Autonomous collision avoidance algorithms as enablers for space congestion management

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2nd Space Capacity Allocation for the Sustainability of Space Activities Workshop

Politecnico di Milano, DAER, Milan (Italy)

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The unstoppable trend of space congestion

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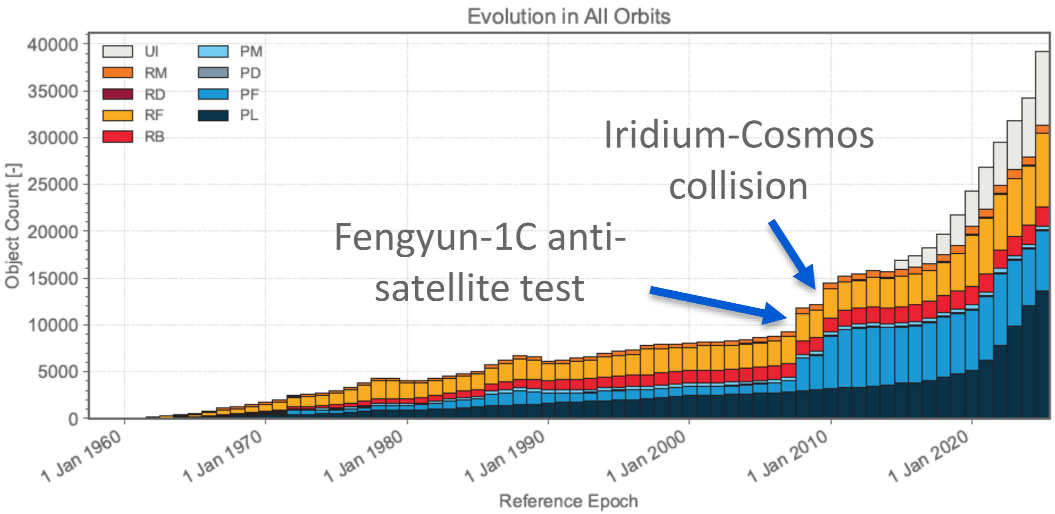
Even adopting **increasingly more strict debris mitigation policies**, the **congestion of commercially relevant orbital regions such as LEO is expected to grow**:



Collisions and other fragmentation events
(source: *ESA Space Debris Office, "ESA's Annual Space Environment Report," 2025*)

Increasing commercial use
(Image: batch of Starlink satellites after launch)

Automation in collision avoidance activities

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Collision avoidance (COLA) activities are both **impacted by** and a **way to deal with this congestion**.

- More close approaches to process
- More collision avoidance manouevres (CAMs) executed

- Reduced collision risk via effective COLA reduces mission impact in space capacity indices like THEMIS

To mitigate the cost in terms of workload and mission downtime, there is a growing interest in **introducing autonomy in COLA operations**.

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Desired features of an autonomous COLA algorithm

What researchers may think about first:

- Optimality of the CAM.
- Closed-form analytical solutions.
- Approximate solution for simplified perturbation models.
- Low runtime in my laptop with MATLAB/Python.

What really matters most:

- Robustness of the algorithm.
- Low algorithmic complexity.
- Capability to include operational constraints.
- Relevant perturbations & noises included.
- Reasonably optimal.

Analytical vs hybrid approaches

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Fully analytical approaches:

- ✓ Can lead to closed-form solutions.
- ✓ Mathematically beautiful and with physical insight.
- ✓ Fast.
- × Difficult to include perturbations & constraints.
- × Algorithmic complexity.

Hybrid approaches:

Numerical iterations over highly-efficient analytical solutions for the core problems.

- ✓ Simple iterative algorithms.
- ✓ Easier to guarantee convergence.
- ✓ The less-strict mathematical formulation eases the introduction of constraints.

Autonomous COLA approach

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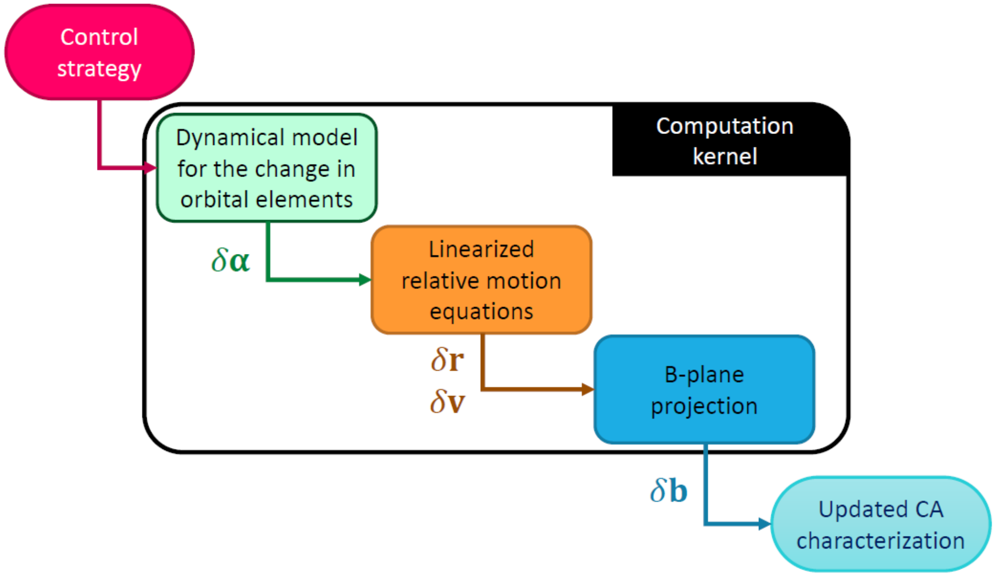
To tackle autonomous COLA, a set of **hybrid numeric-analytical CAM models** have been proposed:

- Founded on **highly efficient analytical solutions for the impulsive case.**
- Support low-thrust CAMs through domain discretization.
- Inclusion of operational constraints.



These models have already been applied to different projects, such as ACTIVA [1]

ACTIVA
Advanced Control Techniques for Increased on Board Autonomy

[1] Oliveira, T., et al., Modular and Scalable Collision Avoidance System for Enhanced Satellite Autonomy (2025), in 9th European Conference on Space Debris, Bonn, Germany, 1–4 April

Application to low-thrust

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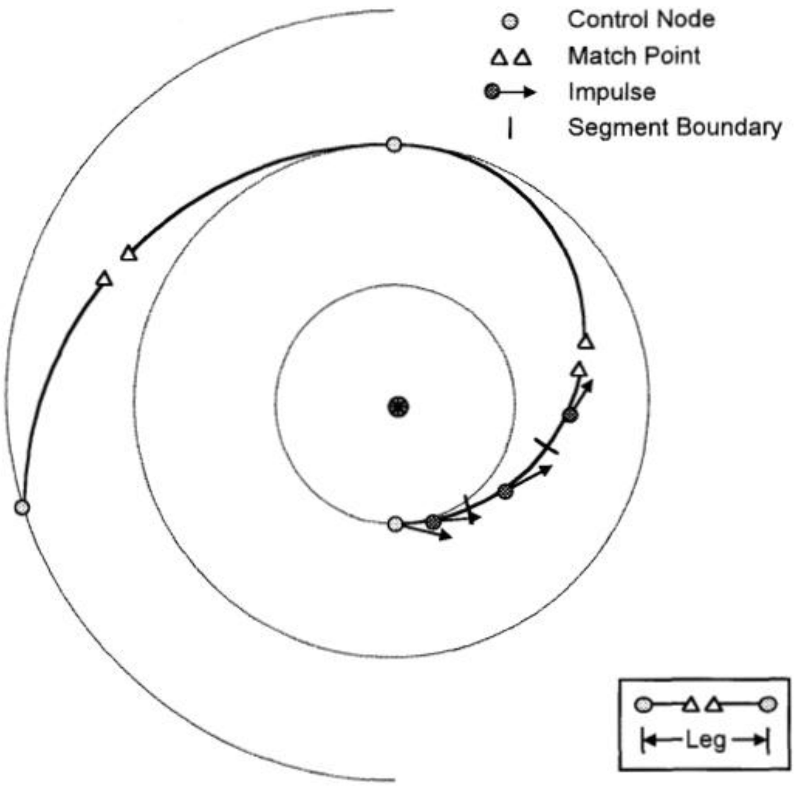
- The optimal impulsive manoeuvre algorithm can be used to optimise low-thrust CAMs exploiting the Sims-Flanagan transcription [2]
- The continuous thrusting is **discretised** into a series of sub-arcs with impulsive manoeuvres at their midpoints.
- The shorter each sub-arc, the better the approximation of the continuous manoeuvre
- The main advantage is that the impulsive manoeuvres are much **easier to optimise**
- **The nominal orbit can include orbital perturbations**, only the differential perturbations due to manoeuvre are discarded.
- **Procedure can be iterated** for increased accuracy



[3] Sims, J. A., & Flanagan, S. N. (1997). Preliminary design of low-thrust interplanetary missions.

Operational constraints

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Eclipse constraints

- Applicable only to electric propulsion low-thrust [3]

Pointing constraints

- Maintain satellite operative during manoeuvre

Thruster failure

- Keep algorithm flexible to account for possible failures

Maximum rotational speed

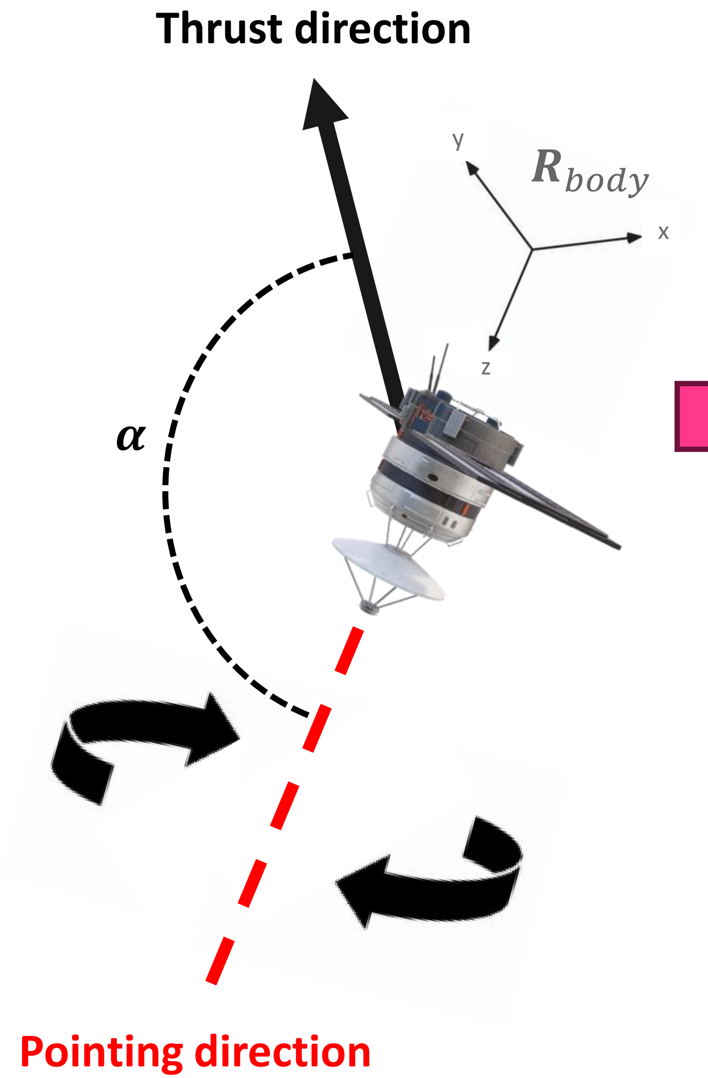
- Limit attitude control to redirect thrust direction

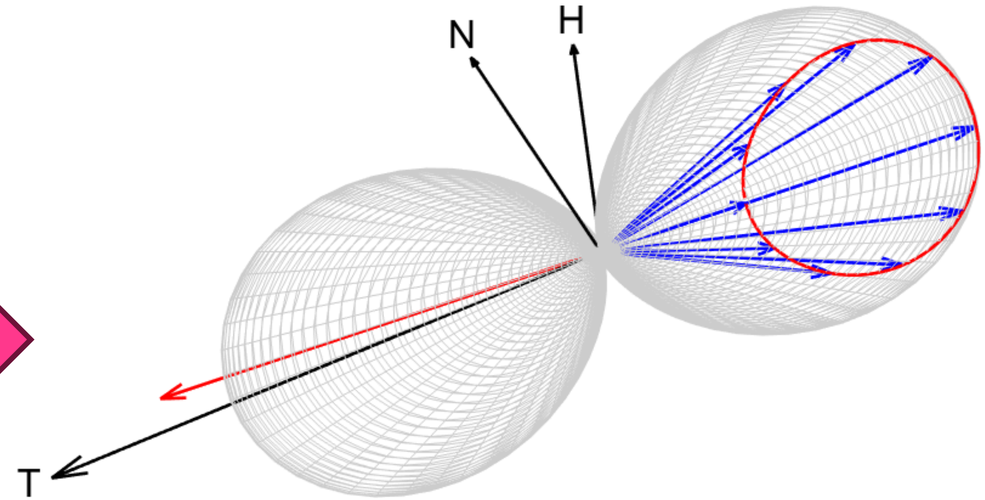
Objects catalogue

- Assess post-manoeuvre conjunctions with neighbourhood objects

[3] Polli, E. M., et al. (2025). Semi-Analytical Model for Autonomous Fuel-Optimal Low-Thrust Collision Avoidance with Eclipse Constraints. In 35th AAS/AIAA Space Flight Mechanics Meeting, 19–23 January

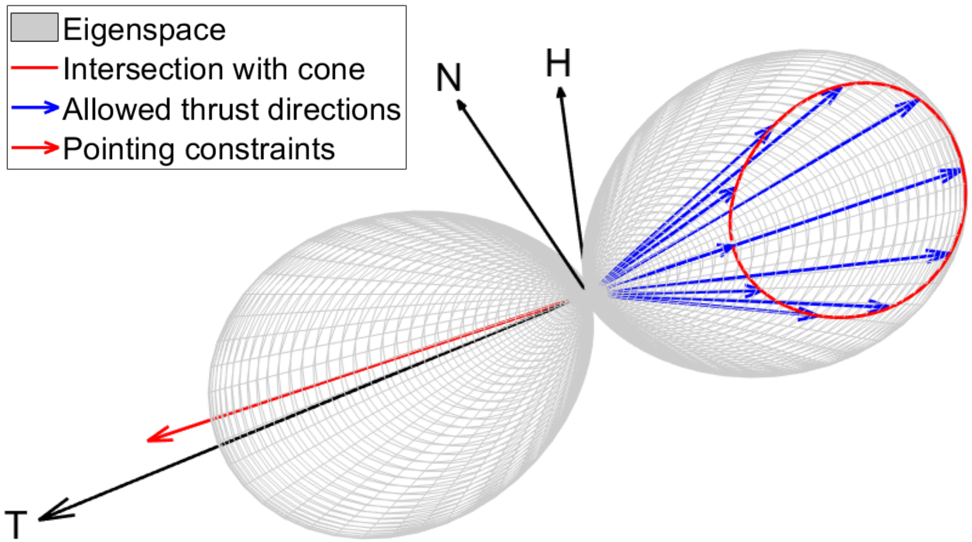
Pointing constraints



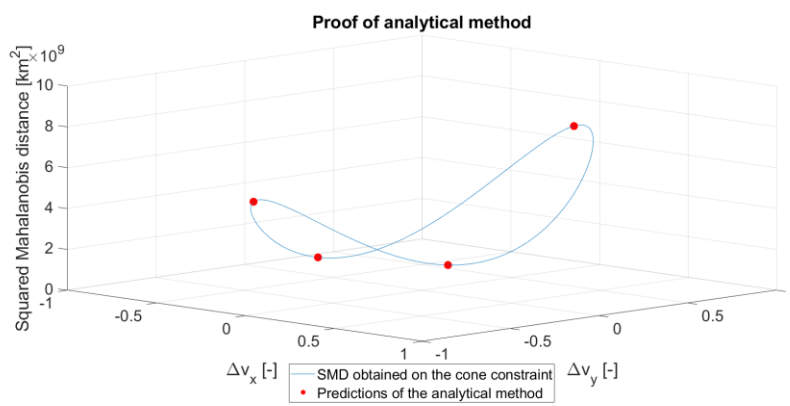


Pointing constraints

- The State Transition Matrix from the impulsive CAM solution provides:
  - Optimal $\boldsymbol{\delta v}$ direction in transversal-normal frame (through an eigenproblem)
  - Squared Mahalanobis distance



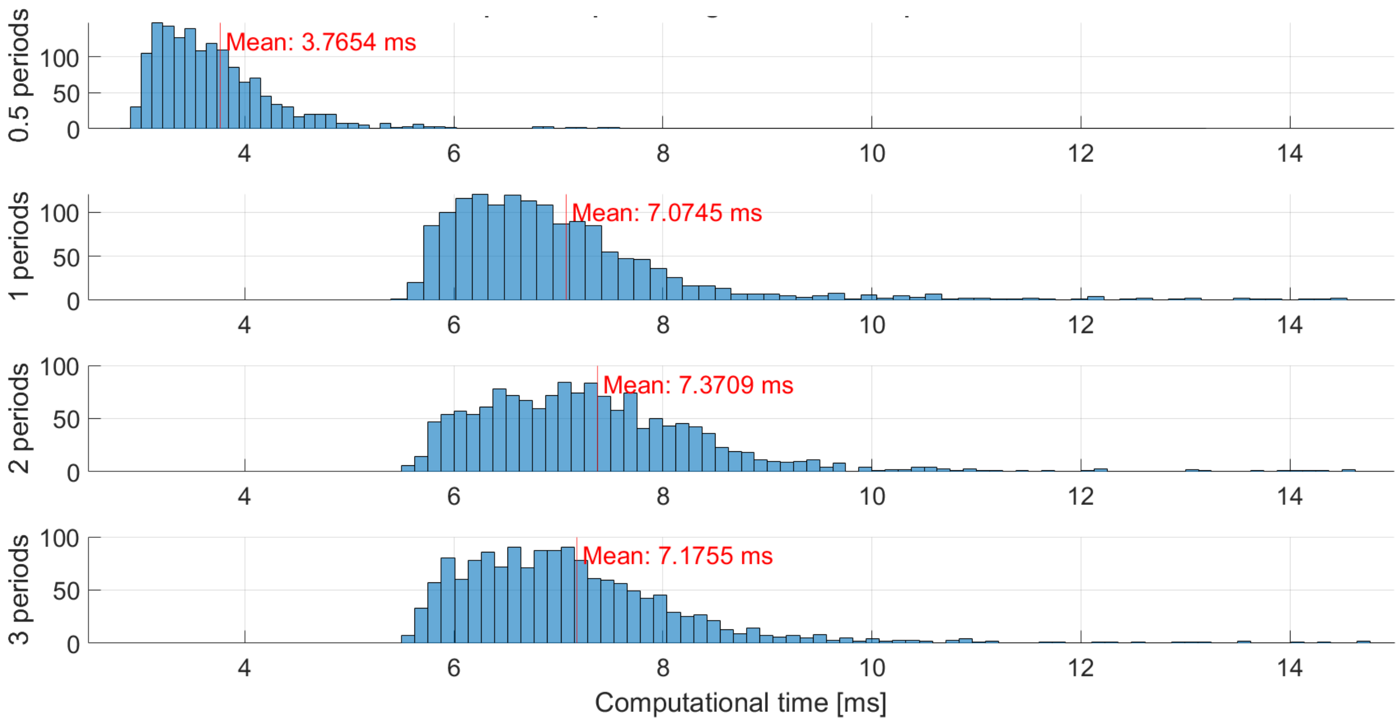
- The surface expresses the **optimality of thrusting in a specific direction**
- Closed curve as intersection between:
  - Eigenspace (from optimal CAM)
  - Thrust direction cone (from constraints)
- Find the maximum effect that lies on the closed curve
  - Reduced to the solution of a **fourth-degree polynomial**



Simulation campaigns

- Dataset of 1438 conjunctions
- Fuel optimal manoeuvre with target collision probability of 10^{-7}

Time optimal Impulsive CAM – Computational time



Simulation campaigns

- Dataset of 1438 conjunctions
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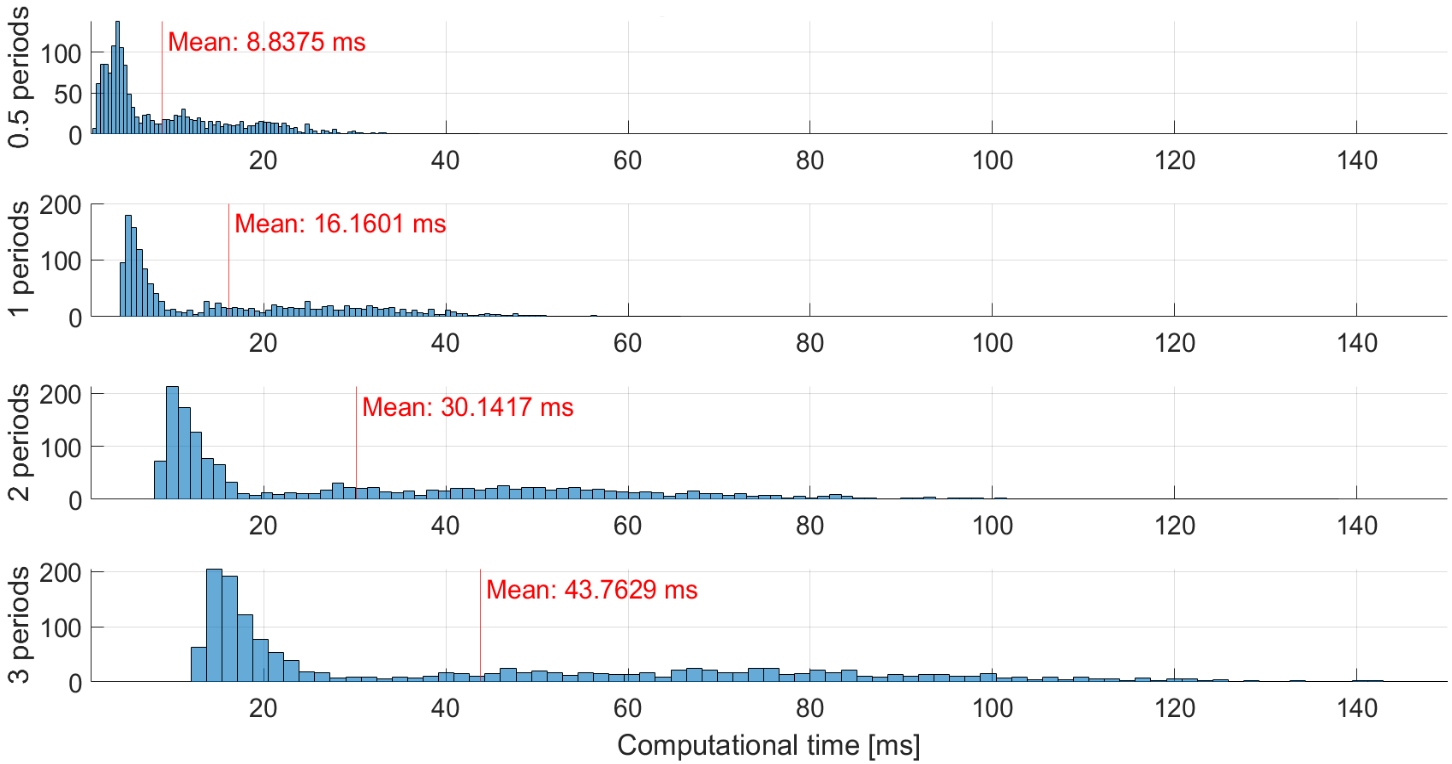
Low-thrust quasi-fuel optimal CAM – Computational time



Conclusions & Way forward

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- ✓ Autonomous collision avoidance capabilities are needed to tackle the increasing congestion in the most-demanded orbital regions.
- ✓ Effective and flexible algorithms for autonomous COLA can be constructed combining highly-efficient analytical solutions with numerical iterations.

- More types of constraints can be incorporated into the current algorithms.
- Accuracy limitations due to some underlying assumptions (e.g., time of closest approach not modified by the manoeuvres) to be addressed.

Acknowledgments

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