Nonlinear Model Predictive Control Guidance for Collision Avoidance in Constellations

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Abstract

The rapid proliferation of mega-constellations in Low Earth Orbit (LEO) has significantly increased the frequency of conjunction events, necessitating robust collision-avoidance strategies. This study develops a Nonlinear Model Predictive Control (NMPC) guidance system to optimise low-thrust collision-avoidance manoeuvres. Analysing the operational differences between a standard orbit return, and a constellation slot return, as well as the ground-service impacts of these manoeuvres. The NMPC system facilitates on-board autonomy by compensating in real-time for unmodeled environmental perturbations.

Case Study

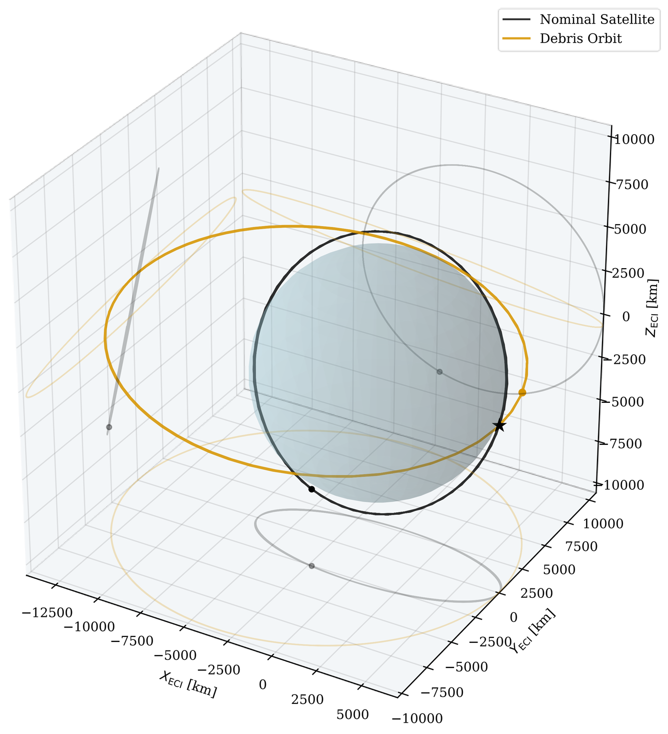
Satellite:

- Orbit: 600 km altitude | 67° inclination
- Hall-effect Thruster: I_{sp}: 2000 s | T_{max}: 0.1 N
- Wet Mass: 200 kg

Debris - derived with MASTER [3] :

- Type: non-manoeuvrable space debris
- Diameter: 0.20 m | 5 km keep-out-zone
- Mass: 14 kg
- Relative Velocity: 14 km/s

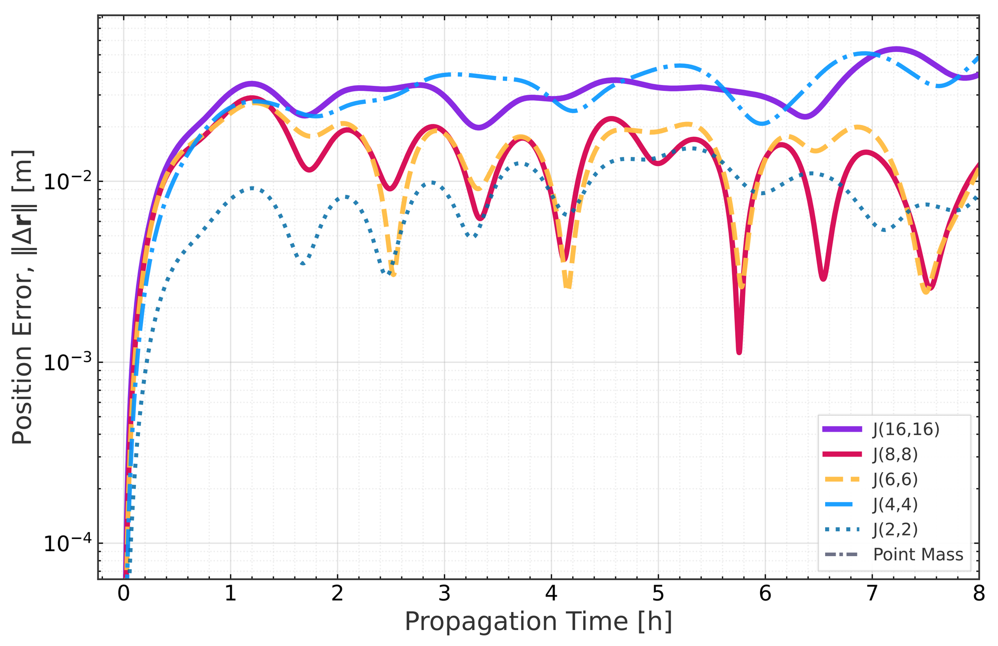
[3]



Conjunction Case study.

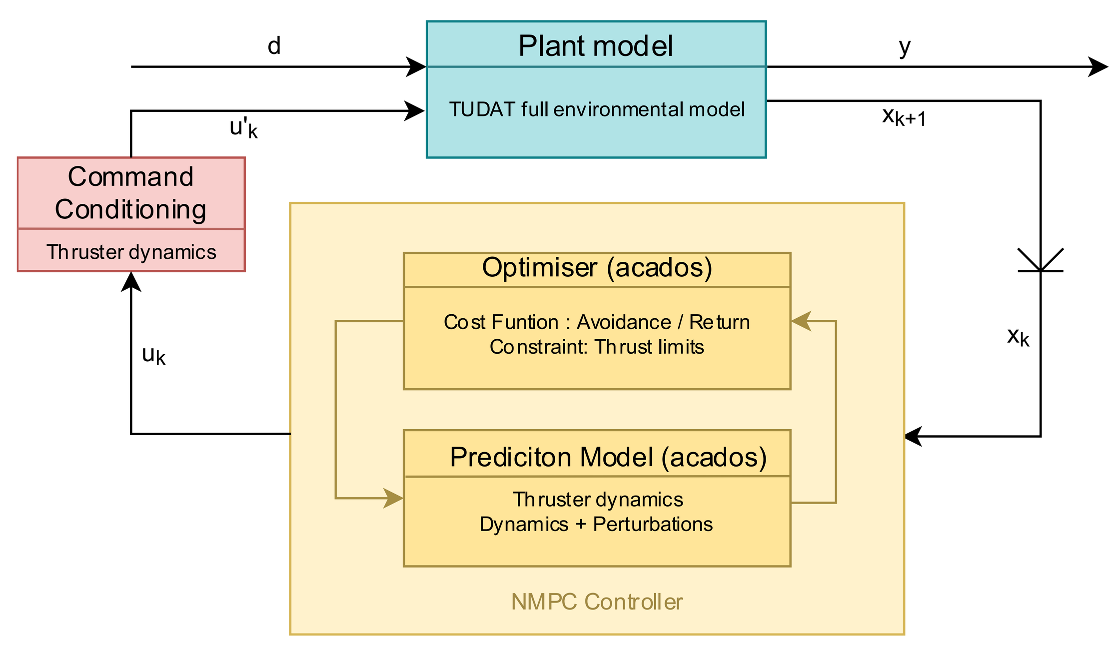
Methodology

The guidance architecture operates within a closed-loop framework, implemented in acados, a python NMPC library, combined with Tudat which serves as the high-fidelity physical plant model for orbit propagation [2,3]. By implementing a simplified prediction model in acados, the guidance system can rapidly generate cost optimal decisions. Additionally, constraining the predictive model's control authority entirely to the along-track direction enhances solver convergence reliability while maintaining solution optimality. The following figures show the closed loop guidance system and the verification of the implemented models.



Prediction model error between Tudat and acados equivalent model.

Given that the internal acados predictive model and the Tudat simulation environment utilise different underlying numerical methods, it is important to isolate and quantify these discrepancies. The resulting discrepancies are low (~10^{-1} in a 12h propagation) but could become significant for longer propagations.



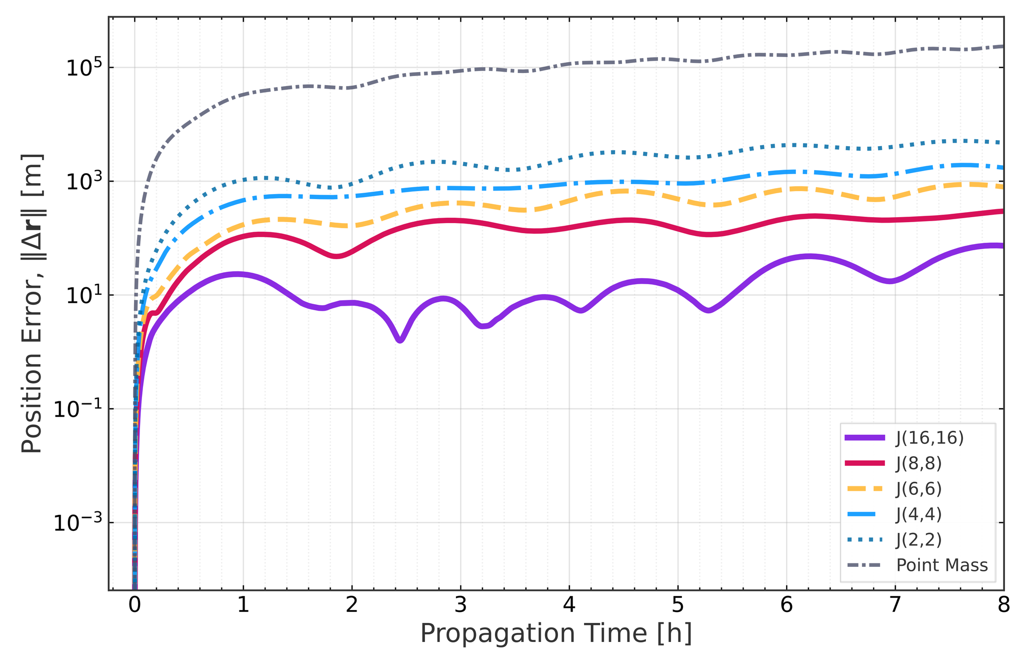
NMPC Guidance System.

Phase I : Avoidance

- Ellipsoid: violation + over-separation
- Fuel minimisation
- ADCS regularisation

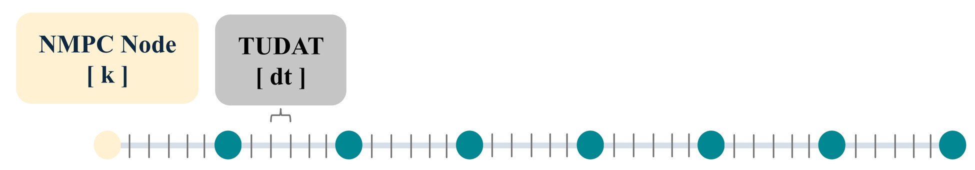
Phase II : Return

- Final Position tracking
- Final Velocity tracking
- Fuel minimisation
- ADCS regularisation



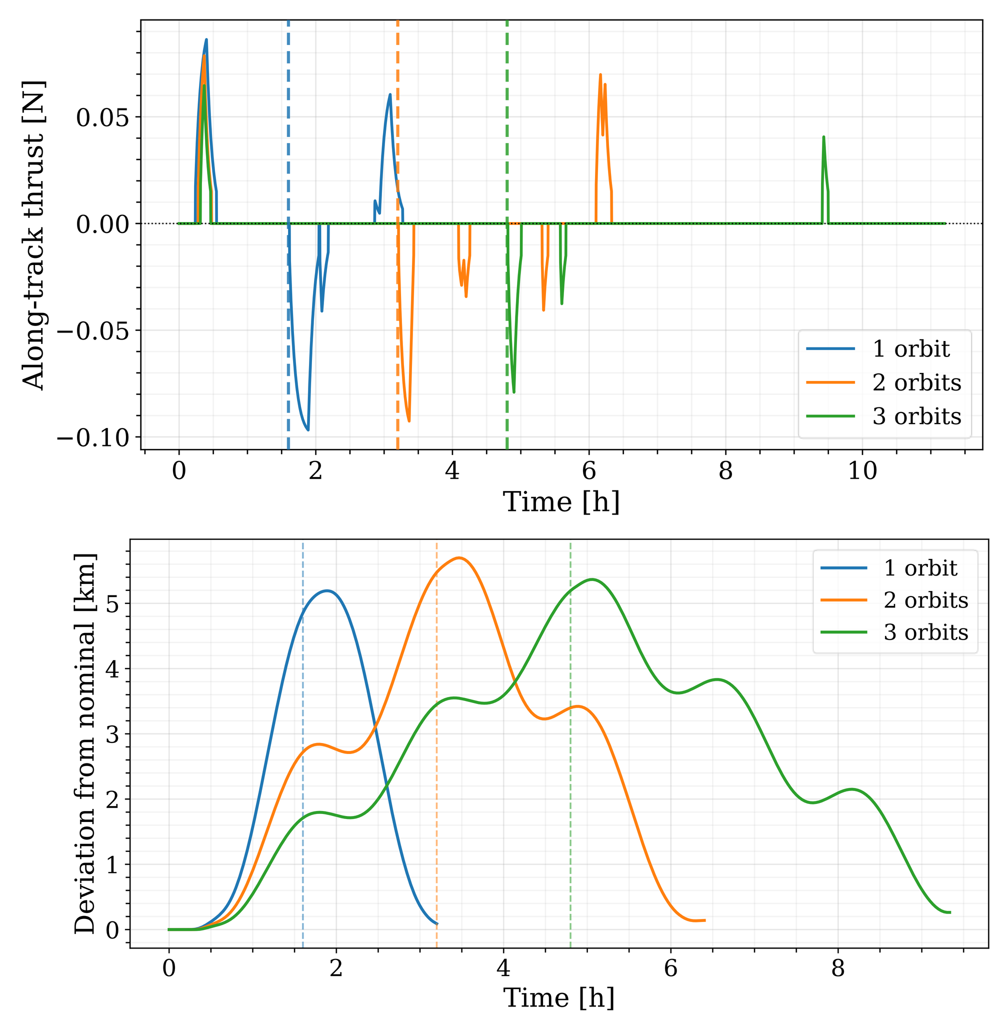
Prediction model simplification error.

The prediction model incorporates spherical harmonic perturbations up to degree and order $J_{8,8}$. This is a compromise between accuracy and convergence, yielding an expected prediction error of up to ~10^2 m on satellite position.



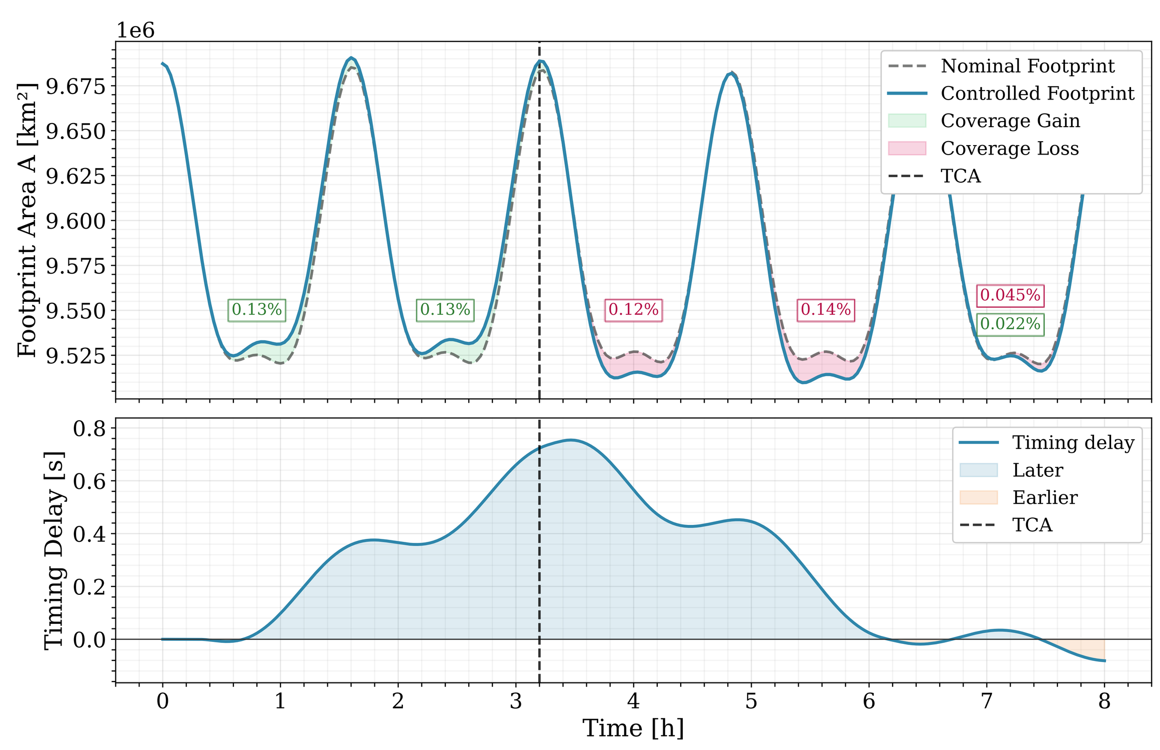
Results

The resulting thrust profile comprises three main burns: a retrograde burn near TCA for collision avoidance, followed by an initial post-TCA retrograde burn to initiate the return, and a final prograde injection burn that inserts the satellite back into its nominal orbital slot. The results confirm robust guidance across various timeframes, with minimal coverage losses given that it is mainly developing along-track separation.



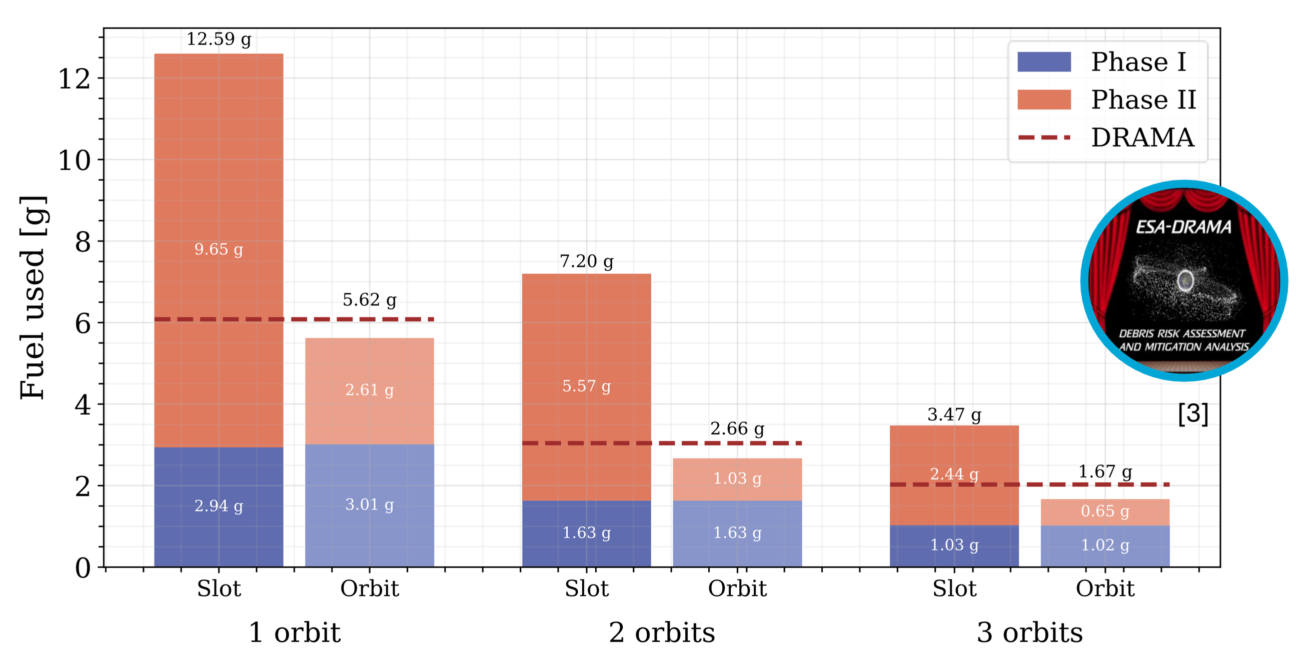
Manoeuvring satellite distance from nominal slot (bottom) and its thrust profile (top).

< 200 m Final position error | **1.5 min** Separation between nodes | **3-6 sec** Average solve time per node



Evolution of ground-coverage footprint and timing delay with respect to nominal (2 orbit scenario).

DRAMA gives an analytical estimate for fuel usage; by assuming a two-impulse manoeuvre: collision avoidance and orbit return [3]. The NMPC return-to-orbit solution aligns closely to the computed DRAMA results, validating the NMPC guidance system. The comparison shows that true return-to-slot manoeuvres require more fuel than budgeted in simple orbit returns.



Fuel consumption across varying collision avoidance and return manoeuvre durations.

Conclusions & Recommendations

The proposed framework demonstrates that NMPC is a viable solution for low-thrust trajectory optimisation in LEO, achieving safe avoidance and recovery trajectories, while adapting to different lead and return times. The return-to-orbit scenarios yield similar results as DRAMA validating the guidance systems performance. Future recommendations are to extend the framework to probabilistic uncertainty-aware guidance, optimise node placement, and verify its real-time implementation on flight-representative hardware.

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[1] Gisolfi, L., D. Dirkx, S. Fayolle, V. Filice, et al. (2025). "Open-Source High-Fidelity Orbit Estimation for Planetary Science and Space Situational Awareness Using the Tudat Software". In: arXiv preprint arXiv:2510.23179.[2] Verschueren, R., G. Frison, D. Kouzoupis, J. Frey, et al. (2021). "acados-A Modular Open-Source Framework for Fast Embedded Optimal Control". In: Mathematical Programming Computation 14, pp. 147–183. doi: 10.1007/s12532-021-00208-8. [3] European Space Agency (2026). Space Debris User Portal: MASTER and DRAMA. https://sdup.esoc.esa.int/. Accessed: 2026-06-11.