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Combined high and low-thrust geostationary orbit insertion with radiation constraint

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ABSTRACT

The sequential use of an electric propulsion system is considered in combination with a high-thrust propulsion system for application to the propellant-optimal Geostationary Orbit insertion problem, whilst considering both temporal and radiation flux constraints. Such usage is found to offer a combined propellant mass saving when compared with an equivalent high-thrust only transfer. This propellant mass saving is seen to increase as the allowable transfer duration is increased, and as the thrust from the low-thrust system is increased, assuming constant specific impulse. It was found that the required plane change maneuver is most propellant-efficiently performed by the high-thrust system. The propellant optimal trajectory incurs a significantly increased electron flux when compared to an equivalent high-thrust only transfer. However, the electron flux can be reduced to a similar order of magnitude by increasing the high-thrust propellant consumption, whilst still delivering an improved mass fraction.

1. Introduction

The use of low-thrust electric propulsion (EP) on-board telecommunications spacecraft in Geostationary orbit (GEO) for station-keeping is well-established. Similarly, GEO orbit insertion using only low-thrust electric propulsion has been extensively studied [1–13]. In the frame of Horizon 2020 project HYPROGEO, which aims to develop synergies between electrical and hybrid propulsion (solid polyethylene fuel with high concentration liquid H_2O_2 oxidizer) systems, in this paper the use of the EP systems is considered in combination with a high-thrust propulsion system for application to the propellant-optimal GEO insertion problem, whilst considering both temporal and radiation flux constraints.

There has been prior research focused on coupling high and low-thrust propulsion technologies to form a hybrid propulsion system; note that in this context, and for the remainder of this paper, hybrid is used to mean combination of different thrust and specific impulse levels. Specifically in this paper, high and low thrust combined with low and high specific impulse, respectively. The advantages of coupling are obvious; reducing the transfer time compared to only low-thrust propulsion, providing a propellant mass saving compared to only chemical propulsion and reducing the time the spacecraft spends in the Van Allen radiation belts, which can cause significant power degradation to the solar panels.

The first indication of using high and low-thrust systems together was in 1962 by Theodore Edelbaum [14], around the time when EP systems were starting to be considered as a feasible propulsion system for spacecraft [15]. Early work on the transfer method, such as the analysis in Ref. [14], assumed the high-thrust segments were impulsive and patched with the low-thrust transfers to form the trajectory. This was also the case in proceeding work [16,17]. In using this method, the transversality condition used in the optimization process offered some conditions for patching the segments together. Other work has made use of primer vector theory, which can provide similar results; however in a more general and direct manner without the need to patch sections together [18]. This was based on a switching function that could be used to switch between propulsion systems and also allow the spacecraft to enter a coast period. This switching methodology was also identified in Refs. [19] and [20] and the similarities between [18–20] were described in Ref. [21].

Work has also considered the practicalities of implementing hybrid propulsion systems, that is, performing an analysis based on launch vehicle technology, spacecraft power availability and efficiencies of current low thrust systems. This has allowed for realistic studies of transfers from Earth to the Moon using chemical-electric systems and also nuclear-electric systems [22–24]. These studies have again identified the advantage of such a propulsion concept. In addition to Earth – Moon

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transfers, there have also been studies of combined propulsion systems for orbit transfers within the Earth's sphere of influence; most notably, transfers to GEO. This research has considered the use of a chemical system on-board the satellite in conjunction with an EP system, also on-board the satellite but for the main use of station keeping maneuvers, to perform part of the orbit raise maneuver [25–27]. In addition, work has considered the effect of the launch vehicle on the transfer [28]. In order to maximize the satellite dry mass and hence minimize the propellant mass, these studies have also considered the effect of varying the propulsion system specification which has shown there could be some advantage to an EP system with variable specific impulse and thrust. The work in Ref. [28] also found the optimum EP system specific impulse depends strongly on the chemical propulsion system specific impulse which is due to a trade-off between minimum propellant mass and minimum time. This is interesting as the hybrid propulsion analysis herein is dependent on the ratio of the high and low-thrust system's specific impulses; however, a similar trend is not observed as the analysis considers a minimum propellant optimization satisfying a user specified time constraint.

Power system degradation due to radiation was studied in Ref. [29] where it was confirmed the time spent in the radiation belts can be reduced drastically by employing a hybrid system as opposed to low-thrust only. The introduction of the high-thrust system does impose a mass penalty but this can be offset again by the reduction in radiation effects on the spacecraft.

Prior studies of hybrid GEO insertion scenarios have mainly focused on transfers that use high-thrust burns to achieve an intermediate orbit someway between the initial injection and target orbits. This method then uses an outward spiral trajectory towards the target orbit. However, by considering the bi-elliptic transfer ethos, see Refs. [30–33], and how it can save propellant mass by using an intermediate orbit far greater than the target orbit, a similar hybrid transfer is also considered herein. In this case, the high-thrust section is used to propel the spacecraft beyond the target to an intermediate orbit, with both perigee and apogee larger than the target, and then the low-thrust propulsion system is used to spiral back in-towards the target orbit. Such a transfer is called a Hohmann Spiral Transfer, HST [34–38], and is expected to yield significant benefits when the radiation flux is incorporated as a constraint to the trajectory design. Furthermore, as the space debris mitigation guidelines state that no object should be jettisoned into an orbit that intersects the GEO ring [39,40], it means that such an intermediate orbit beyond GEO may be used to jettison the exhausted high-thrust propulsion system, hence further increasing the efficiency of the low-thrust system by reducing the spacecraft mass.

It should be noted that throughout this analysis, and much of the literature, it is assumed that the high-thrust burns are executed fully before the low-thrust phase begins, separating the trajectory into two clearly phases. Whilst it is likely that the propellant optimal solution would intertwine these two phases, the operation of the low-thrust system is highly likely to require deployed solar array panels, which would in-turn be incompatible with the operation of a high-thrust propulsion system. Thus, such a propellant optimal solution is highly likely to be a sub-optimal system-wide solution.

2. Hybrid trajectory optimization

Several of the papers previously discussed considered different methods of addressing the issues associated with optimization of hybrid low and high-thrust propulsion transfers. For example, there has been research that used a pre-calculated transfer array that can be interpolated in order to speed up the transfer analysis [26,27]. The initial analysis in this method was therefore computationally heavy but for any other transfers it meant there was a rapid estimation available. This method obviously has a speed advantage but it is limited as it can only evaluate transfers in the region of the initial analysis. The accuracy of the resultant interpolated solutions is also dependent on the discretization of the initial solutions. Other papers have used a patching method allowing the high and low-thrust transfer sections to be decoupled, reducing the overall optimization complexity as each section is analyzed individually as discussed previously [22–24]. Although this patching method can offer near-optimal solutions, it still requires a large amount of user time and knowledge to ensure the different trajectories can be connected. However, a program has been developed to optimize a full hybrid propulsion transfer. This is called SEPSPOT and was developed at the NASA Glen research facility [41]. In coupling the high thrust section this program assumes the spacecraft begins in a circular orbit and can impart a maximum of two high-thrust impulses before the low-thrust system is activated. The total velocity change for the high-thrust section is specified and if the first required impulse is equal or greater than this then the high-thrust section is restricted to one impulse. If the first required impulse is less, then the transfer is a two-burn orbit raise. In this case, the second burn is the difference between the total specified velocity change and the first burn velocity change. Several problems have been identified with SEPSPOT however, specifically related to its sensitivity to the initial guesses and convergence problems [42].

To avoid the need for user input and sensitivity issues, this study employees a hybrid propulsion transfer optimizer that models the high-thrust phase as a Hohmann transfer and generates the low-thrust trajectory using locally optimal control laws.

2.1. Low-thrust trajectory design

Where high-thrust transfers are relatively straightforward to predict due to their impulsive nature, low-thrust transfers require continuous thrust to generate a similar velocity requirement, which can result in many orbital revolutions. This spiral trajectory leads to numerically intensive methods in order to determine a solution to any particular transfer problem. Several techniques have therefore been developed which reduce their complexity and produce trajectories that are near optimal. These methods are good for determining an initial solution to a proposed trajectory problem or forming an initial guess to be used as part of a detailed optimization study.

Locally optimal control laws have been used for trajectory generation herein. These control laws maximize the rate of change of a given orbit element and can be specified in closed analytical form as they can be developed from the variational equations of the orbital elements. This can then be used as the optimal thrust direction vector. The advantage of such control laws is the speed of which they can be implemented in a trajectory problem, whilst the primary disadvantage is the sub-optimal nature of the resulting solution. Previous work developed a form of the control laws for semi-major axis, inclination and radius of perigee using the equinoctial elements to avoid singularities associated with the classical elements [6]. In Ref. [42], this was extended to include the eccentricity control law which, combined with orbital averaging, was used in an optimization process. The control laws were then explained in an analytical form by the same author in Ref. [43]. The control laws have also been derived for use with another form of low-thrust propulsion: solar-sailing [44]. This work was further extended to define the control laws in modified equinoctial elements [45–47] and applied them to many novel missions only possible with a solar-sail [48–52].

Due to the quick implementation and versatility of locally optimal control laws, they will be used within this technical note whenever trajectory design is required. Although they are sub-optimal by nature, it was demonstrated in Refs. [6,42,51] they exhibit an accuracy $\leq 2.5\%$ from the optimal solution.

2.2. Numerical analysis and optimization

The equations of motion are defined in modified equinoctial elements, which are derived in Ref. [53] and validated in Refs. [54,55]. These are used to propagate the trajectory as they are non-singular except for rectilinear orbits when the inclination, $i = \pi$ radians and provide