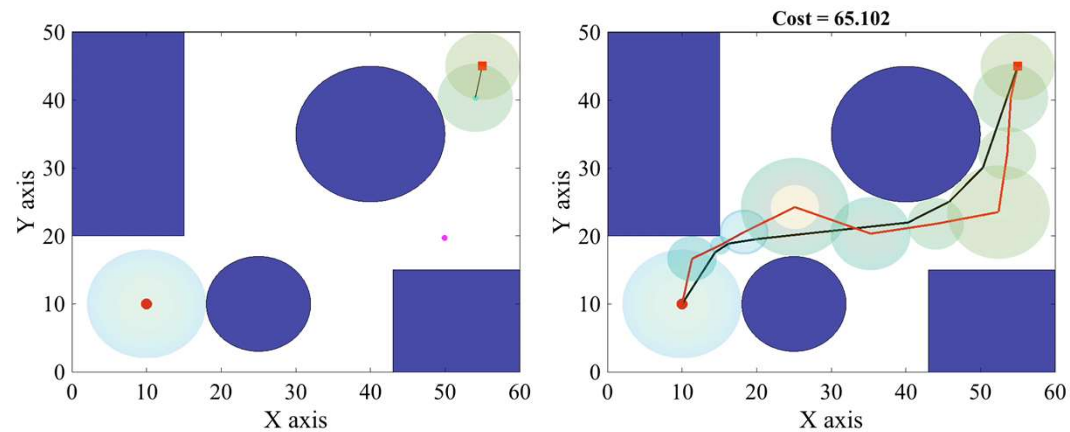
Morgan, Subramanian, Chung, Hadaegh, "Swarm Assignment and Trajectory Optimization Using Variable-Swarm, Distributed Auction Assignment and Model Predictive Control," *The International Journal of Robotics Research, 2016.*

CAST Space Robotics Lab
(Caltech’s Spacecraft Simulation Facility)

JPL-CAST Swarm Project & NSTRF (Fred Hadaegh)
JPL KISS R&TD (M. Quadrelli, R. Hodges)
JPL R&TD on Small Body (I. Nesnas, S. Bhaskaran)
JPL 3x Autonomy (K. Barltrop, L. Fesq)
Mars Helicopter (M. Aung, F. Hadaegh)
NASA CIF Mars Distributed Gliders (S. Bandyopadhyay)

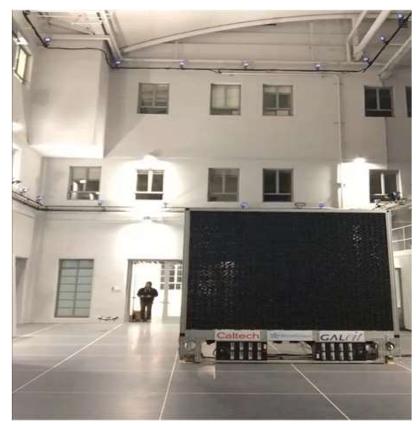
Fast Real-Time Motion Planning

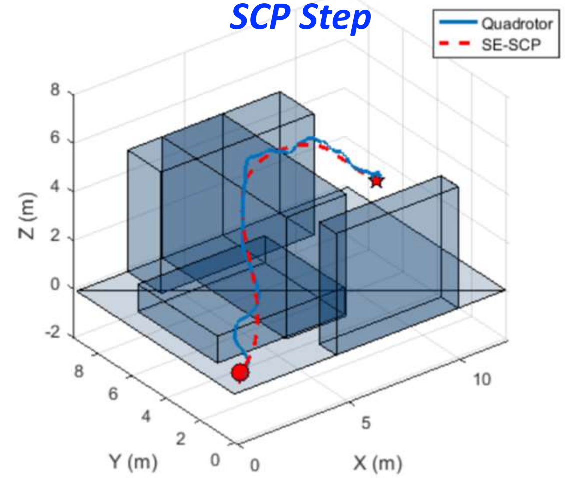




Spherical Expansion Step

SCP Step





SE-SCP solution approach has 2 steps:

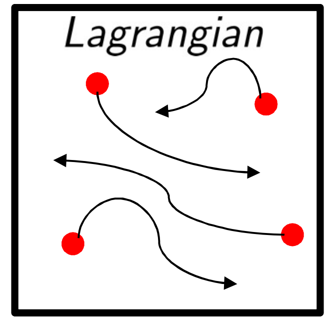
Explore: Spherical Expansion

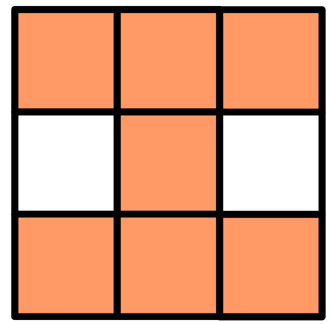
Optimize: Sequential Convex Programming

S. Bandyopadhyay, F. Baldini, R. Foust, K. Kim, S.-J. Chung, A. Rahmani, J.-P. de la Croix, F. Y. Hadaegh, Fast Motion Planning for Agile Autonomous Vehicles in Cluttered Environments, JPL Topical R&TD 2015-2017.

Large-Scale Swarms: Probabilistic Swarm Guidance

- Motion planning algorithm for a large-scale swarm should be:
  - Versatile: perform multiple tasks like maintaining the formation shape or exploring the area
  - Robust: handle addition or removal of robots
  - Scalable: easily scale with the number of robots and the size of the area
- Objective: Guide a large-scale swarm of agents into a desired formation shape in a distributed and scalable manner
- *Lagrangian* framework: each agents trajectory is generated separately [1]-[6]
- We adopt an *Eulerian* framework: control the collective properties of the swarm (e.g., swarm density distribution)

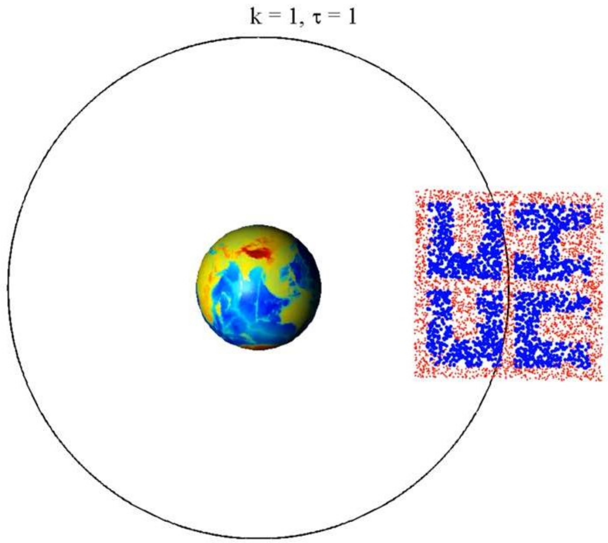


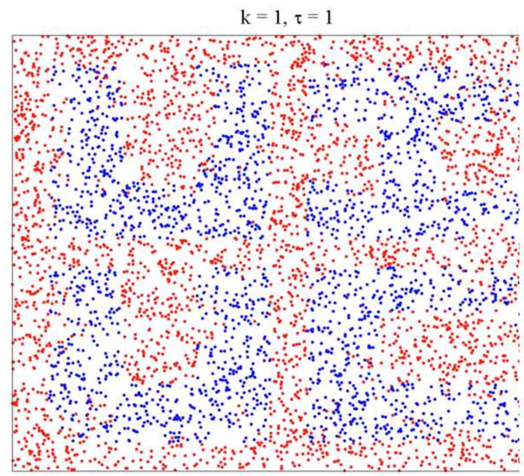


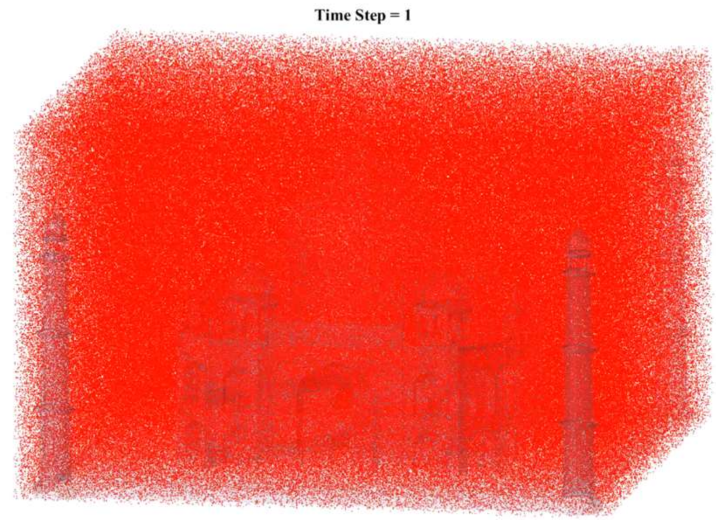
Eulerian

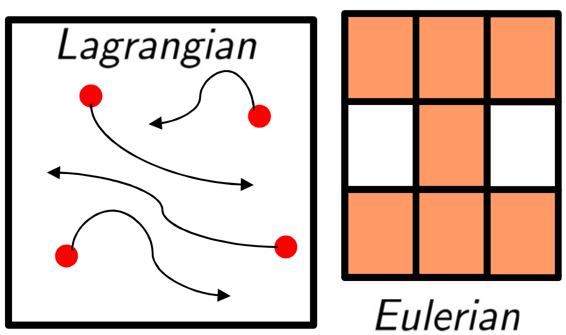
[1] M. Dorigo, "Autonomous selfassembly in swarm-bots," IEEE Trans. Robotics, 2006.
[2] V. Kumar, "Towards a swarm of agile micro quadrotors," 2013.
[3] K. M. Lynch, "Multi-agent coordination by decentralized estimation and control," IEEE Trans. Autom. Control, 2008.
[4] S.-J. Chung, "Phase synchronization control of complex networks of Lagrangian systems on adaptive digraphs," Automatica, 2013.
[5] J. Cortés, "Coverage control for mobile sensing networks," IEEE Trans. Robotics and Automation, 2004.
[6] A. Martinoli, "Robust distributed coverage using a swarm of miniature robots," IEEE Int. Conf. Robotics Automation, 2007.

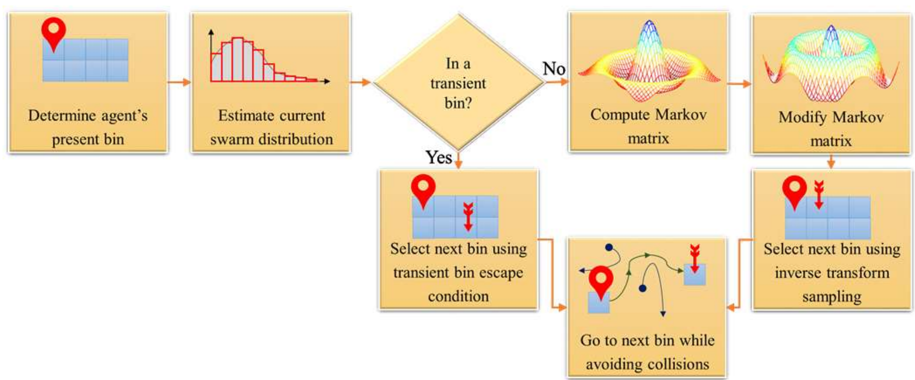
Probabilistic Swarm Density Control











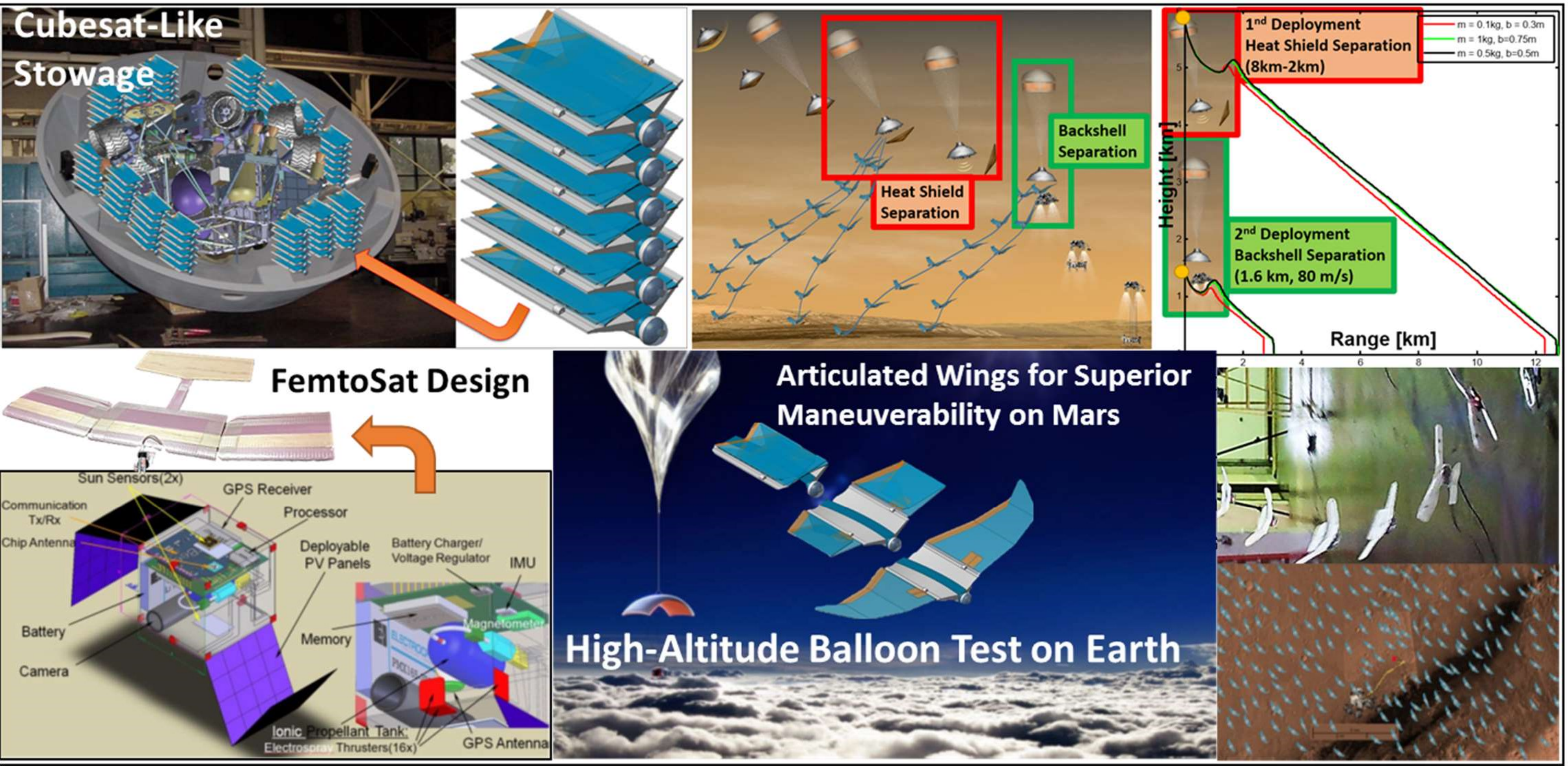
S. Bandyopadhyay, S.-J. Chung, and F. Y. Hadaegh, "Probabilistic and Distributed Control of a Large-Scale Swarm of Autonomous Agents," **IEEE Transactions on Robotics**, 2017

National Aeronautics and
Space Administration

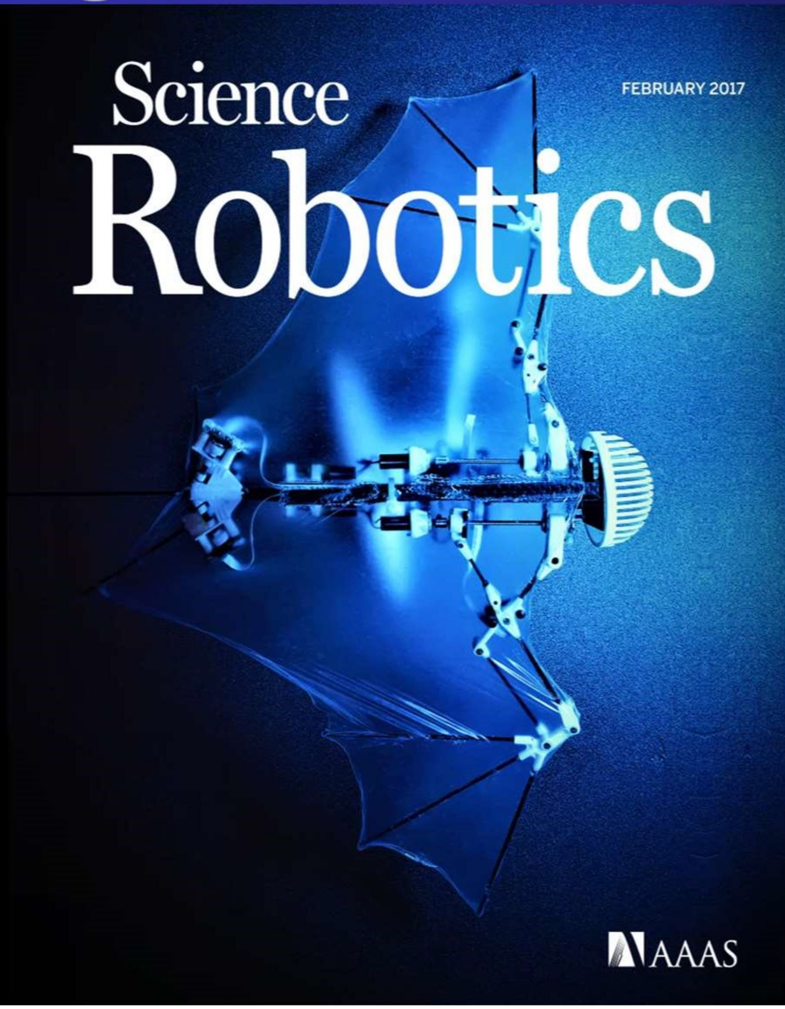
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

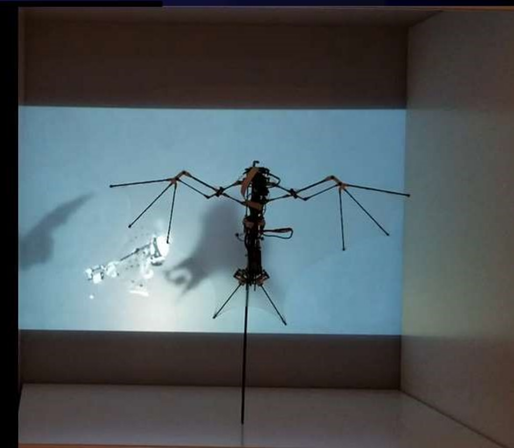
Probabilistic Guidance of a Swarm Deployed from the Back Shell of the Mars Spacecraft

with S. Bandyopadhyay, J.-P. de la Croix, D. Bayard, I. Nesnaz, and F. Y. Hadaegh,

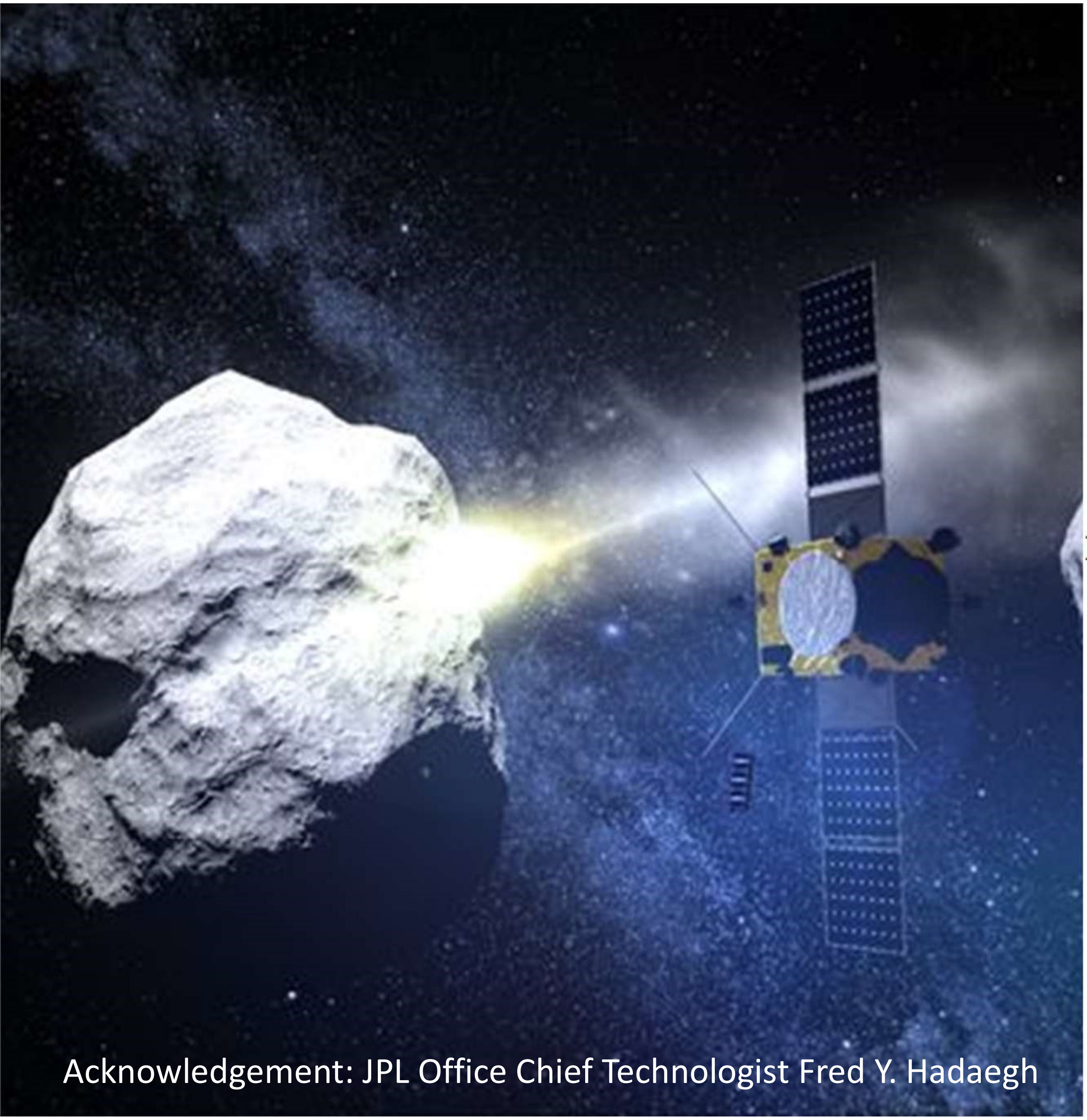


93-gram Autonomous Bat Bot (B2)





Alirez Ramezani, Soon-Jo Chung, and Seth Hutchinson, "**A Biomimetic Robotic Platform to Study Flight Specializations of Bats**," *Science Robotics (AAAS)*, vol. 2, no. 3, eaal2505, February 2017. **Cover Article**



Caltech

Autonomous Small Body Mapping and Spacecraft Navigation

Francesca Baldini[1], Alexei Harvard[1], Soon-Jo Chung[1], Issa Nesnas[2], and Shyamkumar Bhaskaran[2]

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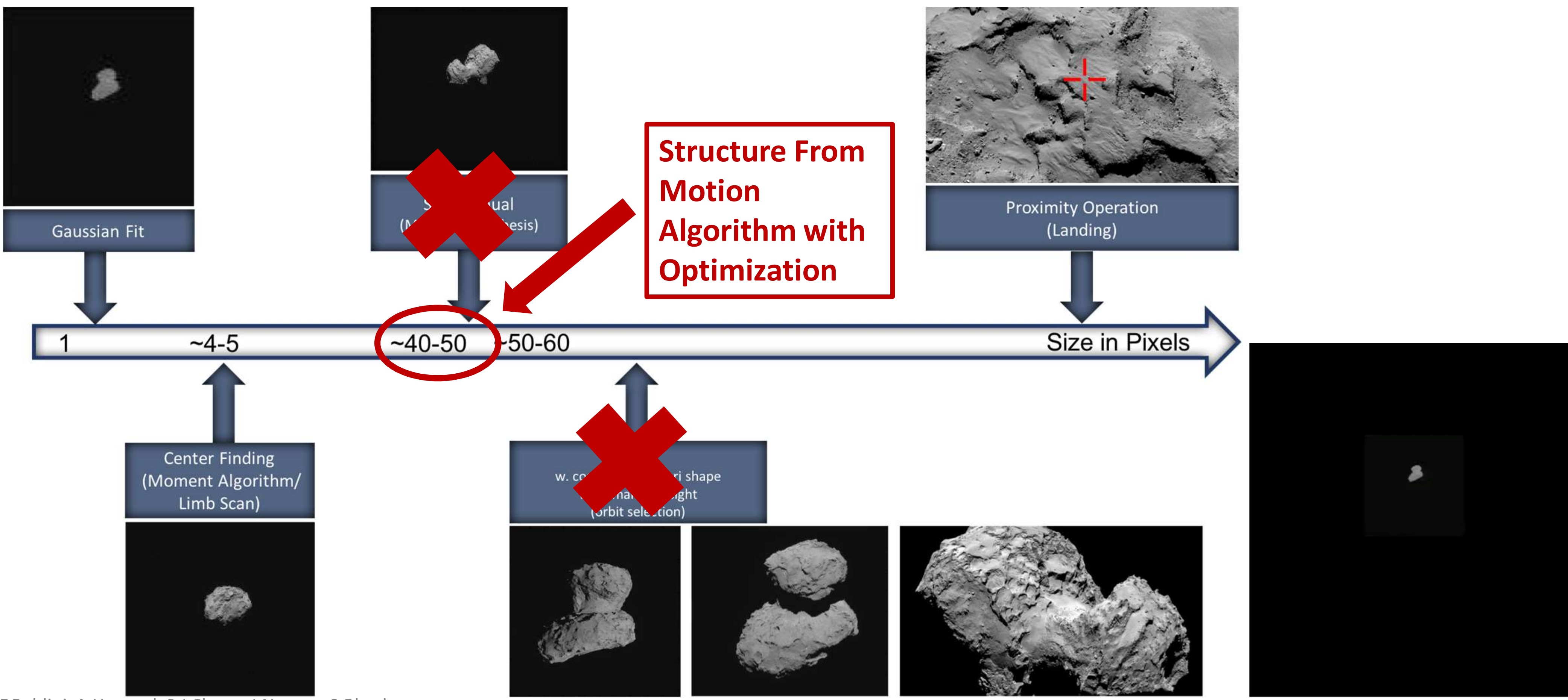
JPL
Jet Propulsion Laboratory
California Institute of Technology

Phase of the Rosetta Mission

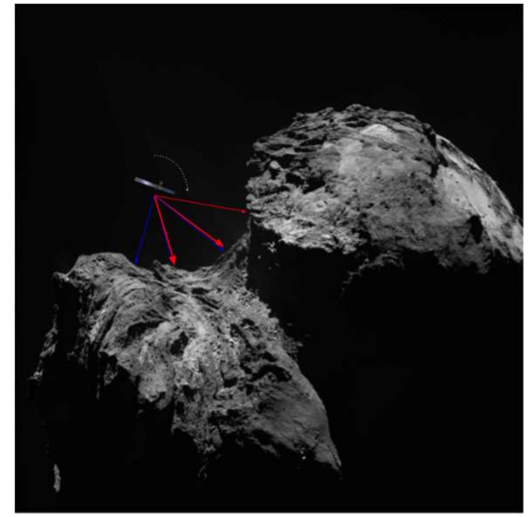


F.Baldini, A.Harvard, S.J.Chung, I.Nesnas, S.Bhaskaran

Alexei Harvard: Realtime Swarm Localization and 3D Mapping

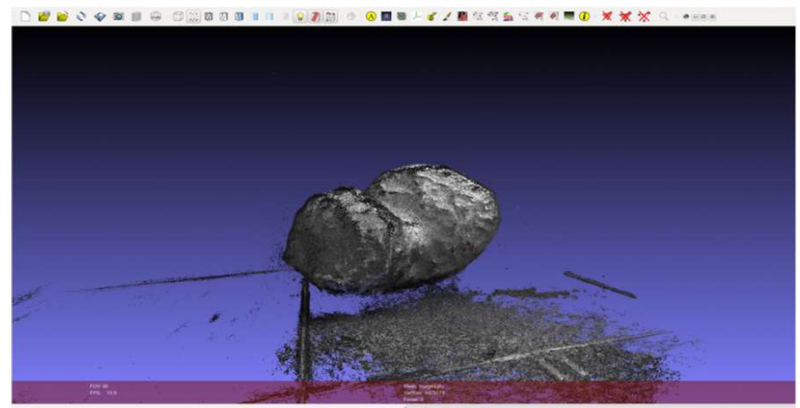
To analyze and implement on board image-based localization and 3D reconstruction for use with navigation and coverage determination.

- Created and used existing GPU implementations to accelerate feature detection/matching/3D processing.



- Standard reconstructions work by creating maps of 3D points and localizing through find correspondences and solving the PnP problem.
- In space, a pure rotation of an orbiting satellite would cause issues since the bearings of the 2D points would have very small relative angles.
- Proposed solution is to do a mixed 2D-3D mapping.

- Scale ambiguity: Use inter-drone communication through varying RF bands to obtain range and velocity information via radio interferometry and TOF measurements. Can obtain relative velocities through doppler shifts.

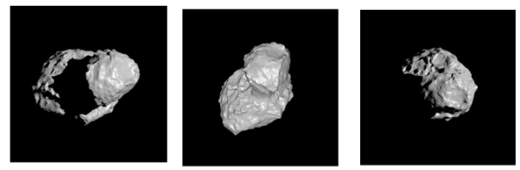


Post-processed dense cloud

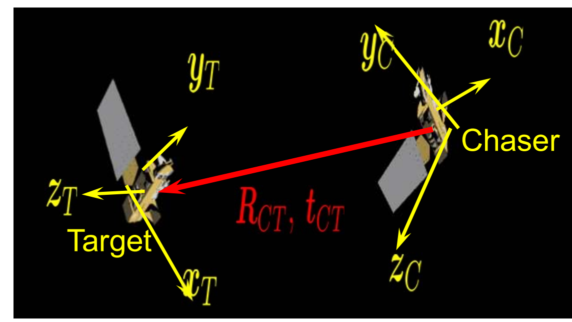
Relative Pose Estimation between Spacecraft Swarms

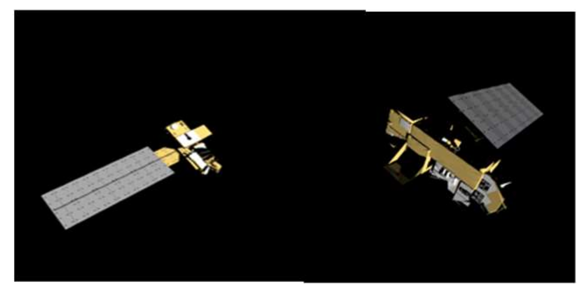
With Ryan Alimo (JPL), Vincenzo Capuano, Kyunam Kim (Caltech)

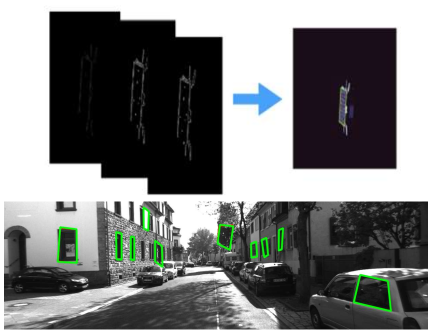
- Dealing with more realistic data including shadows, noise, and varying illumination conditions for online pose estimation of spacecraft and asteroids.
- Estimating the pose using small labeled dataset, i.e., few-shot imitation learning.



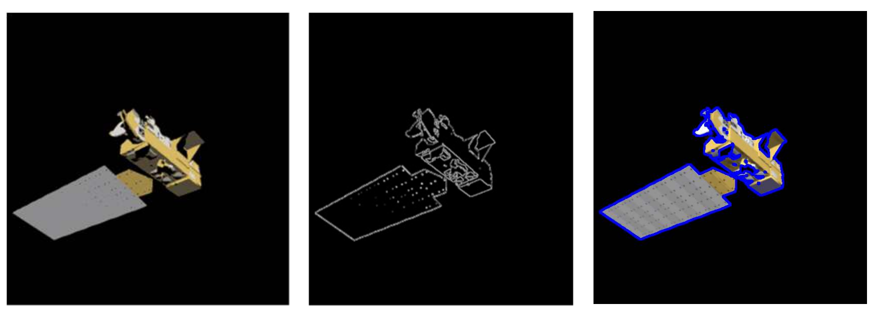
- Couple of hundreds images,
- Distance of 80 to 120 kilometers,
- Dataset with random noise,
- Shadows decrease visibility.







Monocular Vision-based Navigation using Image Moments of Polygonal Features (in progress).



Feature-based localization for Robust model-based pose estimation of uncooperative spacecraft from monocular images (Alimo et al. 2018, Capuano et al 2019).

In-Space Construction: How to Do the Impossible

- Autonomously Create a Very Capable Science Instruments in Space using Swarms (applications are limitless!) → Complexity of Autonomous GNC

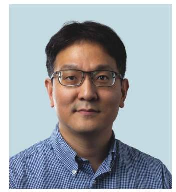
JPL-Caltech/ CAST Swarm Autonomy Team

Project Leads and Core Researchers

Adrian Stoica

Michael Wolf

Morteza Gharib



Soon-Jo Chung

Yisong Yue

S. Ryan Alimo
Navigation
Machine Learning

Changrak Choi
Planning

Ravi Lanka
Planning
Machine Learning

Ali Agha
Navigation
Planning

Hiro Ono
Planning
Machine Learning

Kyunam Kim
Hardware Demo
Navigation

Vincenzo Capuano
Navigation

Alexei Harvard
Localization
3D Mapping

Yashwanth Nakka
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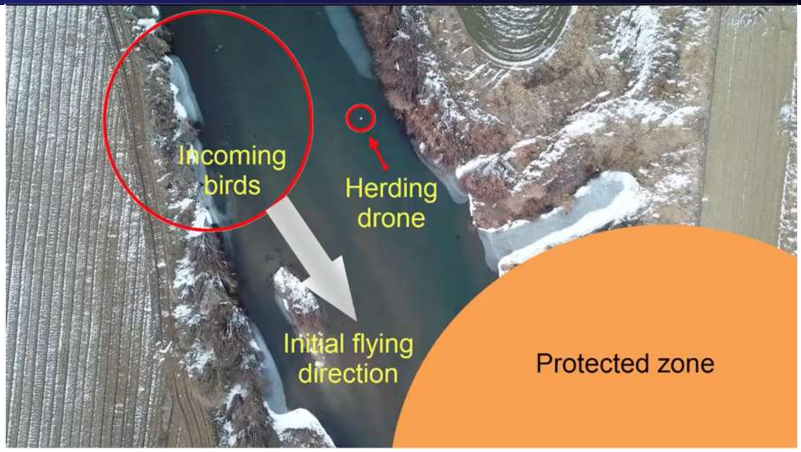
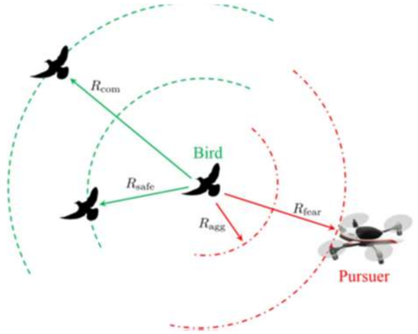
Prevent Bird Strikes on Airfields



(1) novel control strategies to realize such bird-like aerial robots;
(2) vision-based sensing solutions;
(3) strategies for cooperative pursuit and herding.



A. A. Paranjape, S.-J. Chung, K. Kim, and D. H. Shim, "**Robotic Herding of a Flock of Birds Using an Unmanned Aerial Vehicle**," *IEEE Transactions on Robotics*, 2018

National Science Foundation
WHERE DISCOVERIES BEGIN


A. A. Paranjape, S.-J. Chung, K. Kim, and D. H. Shim, "**Robotic Herding of a Flock of Birds Using an Unmanned Aerial Vehicle**," *IEEE Transactions on Robotics*, 2018

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