uc3m Universidad Carlos III de Madrid
Department of Aerospace Engineering

PhD Aerospace Engineering UC3M
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GUIDANCE, NAVIGATION, AND CONTROL OF SPINNING ELECTRODYNAMIC TETHERS APPLIED TO ON-ORBIT SERVICES

PhD Student: Livia Marciano
Supervisor: Gonzalo Sánchez Arriaga

Motivation

Why On-Orbit Servicing?

- In-orbit servicing, including life extension, refueling, active debris removal, and space tugs, is a growing market.
- IoS vehicles need efficient propulsion technologies to change their orbits, approach customers, relocate them, and perform other maneuvers.
- If propellant-based technologies are used, the number of services each vehicle can perform is limited.

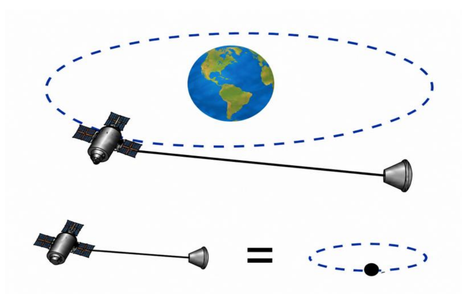
Why Spinning Electrodynamic Tethers (EDTs)?

- EDTs provide propellantless propulsion by using the Lorentz force.
- Spinning EDTs, unlike vertical EDTs, offer good dynamic stability and excellent performance regardless of orbital inclination.

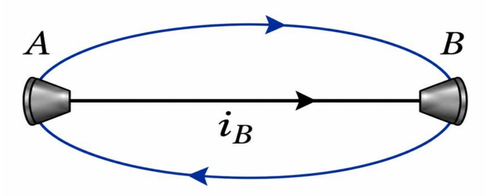
What is the GNC gap?

- The control force depends on environmental variables, tether attitude and electric current, which is the control variable.
- Orbital motion, spinning-tether dynamics and control law for the electric current are strongly coupled.
- Optimal control for spinning EDTs has been studied [1-3], but there are still gaps.

Model



Dynamic



The spacecraft-EDT (whose length is L_t) system is modeled as a single point of mass (M). Its dynamic is propagated by using the Lagrange planetary equations

$$\frac{da}{dt} = \frac{2}{\sqrt{\mu/a^3}\sqrt{1-e^2}}\left(e\, f_x^O \sin\nu + \frac{a(1-e^2)}{r}\, f_y^O\right)$$

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{\sqrt{\mu/a^3}\,\mathrm{a}}\left[f_x^O \sin\nu + f_y^O\left(\cos\nu + \frac{e + \cos\nu}{1 + \mathrm{e}\cos\nu}\right)\right]$$

$$\frac{di}{dt} = \frac{r\, f_z^O \cos l}{\sqrt{\mu/a^3}\, a^2\sqrt{1-e^2}}$$

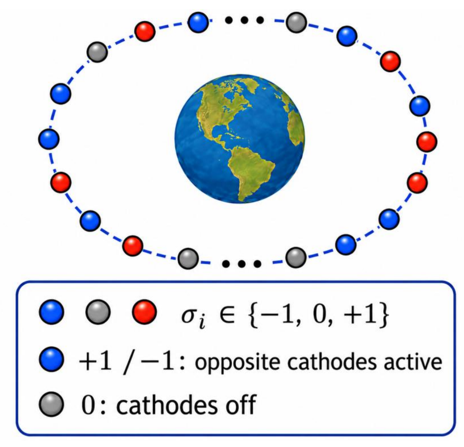
where a, e, i, ν are the semi major axis, eccentricity, inclination, and true anomaly, respectively, μ is the Earth gravitational parameter, r is the norm of the position vector, $\boldsymbol{f}$ is the acceleration produced by the Lorentz force perturbation generated by the interaction between the geomagnetic field $\boldsymbol{B}$ and the average current I_{av} along the tether: $\boldsymbol{F}_L \approx L_t I_{av}(\boldsymbol{i}_t \times \boldsymbol{B})$, with $\boldsymbol{i}_t = \pm\boldsymbol{i}_B$.

In this work, the tether spins at a rate much higher than the orbital angular velocity. As a result, the spin plane can be considered fixed, with its normal vector forming an angle β with the Earth's rotation axis. The vector $\boldsymbol{i}_t = \pm\cos\varphi\, \boldsymbol{i}_\mathbf{I} + \sin\varphi\left(\cos\beta\, \boldsymbol{j}_\mathbf{I} + \sin\beta\, \boldsymbol{k}_\mathbf{I}\right)$, where $\varphi = \varphi_0 + \mathrm{k}\,\nu$ the spin angle, φ_0 is the initial spin angle and the integer k is the number of tether revolutions per orbit.

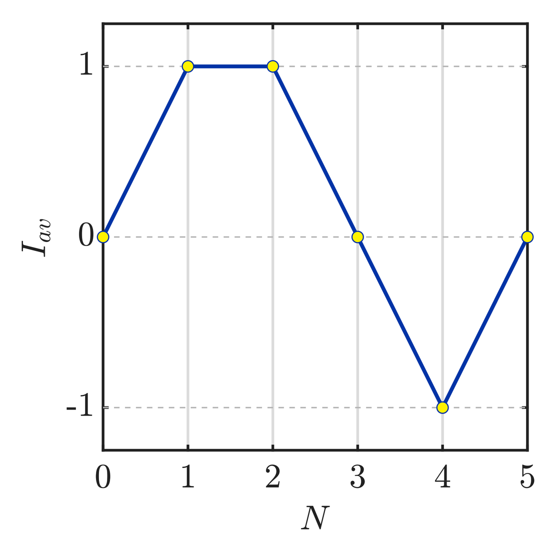
The tether is assumed straight, with cathodes located at the two tips A and B, which can be toggled independently. Cathode activation, combined with power supplies, can be used to control current level and direction $I_{av} = I_{av,0}\,\sigma(\nu)$.

Methodology

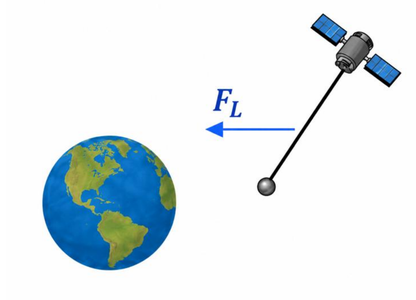
Discrete cathode control



Discretize the orbit into i=1,...,N control nodes and define a discrete control sequence giving the control parameter I_{av}



Secular dynamics



The orbital dynamics are averaged over one revolution to compute the secular variation of the dimensionless state vector $\tilde{\mathbf{y}}(\tau)$. The Lorentz-force contribution is written as:

$$\delta\tilde{\mathbf{y}}_L \equiv \overline{\boldsymbol{W}}\boldsymbol{\sigma}^T$$

$\overline{\boldsymbol{W}}$ describes how the Lorentz force changes the orbital elements along the orbit and $\boldsymbol{\sigma}$ is the control vector.

Control law

Optimal control law

The law is used to maximize or minimize one selected orbital element j:

$$max\left(\delta\tilde{y}_j\right) \Rightarrow \sigma_i = sgn\left(W_{\mathrm{j,i}}\right)$$

$$min\left(\delta\tilde{y}_j\right) \Rightarrow \sigma_i = -\,sgn\left(W_{\mathrm{j,i}}\right)$$

Optimization algorithm

The objective function is defined as:

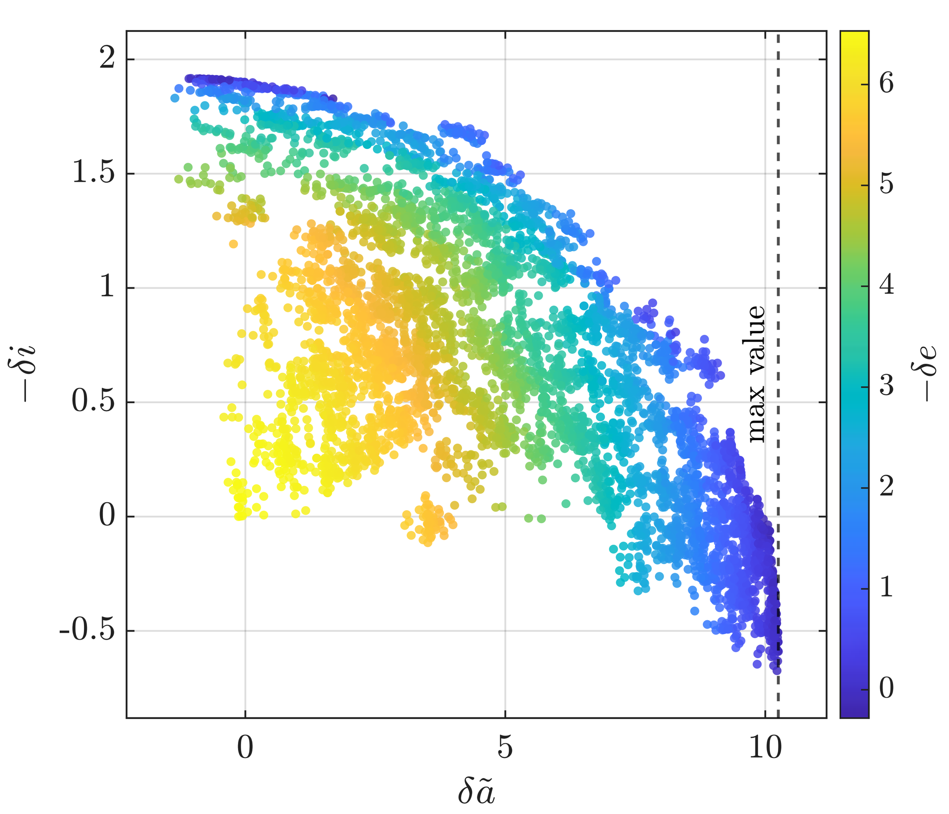
$$\mathbf{F} = [s_1\delta\tilde{a},\ s_2\delta e,\ s_3\delta i]$$

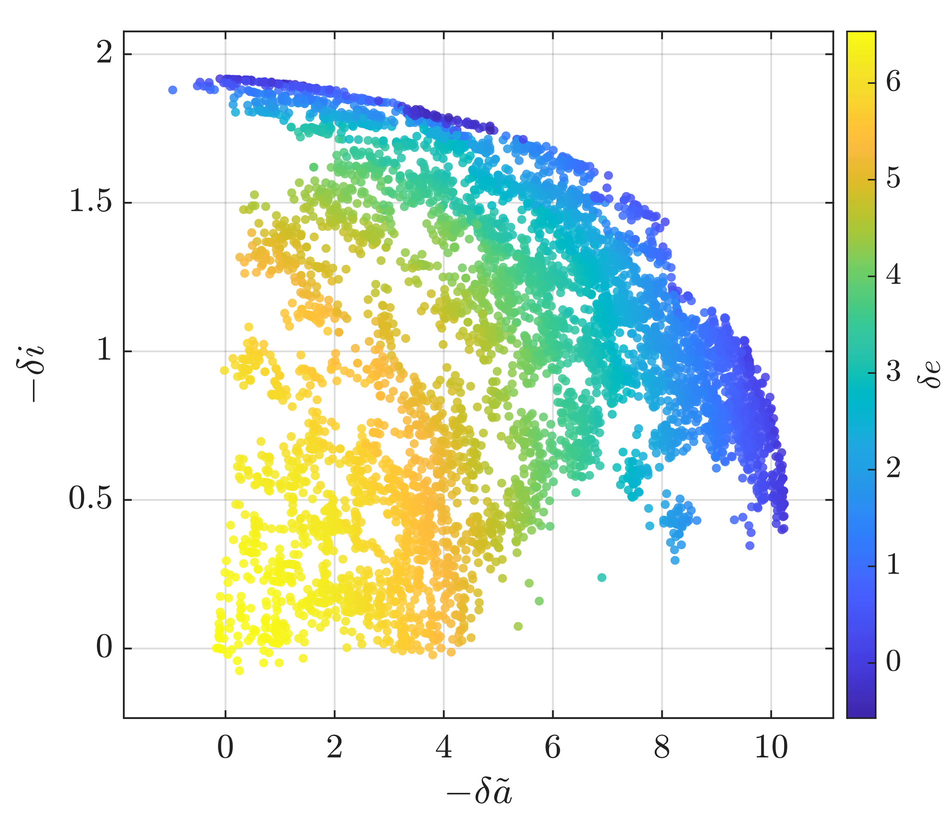
where $s_j = \pm 1$ selects whether each orbital element is maximized or minimized

NSGA-II + local search to identify Pareto-optimal trade-offs

Results

The results show a dense distribution of Pareto-optimal points, indicating that the control law can generate many feasible orbital responses. This highlights the flexibility of spinning EDT control, but also the strong coupling and trade-offs among $\delta\tilde{a}$, δe, and δi.





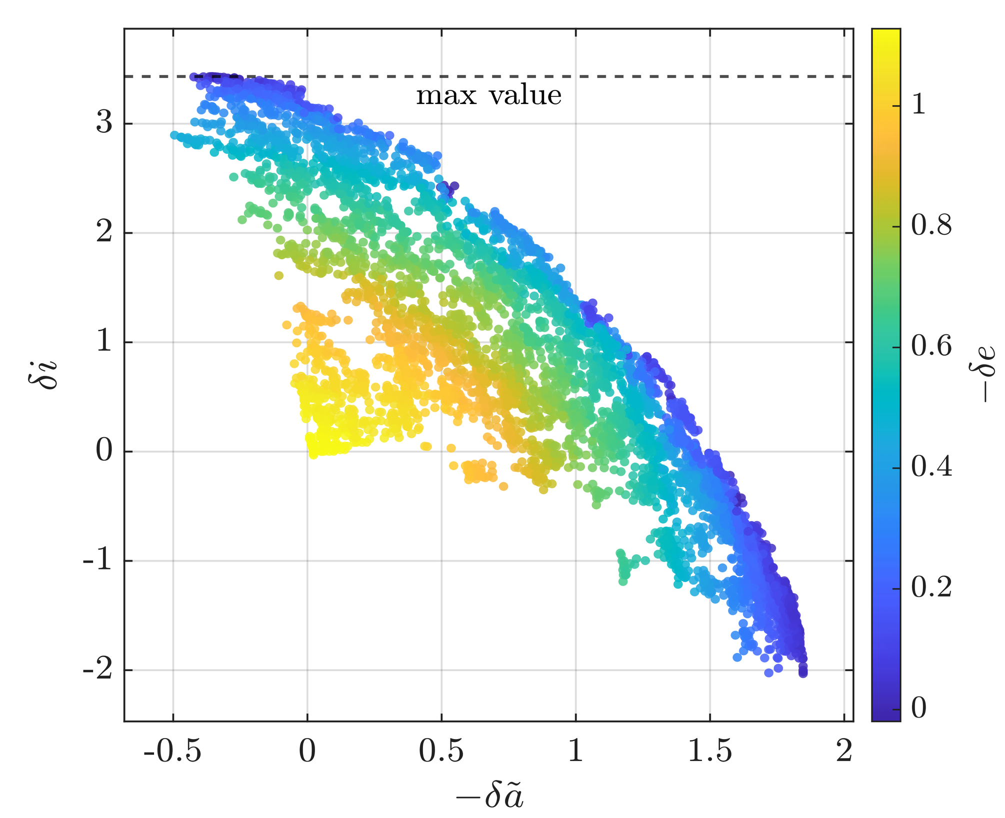


Figure 1. Pareto sets obtained with NSGA-II for different spin-plane selections: the first case maximizes $\delta\tilde{a}$, the second maximizes δe, and the third maximizes δi, while minimizing the variations of the remaining orbital elements. The case of study is: $L_t = 5$ km, $M = 1000$ kg, initial altitude 800 km, $i_0 = 98$º.

Future work

Closed-loop GNC → Uncertainty estimation → High-fidelity validation → Monte Carlo campaigns → Experimental testing

References

[1] S.G. Tragesser, and H. San, H., Orbital Maneuvering with Electrodynamic Tethers," Journal of Guidance, Control, and Dynamics, 26 (5), 805–810, 2003.
[2] P. Williams, Optimal Orbital Transfer with Electrodynamic Tether, Journal of Guidance, Control and Dynamics, 28 (2), 2005.
[3] Y. Wang, A. Li, H. Lu, Y. M. Zabolotnov, and C. Wang, Current Analysis and Optimal Control of a Spinning Bare Electrodynamic Tether System During its Spin-up Process, Guidance, Navigation and Control, 1-15, 2025.

PERSEI Space
Aero space
Space Tethers Group (STG)
PhD Student: lmarcian@pa.uc3m.es
Supervisor: gonzalo.sanchez@uc3m.es

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