PhD Aerospace Engineering UC3M
Doctoral Meetings 2026

Real-time Optimal Initialization and Maintenance of Spacecraft Formation Flying

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Motivation

- **The shift to distributed systems:** Emerging missions (interferometry, in-orbit servicing, Earth observation, asteroid formation flying) demand **multi-agent formations**, rendering traditional ground-in-the-loop control unscalable and cost-prohibitive.
- **The need for autonomy:** Managing a distributed fleet under strict relative-motion constraints and dynamic perturbations drives system complexity, demanding **onboard autonomy** for safe close-proximity operations.
- **Optimizing Guidance & Control:** We focus on guidance and control optimization for formation initialization and maintenance, enabling spacecraft to compute precise, **fuel(time)-optimal, collision-free trajectories** autonomously in real-time.

Formation Flying

Initialization

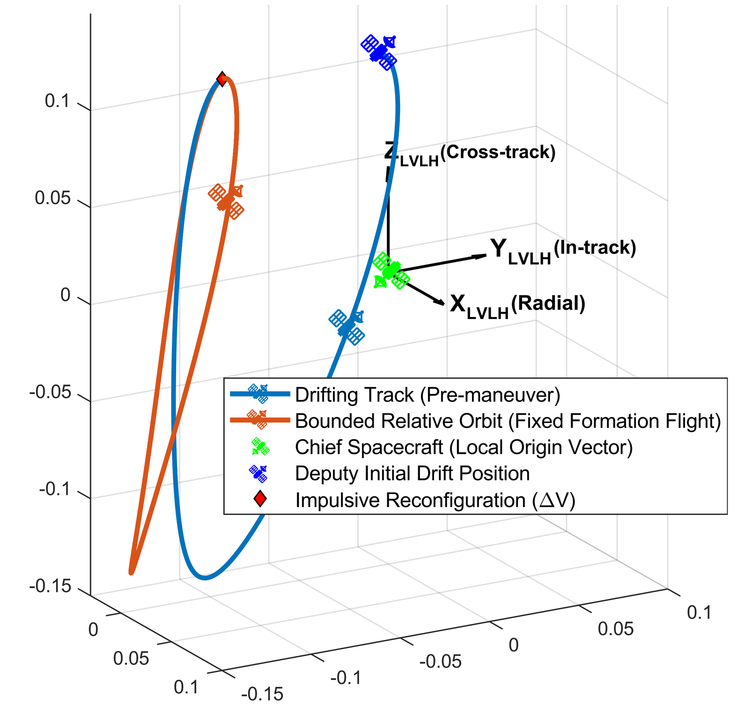
Maintenance & Reconfiguration

Launcher injection → Trajectory Optimization → Formation establishment - - - Mission Design / Optimal Formation problem - - - Formation perturbed → Station-Keeping Optimization → Recovered formation

Mission reconfiguration → Switch mode Optimization → New formation establishment

Problem Equivalence: Solved as a relative trajectory optimization, proximity rendezvous, and docking problem within the local frame.

- **Active G&C:** Optimal **multi-impulse or continuous maneuvers** for station-keeping and reconfiguration. Formation flying demands guarantees of safety and/or convergence to the desired equlibrium.
- **Distributed motion planning:** Decentralized optimization algorithms guaranteeing **constraint satisfaction** and formation requirements independently of full network state knowledge.
- **Passive safety:** Designing **passively stable relative orbits** that prevent collisions (e.g., via eccentric/inclination vector separation or deploying differential drag surfaces).
- **Optimization Constraints:** Enforcing geometric collision avoidance (keep-out zones), hardware thruster saturation, payload pointing restrictions, and proximity plume impingement.



State of the Art

Dynamics models [1]

- **Cartesian state vector:**
Linearization of exact non-linear equations into the Hill-Clohessy-Wiltshire eqs. for near-circular orbits or the Tschauner-Hempel eqs. for eccentric orbits. State Transition Matrice (STM) solutions for perturbed or eccentric orbits.
Simple, fast convergence for short-term control.
Accuracy degrades with time and large relative distances.

- **Relative Orbital Elements:**
Non-linear differences in orbital elements for advanced analytical propagation. Closed-form STM with perturbations for long-term modeling.
Valid for large separations and eccentric orbits; excellent geometric insight for formation design.
Complex Cartesian mapping for sensors, equatorial singularities and linearization errors.

- **Mean Orbital Elements:**
Filters out short-period periodic oscillations to isolate long-term secular drift and evolution, modeled through Gauss's Variational Equations. STMs solutions for perturbed and/or eccentric orbits.
Large step sizes and high stability for long-duration convergence.
Unsuitable for precise, instantaneous collision avoidance or high-frequency control.

G&C Strategies

- **Relative Orbital Elements [2]:** Framework for guidance strategies and impulsive maneuvering, as well as passive safety and collision avoidance. Less effective to manage position constraints through the optimization process.
- **Indirect methods: Calculus of variations** to convert the Optimal Control Problem into a Two-Point Boundary Value Problem (TPVBP). Necessary conditions for optimal guidance and control. Initial guess sensitivity, convergence not guaranteed.
- **Model Predictive Control:** Relies on dynamics models of the process, then repeatedly optimizes over a **receding forward-looking time horizon**. Real-time enforcement of constraints and perturbations. High computation in nonlinear cases.
- **G&C Neural Networks [3]:** Offline learning, enabling real-time onboard execution. Backward Generation of Optimal Examples to generate a huge **optimal state-G&C commands dataset**. "Black box" lacking safety and stability guarantees.
- **Convex Programming:** Reformulates non-linear trajectory optimization into convex subproblems. Fast convergence for real-time onboard execution. Linearization gaps and artificial infeasibility.
- **Dynamic Programming:** Bellman Principle of Optimality. Multi-stage subproblems to systematically compute globally optimal control policies. Complex implementation, relaxation needed for high-dimensional state spaces.
- **Control Lyapunov Functions / Control Barrier Functions:** CLF provide certifiably stable optimal guidance, while CBF enforce forward invariance of safe sets with minimal control (safety filter). Difficult to build proper functions for complex systems.

Preliminary Research

The LISA mission consists of three spacecraft flying in a massive, **Earth-leading/trailing orbit** on a **equilateral triangle formation**. The objective is to achieve a naturally stable compliant geometry for 10 years (science phase), relying solely on a drag-free attitude control system.

Formation Optimization
Optimizes the cartwheel orbital elements to achieve a stable formation that requires zero orbit control throughout the entire mission duration **[4]**.

COUPLED

Transfer Optimization
Optimizes the interplanetary trajectory from Earth direct escape launch to the target cartwheel formation minimizing propellant consumption.

Our approach for Solar Electric Propulsion (SEP) transfer optimization:

- Indirect method with real ephemeris and mission parameters.
- TPBVP Single Shooting method with MATLAB's *fsolve*.
- Dual Homotopy to ensure solver convergence **[5]**:
  - Achieve very low-thrust: $T_{\max}(\kappa) = \kappa T_{max}, \kappa \to 1$.
  - Smoothing control: energy- to fuel-optimal (bang-bang) $\epsilon \to 10^{-5}$.

$$\min_{u,\boldsymbol{i}} \quad J = \lambda_0 \frac{T_{max}(\kappa)}{I_{sp} g_0} \int_{t_0}^{t_f} \left[u + \epsilon \, ln\big(u(1-u)\big)\right] dt$$

s.t.

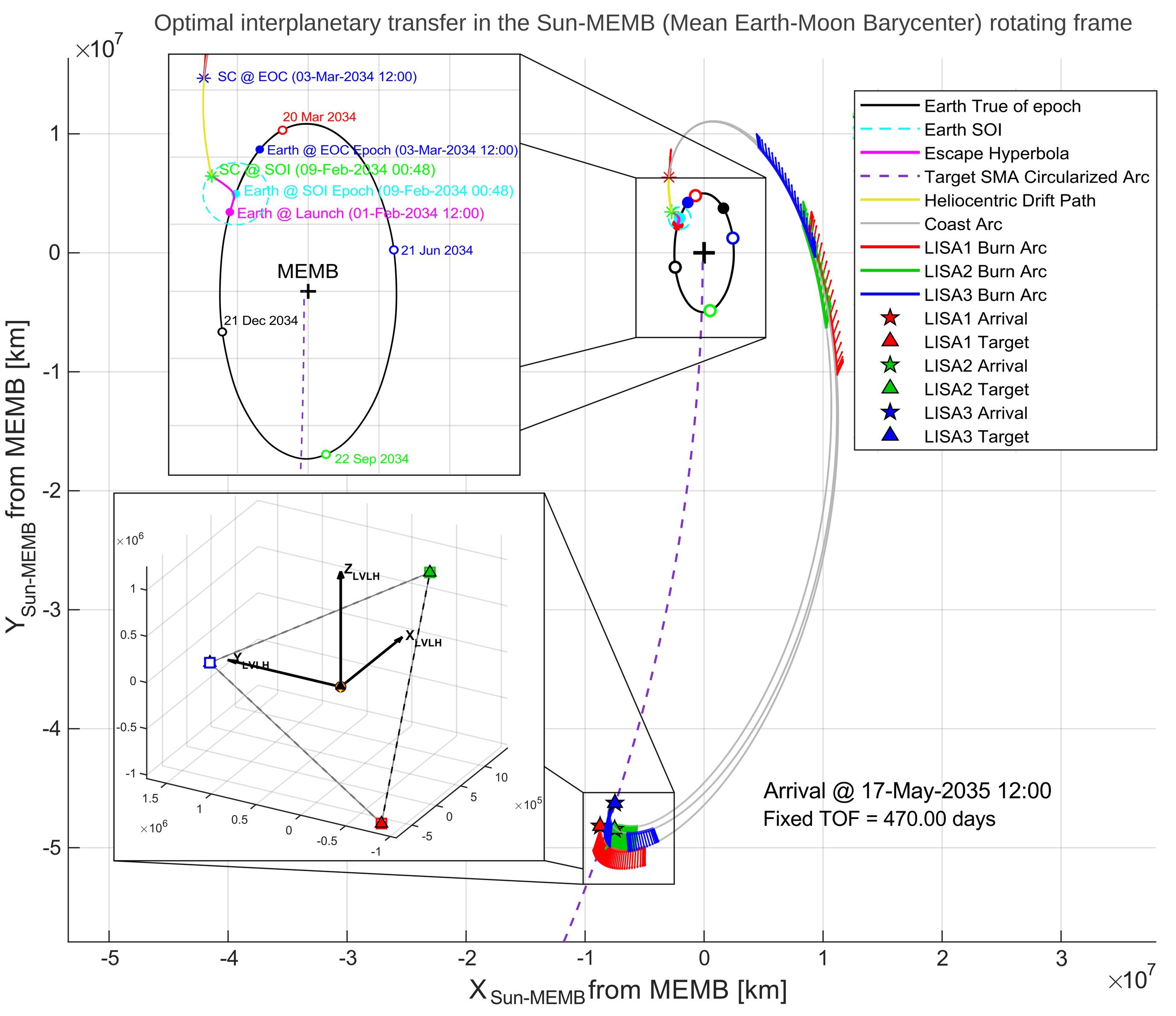
$$\dot{\boldsymbol{r}} = \boldsymbol{v}, \qquad \boldsymbol{r}(0) = \boldsymbol{r_0}, \quad \boldsymbol{r}(t_f) = \boldsymbol{r_f}$$

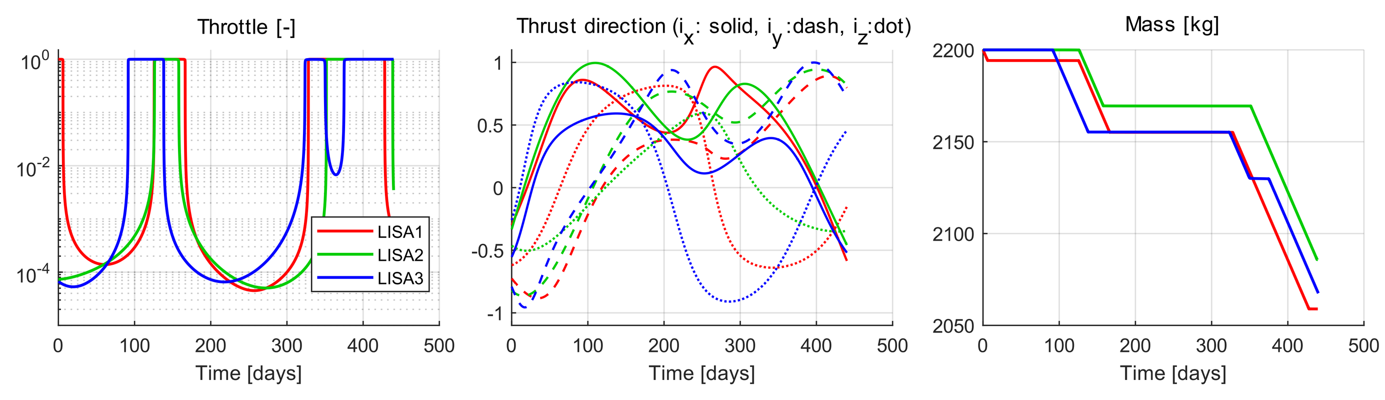
$$\dot{\boldsymbol{v}} = -\frac{\mu}{r^3}\boldsymbol{r} + \frac{T_{max}}{m} u\boldsymbol{i}, \qquad \boldsymbol{v}(0) = \boldsymbol{v_0}, \quad \boldsymbol{v}(t_f) = \boldsymbol{v_f}$$

$$\dot{m} = -\frac{T_{max}}{I_{sp} g_0} u, \qquad m(0) = m_0, \quad u \in [0,1], \ \|\boldsymbol{i}\| = 1$$

Assumptions for SEP transfer

Wet mass	2200 kg
Maximum thrust	81 mN
Specific impulse	1660 s
Transfer duration	470 days
Commissioning time	30 days
v_∞ (Ariane 64)	300 m/s





[1] Sullivan, Joshua, Sebastian Grimberg, and Simone D'Amico. "Comprehensive Survey and Assessment of Spacecraft Relative Motion Dynamics Models." *JGCD* 40, no. 8 (2017): 1837–59.
[2] D'Amico, Simone. *Autonomous Formation Flying in Low Earth Orbit*. Ridderprint, 2010.
[3] Izzo, Dario, and Sebastien Origer. "Neural Representation of a Time Optimal, Constant Acceleration Rendezvous." *Acta Astronautica* 204 (March 2023): 510–17.
[4] Martens, Waldemar, and Eric Joffre. "Trajectory Design for the ESA LISA Mission." *The Journal of the Astronautical Sciences* 68, no. 2 (2021): 402–43.
[5] Taheri, Ehsan, and John L. Junkins. "Generic Smoothing for Optimal Bang-Off-Bang Spacecraft Maneuvers." *JGCD,* 41, no. 11 (2018): 2470–75.

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This research is supported by the grants for research activity of young PhD holders, part of the Universidad Carlos III de Madrid (UC3M) Own Research Program (Ayudas para la Actividad Investigadora de los Jóvenes Doctores, del Programa Propio de Investigación de la UC3M)

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