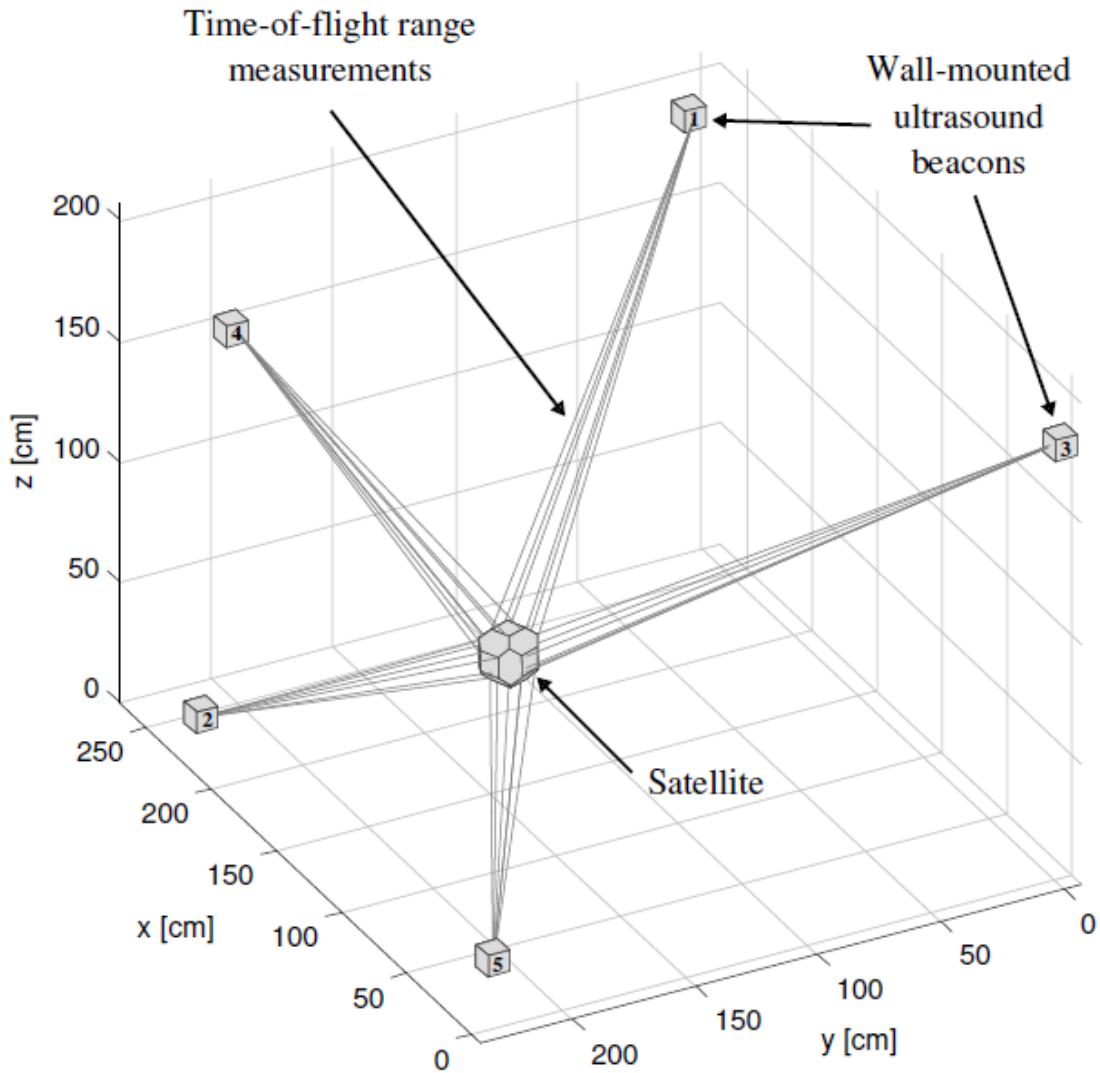
Recent / On-going Projects

- **SPHERES**
  - Synchronized, Position, Hold Engage and Reorient Experimental Satellites
  - Established in 2001-2002 by MIT, in partnership with NASA, DARPA, and Aurora Flight Sciences
  - Enables experimental research on autonomous GN&C algorithms critical to complex space missions

Recent / On-going Projects

- **ISS-SPHERES**
  - Microgravity
    - 6 DOF
  - Propulsion
    - 12 CO_2 thrusters
  - TI DSP
    - programmed in C code
    - 167 MHz
    - 16 MB RAM
  - EKF-based navigation
    - IMU
    - ultrasonic beacons



Recent / On-going Projects

- **Machine Vision for Uncooperative Targets (SPHERES)**

Massachusetts Institute of Technology

NSERC CRSNG

Fourie, D. Tweddle, B., Ulrich, S., Saenz-Otero, A., "Flight Results of Vision-Based Navigation and Control for Autonomous Spacecraft Inspection of an Unknown Object," *AIAA Journal of Spacecraft and Rockets*, Vol. 51, No. 6, 2014, pp. 2016–2026.

Recent / On-going Projects

- **Machine Vision for Uncooperative Targets (SPHERES)**

Data collection
10 RPM intermediate axis spin

Offline map creation
using a laptop (45 min)

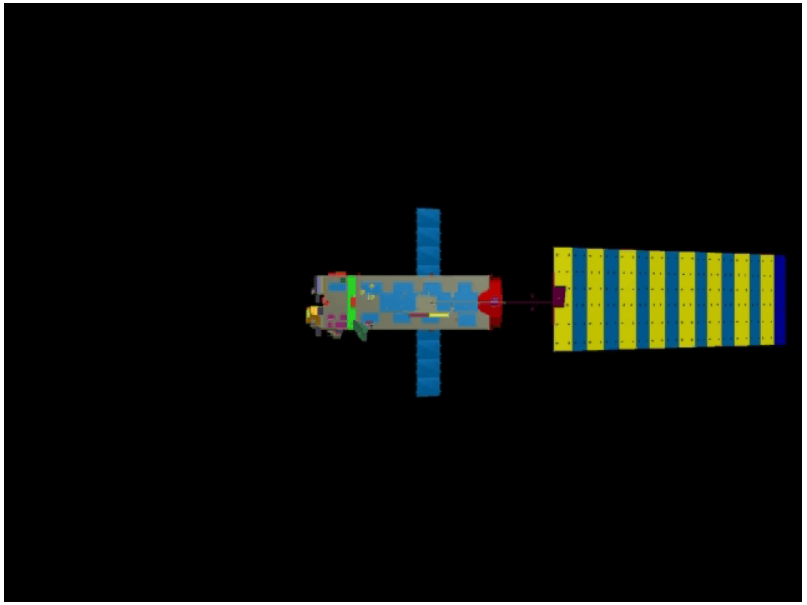
Massachusetts Institute of Technology

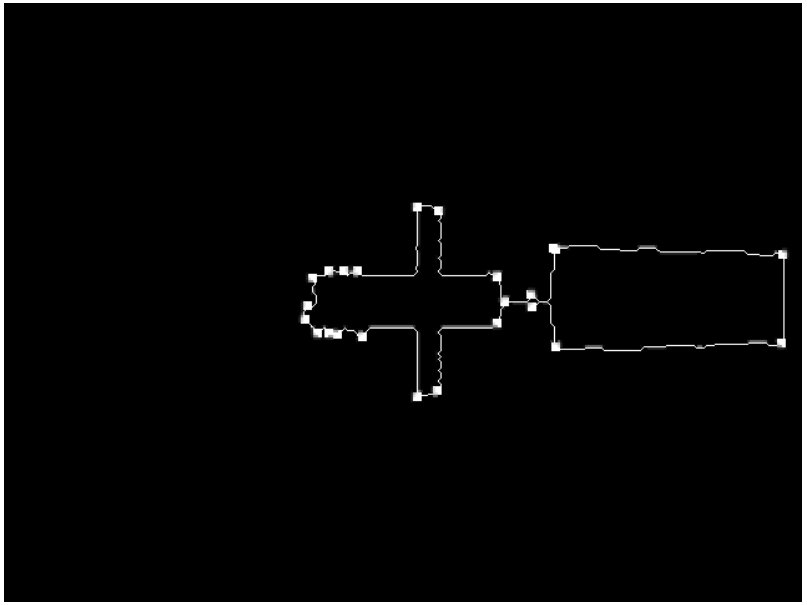
NSERC CRSNG

Tweddle, B. E., Ulrich, S., Setterfield, T., Saenz-Otero, A., and Miller, D. W., "The SPHERES-VERTIGO Goggles: An Overview of Vision-Based Navigation Research Results from the International Space Station," *12th International Symposium on Artificial Intelligence, Robotics, and Automation in Space*, Montreal, Canada, 17-19 June, 2014.

Recent / On-going Projects

- **Machine Vision for Uncooperative Targets (Envisat)**

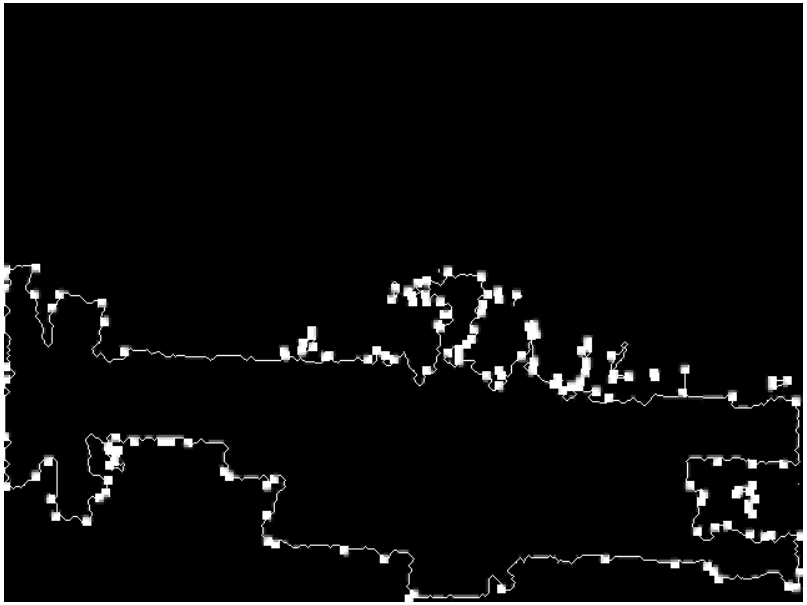




Shi, J.-F., Ulrich, S., Ruel, S., and Anctil, M., "Uncooperative Spacecraft Pose Estimation Using an Infrared Camera During Proximity Operations," *AIAA Space and Astronautics Forum and Exposition*, Pasadena, California, 31 August-2 September, 2015, accepted.

Recent / On-going Projects

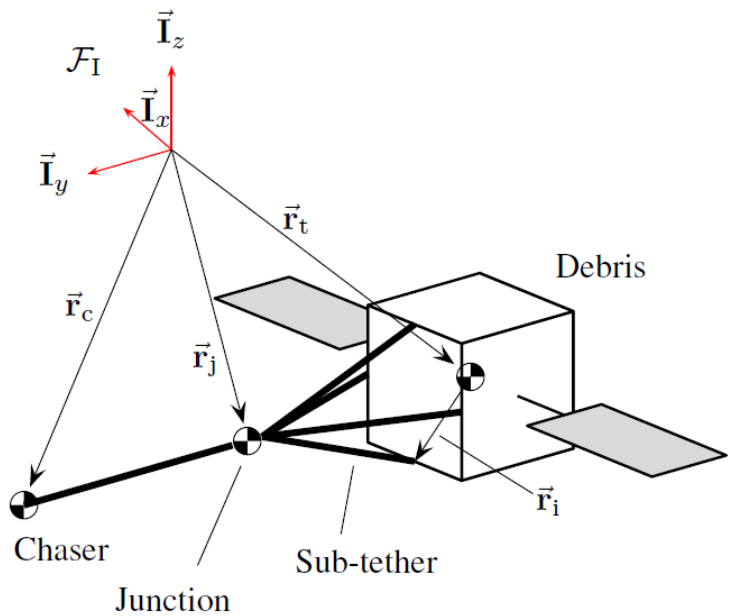
- **Machine Vision for Uncooperative Targets (ISS-TriDAR)**

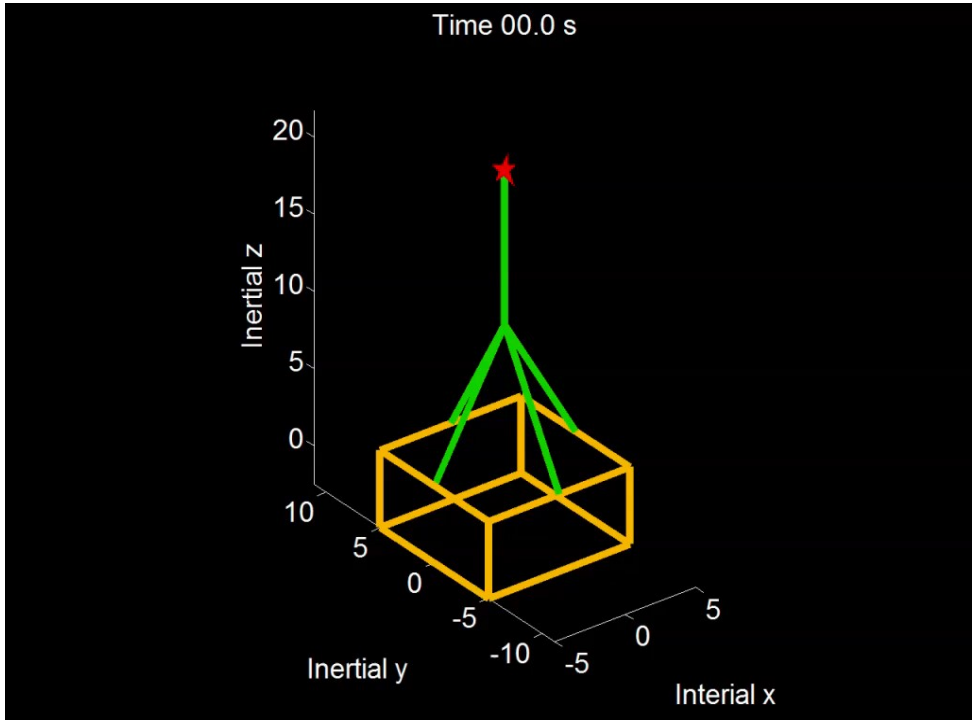


Shi, J.-F., Ulrich, S., Ruel, S., and Anctil, M., "Uncooperative Spacecraft Pose Estimation Using an Infrared Camera During Proximity Operations," *AIAA Space and Astronautics Forum and Exposition*, Pasadena, California, 31 August-2 September, 2015, accepted.

Recent / On-going Projects

- **Attitude Stabilization with Visco-Elastic Tether**





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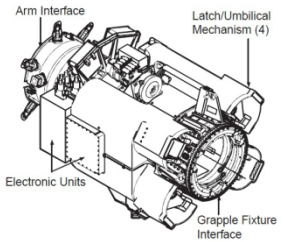
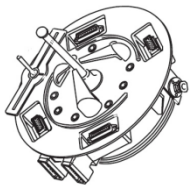
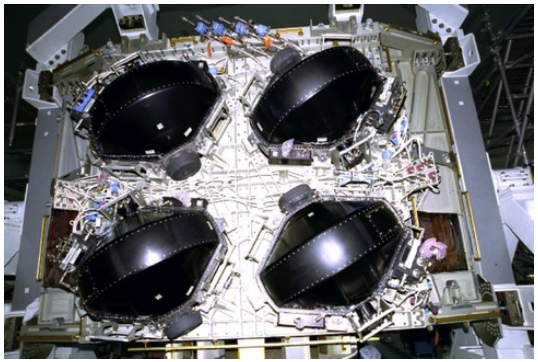
Hovell, K., and Ulrich, S., "Attitude Stabilization of an Unknown and Spinning Target Spacecraft Using a Visco-Elastic Tether," *13th Symposium on Advanced Space Technologies in Robotics and Automation*, Noordwijk, The Netherlands, 11-13 May, 2015.

Recent / On-going Projects

- **ISS Stabilization for Robotic Free-Flyer Capture**







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Shi, J.-F., Ulrich, S., and Allen, A., "Spacecraft Adaptive Attitude Control with Application to Space Station Free-Flyer Robotic Capture," *AIAA Guidance, Navigation, and Control Conference*, Kissimmee, FL, 5-9 Jan, 2015.

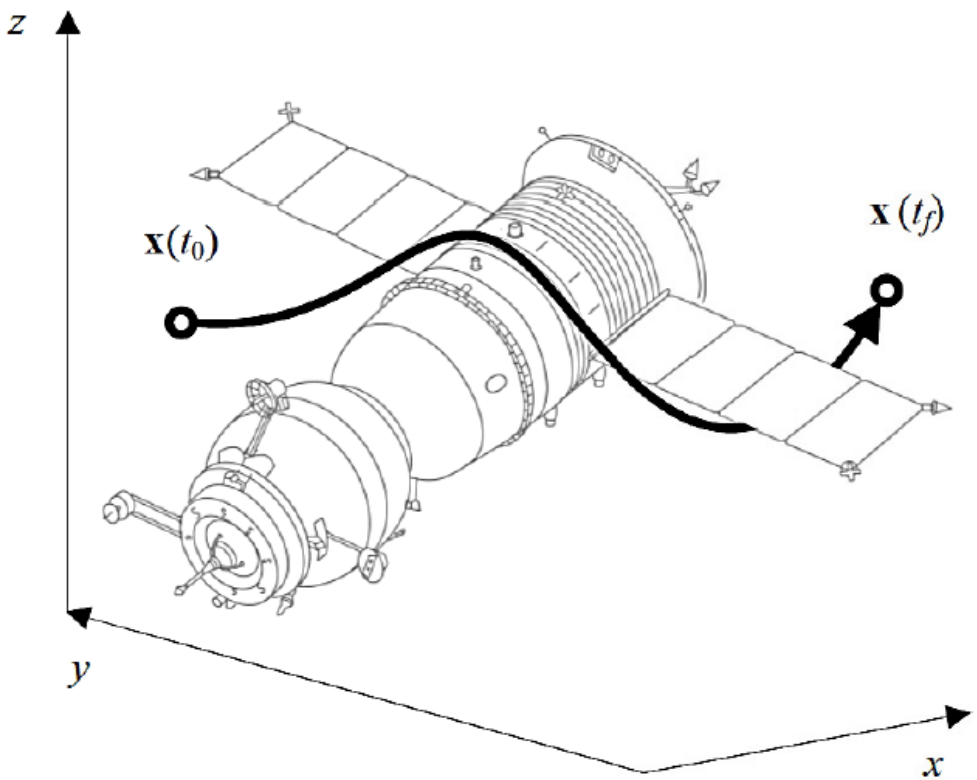
Optimal Trajectory Guidance for Spacecraft Robotic Servicing Missions

Jian-Feng Shi and **Steve Ulrich**
Department of Mechanical and Aerospace Engineering
Carleton University
Ottawa, ON, Canada

Andrew Allen
Guidance, Navigation and Control Department
MacDonald, Dettwiler and Associates Ltd. (MDA)
Brampton, ON, Canada

Optimal Trajectory Guidance

- **Problem Statement**



meets boundary conditions

avoids physical constraints

respects performance limits

minimizes the path length

Optimal Trajectory Guidance

- **Two-step Approach**
  - First step (sub-optimal solution)
    identify admissible trajectories as quickly as possible.

$$f_{BC_1} = (\mathbf{x}(t_0), \dot{\mathbf{x}}(t_0)) = 0$$
$$f_{BC_2} = (\mathbf{x}(t_f), \dot{\mathbf{x}}(t_f)) = 0$$

$$f_{c_i}(\mathbf{x}(t), \dot{\mathbf{x}}(t), \ddot{\mathbf{x}}(t)) \leq 0, \quad \forall i \in [1, n], \quad \forall t \in [t_0, t_f]$$

  - Second step (optimal solution)
    uses any remaining computation time to refine the solution towards the optimal path (minimize length).

$$S = \int_{x_0}^{x_f} \mathrm{d}s = \int_{t_0}^{t_f} \sqrt{\dot{x}(t)^2 + \dot{z}(t)^2 + \dot{z}(t)^2}\mathrm{d}t$$

Optimal Trajectory Guidance

- Augmented Cost Function

$$J = f_s^2(S) + \sum_{j=1}^{n} K_j \max_{t \in [t_0, t_f]} f_{c_j}^2$$

The relative weights need to be chosen to ensure that the constraint violations dominate the cost function

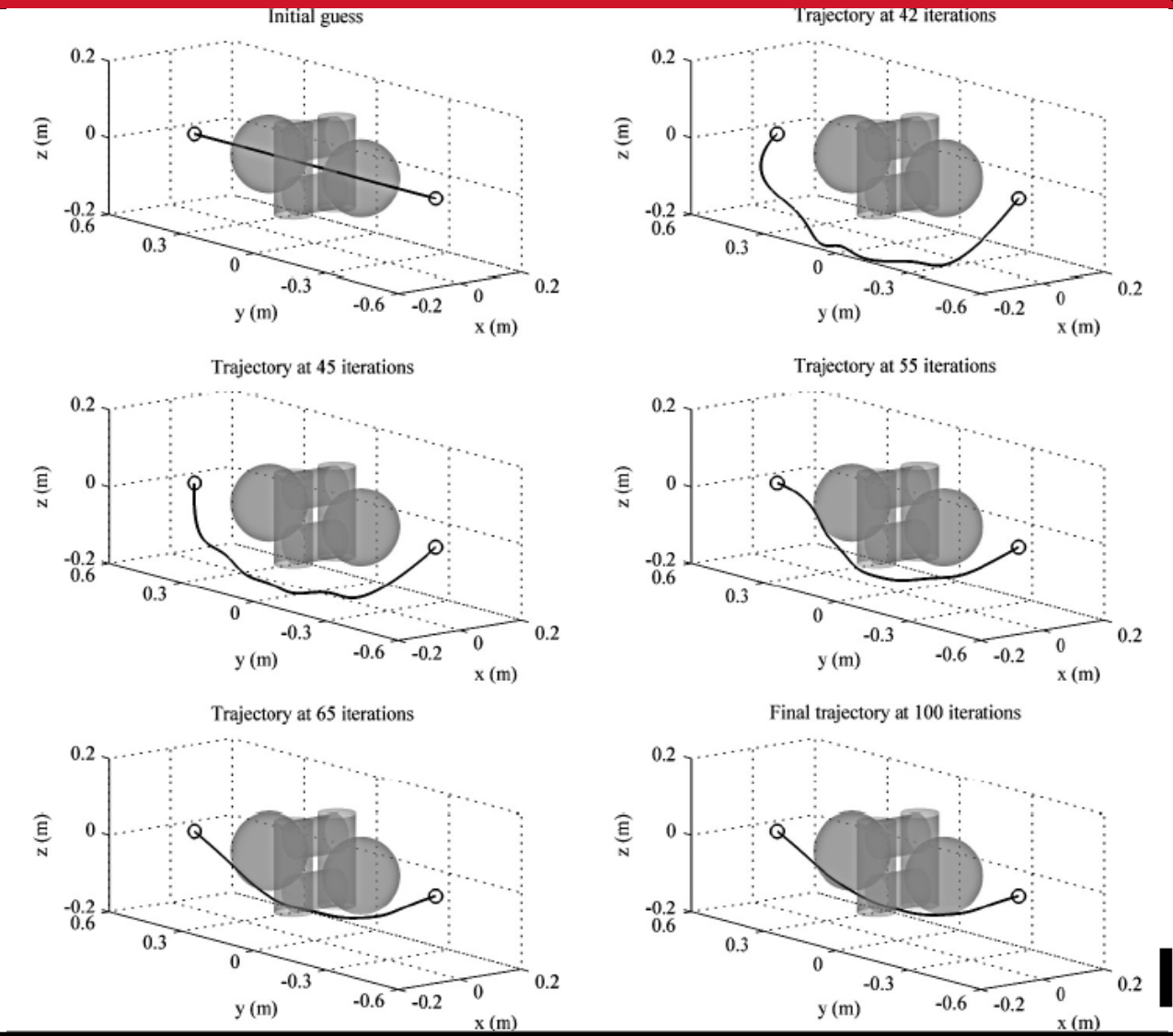
Once a solution is found that drives the second term to zero, then the resulting trajectory is admissible.

Optimal Trajectory Guidance

- **Algorithm Overview**
  - Parameterize the trajectory with Legendre polynomials to simplify the nonlinear, constrained optimization problem.
  - Define the constraints appropriately, such that a simple gradient descent search strategy will find the optimal solution.
  - Start optimization with initial guess that meets the boundary conditions.
  - Enforce the BCs by a projected gradient algorithm to quickly find sub-optimal solutions.

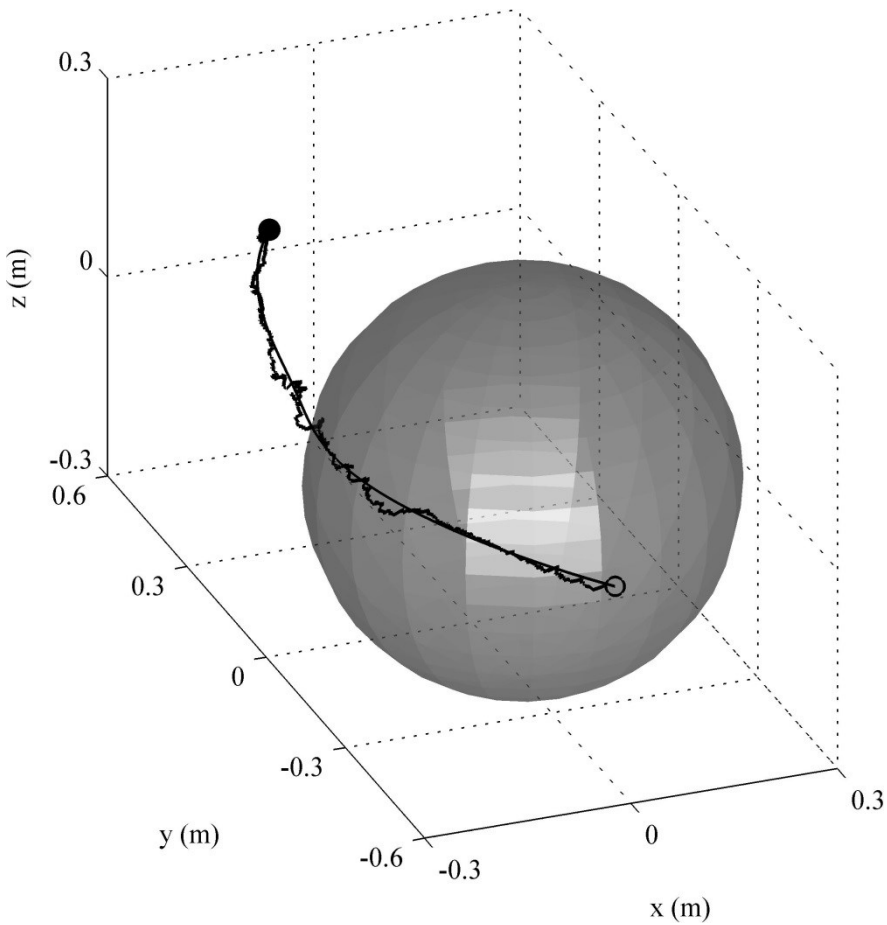
$$x_i f_c \delta \mathbf{C}_\perp = \left[\mathbf{I} - \mathbf{P}_{BC}^T \left(\mathbf{P}_{BC} \mathbf{P}_{BC}^T \right)^{-1} \mathbf{P}_{BC} \right] \delta \mathbf{C}$$

Optimal Trajectory Guidance



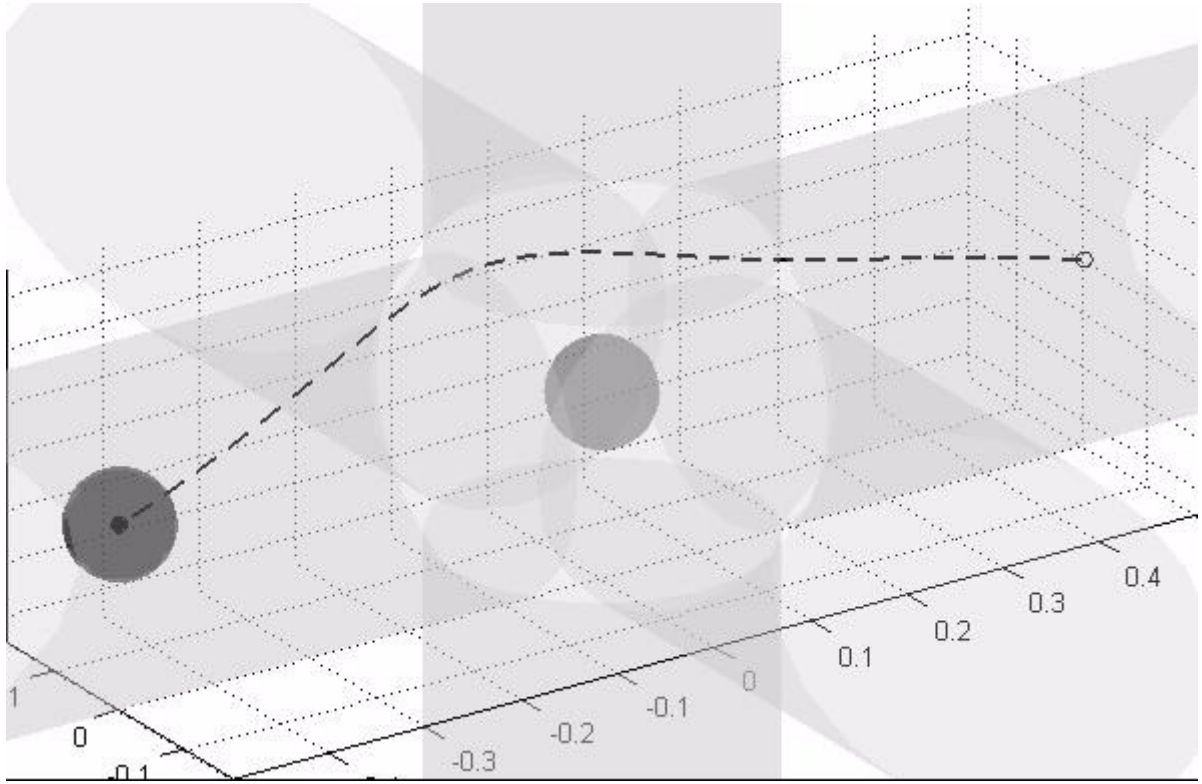
Optimal Trajectory Guidance

- **ISS-SPHERES**
  - Static obstacle test
    - 0.3 m spherical obstacle
    - max. acceleration = 0.05m/s^2
    - 17 seconds of computation time



Optimal Trajectory Guidance

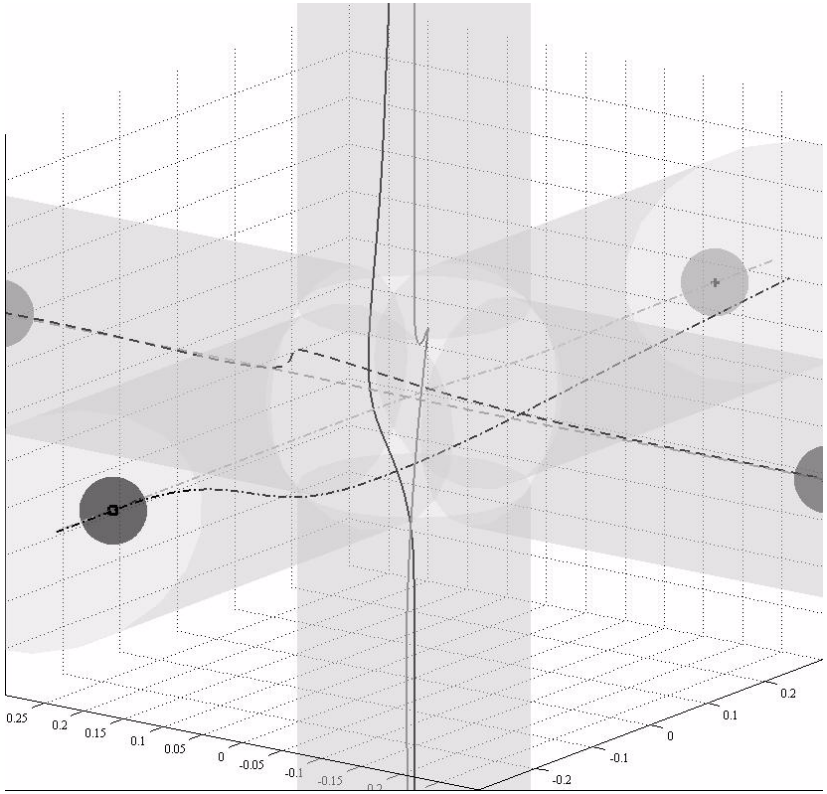
- **Translating Constraints**



Chamitoff, G., E., Saenz-Otero, A., Katz. J. G., Ulrich, S., Morell, B., and Gibbens, P. W., "Real-time Maneuver Optimization of Space-Based Robots in a Dynamic Environment: Theory and On-Orbit Experiments," *AIAA Journal of Guidance, Control and Dynamics*, under review.

Optimal Trajectory Guidance

- **Translating Constraints**

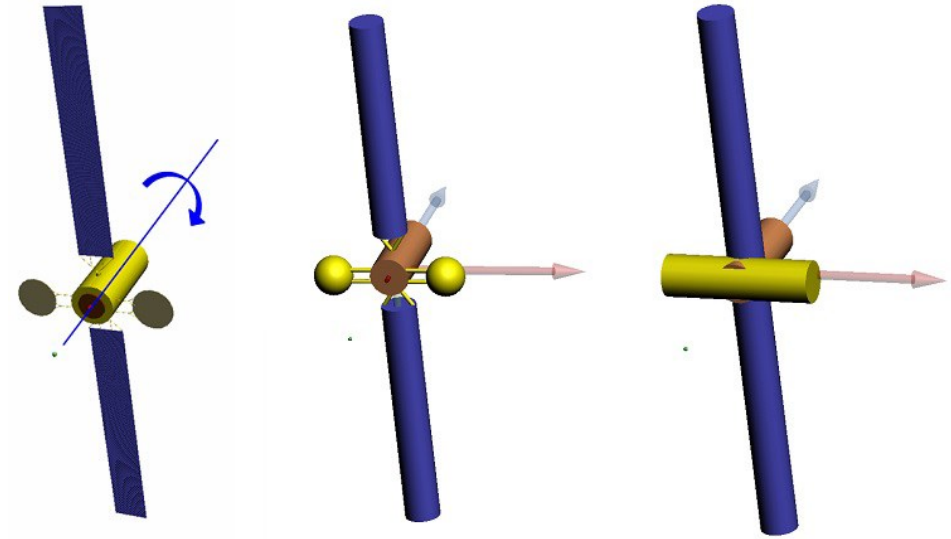


Chamitoff, G., E., Saenz-Otero, A., Katz. J. G., Ulrich, S., Morell, B., and Gibbens, P. W., "Real-time Maneuver Optimization of Space-Based Robots in a Dynamic Environment: Theory and On-Orbit Experiments," *AIAA Journal of Guidance, Control and Dynamics*, under review.

Optimal Trajectory Guidance

- **Translating and Rotating Constraints**
  - Modeling of the geometric constraint (i.e., target satellite)

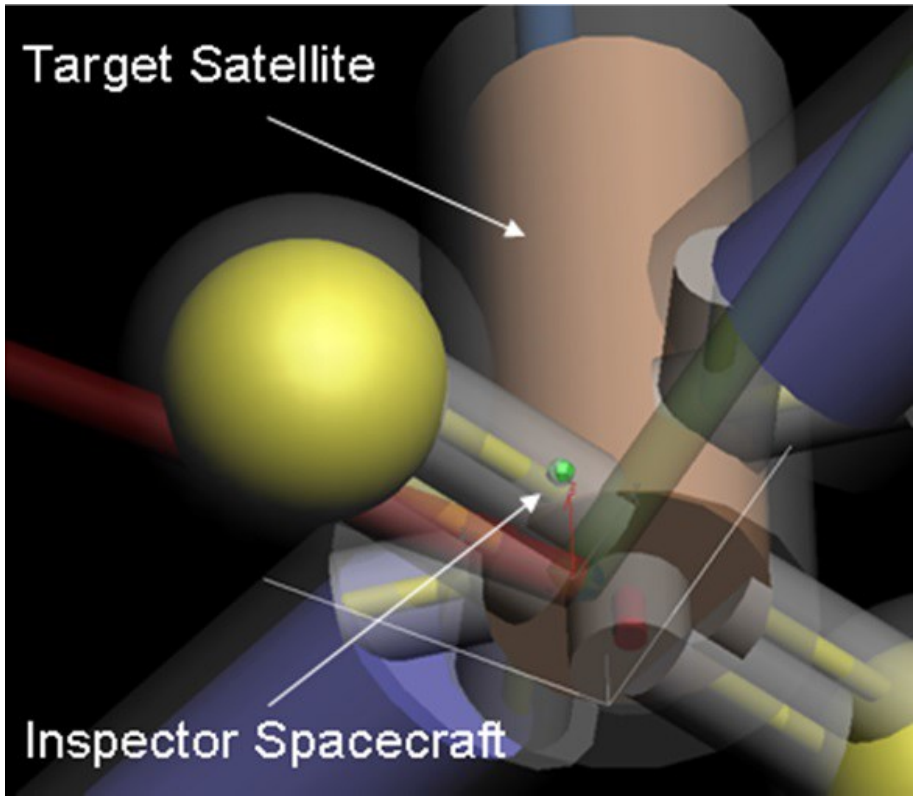
Loral FS1300



196 bodies 17 bodies 3 bodies

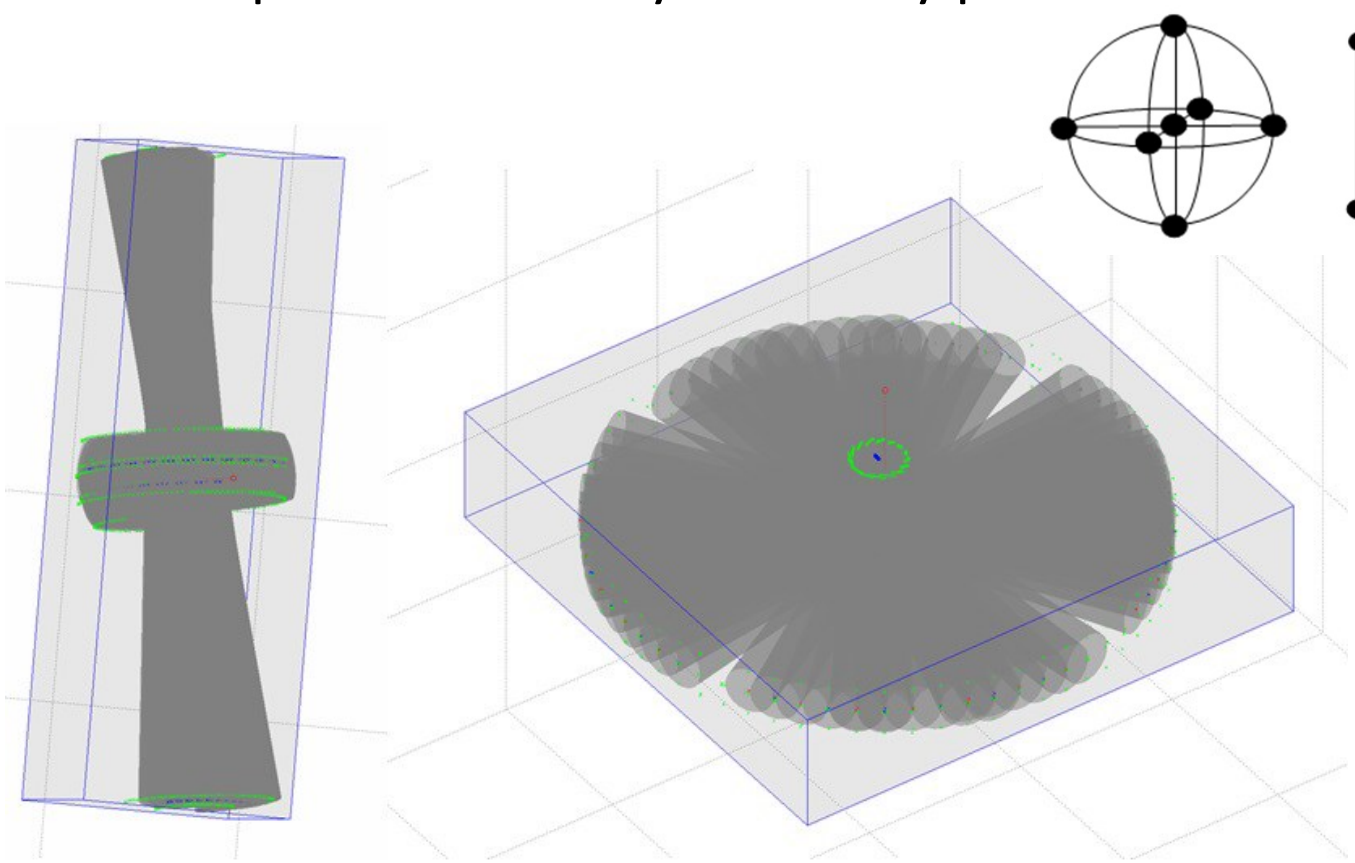
Optimal Trajectory Guidance

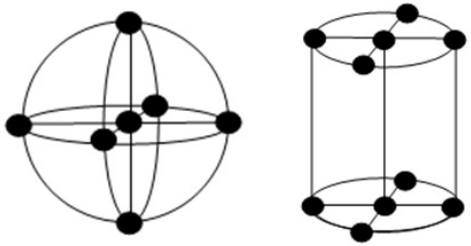
- **Translating and Rotating Constraints**
  - Safety buffer



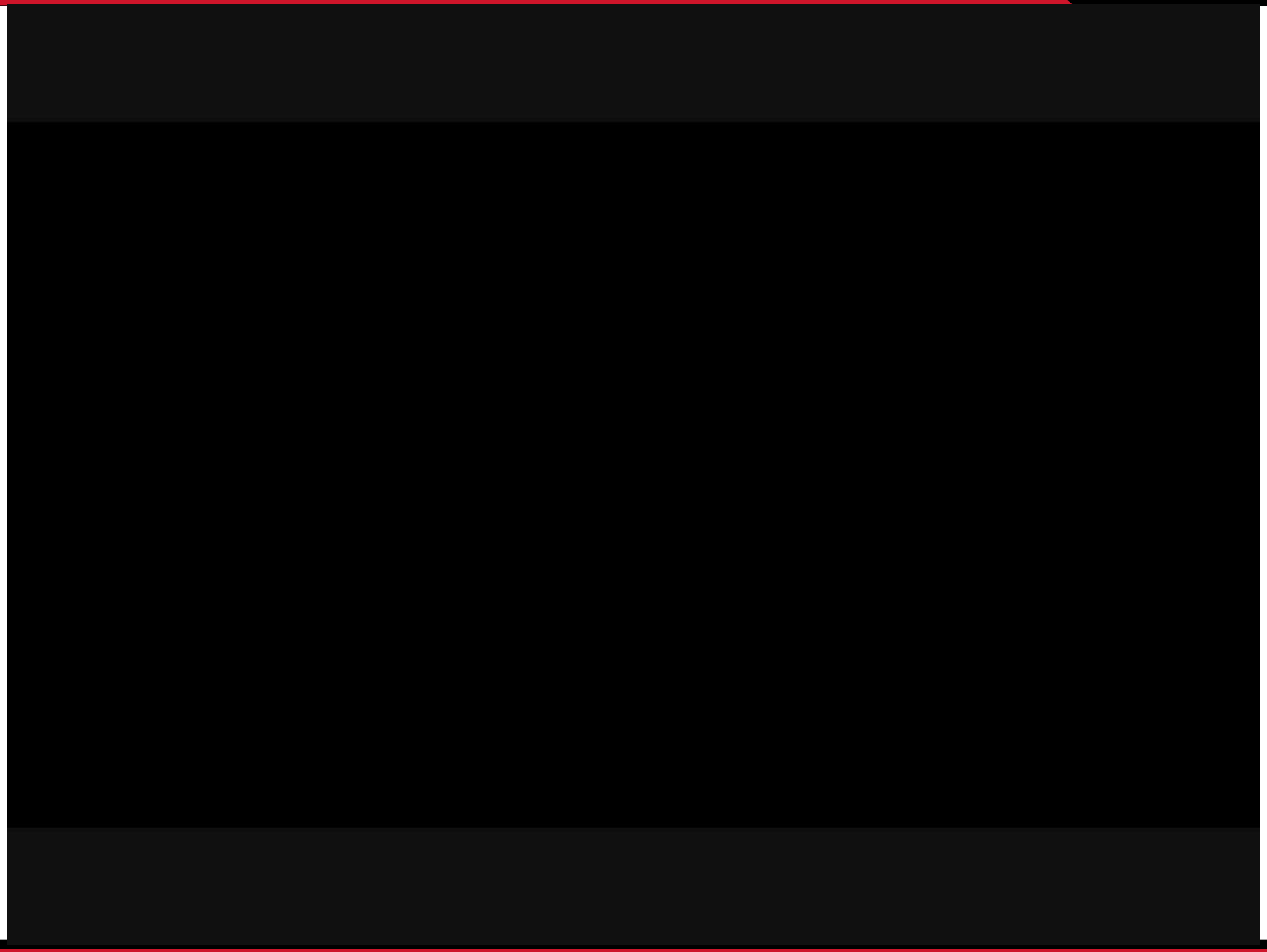
Optimal Trajectory Guidance

- **Translating and Rotating Constraints**
  - Motion envelope traced out by boundary points





Optimal Trajectory Guidance



Optimal Trajectory Guidance

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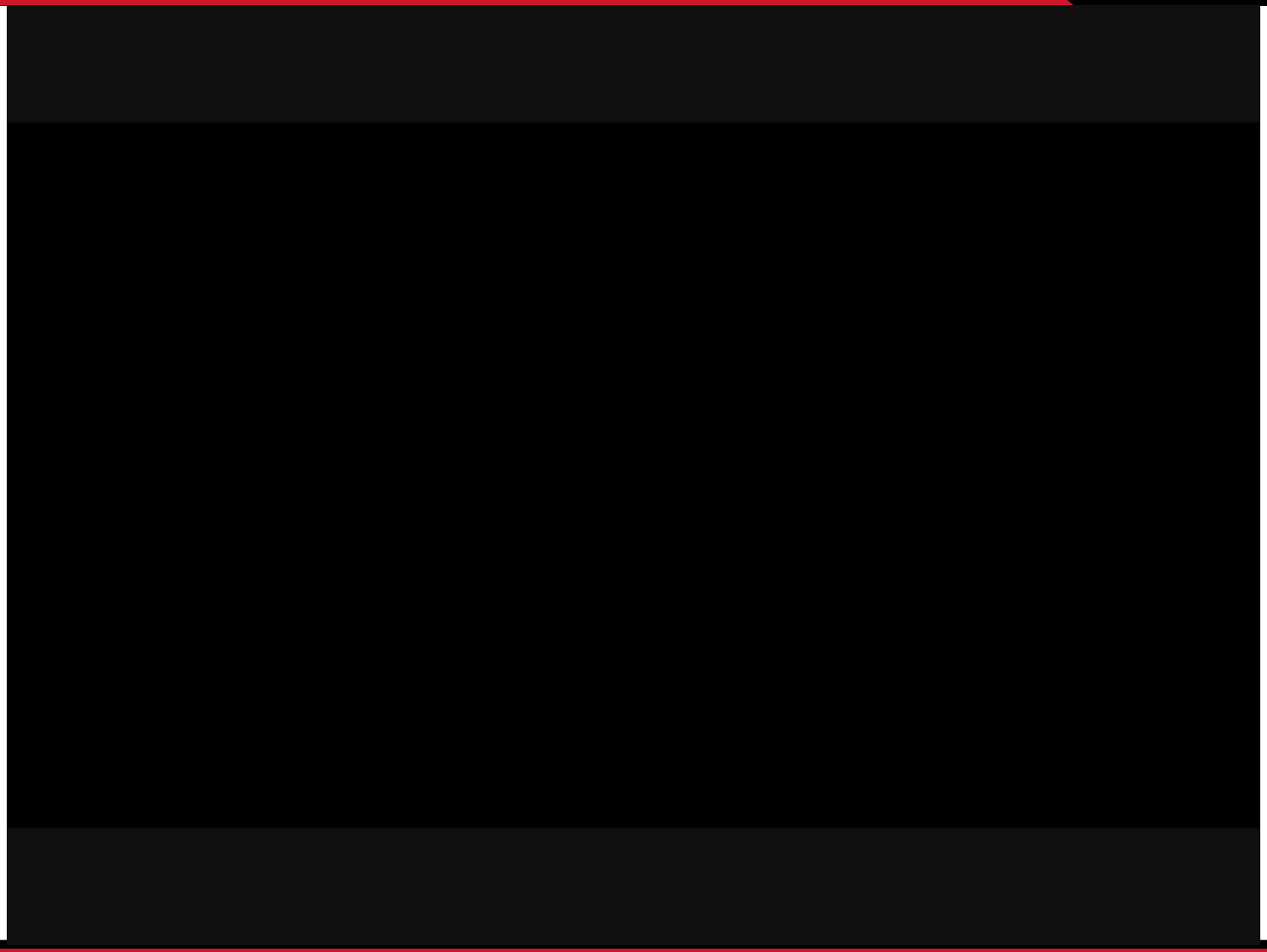
carleton.ca/spacecraft



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Conclusions

- **Summary**
  - Recent and on-going research projects related to uncooperative proximity operations GN&C were overviewed.
  - A real-time trajectory guidance law to solve the proximity operation problem in the vicinity of an uncooperative, complex, spinning, spacecraft was proposed.
  - The performance was evaluated in a numerical simulation environment for both a slow tumbling and a fast spinning target.