Indirect Optimization of End-of-Life Disposal for Galileo Constellation Using Low Thrust Propulsion

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The commercial use of space is expected to rapidly grow in the coming years, including satellite constellations for diverse applications such as navigation, communications, Earth imaging or resource mapping. Given the increasing number of objects launched into orbit, a sustained, secure and profitable exploitation of space requires end-of-life disposal strategies to be applied. In the case of MEO regions two options are available: 1) move the satellites into graveyard orbits, 2) insert them into Earth's re-entry paths. The latter shall be preferred as it physically removes the satellite, however it is generally associated with high ΔV and re-entry times (~100 m/s for a re-entry in 100 years). With current chemical propulsion systems this solution is not practical, but the scenario will change when fully-electric platforms will be utilized. This can be the case for the next generation of satellites in the Galileo constellation [1].

The proposed low thrust maneuver aims to move the satellite from its original orbit into a new one leading to its re-entry, but the particular positions at which the transfer starts and ends need not to be fixed. Therefore, this optimal control problem is more naturally expressed using an orbital elements-based formulation, such as the modified equinoctial elements [2]. However, this choice introduces additional complications compared to the classic Cartesian coordinates when solving the problem using the indirect method. The well-known result of the primer vector is no longer valid, and the straightforward analytical derivation of the variational equations, required to efficiently solve the associated two-point boundary value problem, becomes too cumbersome to be practical (even with symbolic manipulators). A careful treatment of the state and costate equations is then needed to derive variational equations and to develop an efficient and robust solver.

In this work, the design of low thrust end-of-life disposal trajectories for satellites in the Galileo constellation is studied, using the modified equinoctial elements to model dynamics and the indirect method to solve the associated optimal control problem. A set of previously computed orbits that exploit the lunisolar perturbation forces in the MEO region to naturally achieve re-entry times within 100 years [2] are considered as candidate arrival conditions, while the departure ones are given by the actual orbits of the Galileo constellation. The use of the modified equinoctial elements allows us to express the boundary conditions in a simple way, where all the initial and final elements are fixed except for the true longitude (determining the particular points in the initial and final orbits where the transfer maneuver starts and ends respectively). This easier treatment of the boundary conditions comes at the cost of more complex expressions for the two-point boundary value problem (TPBVP) arising from the first order optimality conditions in the indirect method. A careful study of these equations and their behavior is then performed to implement an efficient and robust solver for the TPBVP following the structure in [3], including the integration of the analytically-derived variational equations to obtain the State Transition Matrix and the accurate detection and treatment of thruster-switching events. Finally, a representative set of test cases for different initial and final orbits is studied using this solver. The results obtained prove the practical interest of this strategy for the end-of-life disposal of Galileo satellites, and could be extended in future works to other constellations in the MEO region.

References

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