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Low-thrust tour of the main belt asteroids

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Abstract

This work presents some initial results on a possible low-thrust tour of the main asteroid belt. The asteroids are visited through a series of fly-by's to be completed within a given time-frame and limit on the mass of the spacecraft at launch. The asteroids to be visited are automatically selected out of a large database of possible candidates. The initial shortlist of targets is based on the Minimum Orbit Intersection Distance (MOID) between the orbit of the asteroids in the database and the initial orbit of the spacecraft traversing the main belt. The final sequence is then obtained with an efficient deterministic branch and prune algorithm. The transfers between asteroids are designed using a low-thrust analytical model that provides a good estimation of the propellant consumption and transfer time. The mission analysis is completed with a study of the cost of the launch. In this paper two databases will be analysed: one containing only targets with a particular scientific relevance and one containing all available asteroids.

Keywords: Main asteroid belt; Low-thrust mission

1. Introduction

The main belt houses the majority of the asteroids in the Solar System. It extends from 2.1 AU to 4 AU (Minton et al. (2009)) and is estimated to contain several million asteroids, ranging in size from few millimeters to the 959 km diameter of Ceres (Millis et al., 1987). Although larger asteroid are observable from Earth and are easy to identify, the classification of smaller objects still remains an open problem. Furthermore, there is an interest in a characterisation of the larger ones to better understand their composition and evolution from the primordial stages of the Solar System till now. Key information on the composition of objects in the main belt can only be obtained from space-based spectroscopy and close encounter analysis (Bowles et al., in press). A mission that could visit at least ten objects will double the number of asteroids visited to date. However, designing a mission to characterise that many asteroids in the main belt is not an easy task. The main difficulty is to identify long sequences of asteroids that can be visited in a given time and with limited ΔV. The number of known objects exceeds 641,933 [1] and the number of possible combinations of encounter is unmanageable.

The mission currently targeting objects in the main belt, Dawn,[2] is visiting only two proto-planets using low-thrust propulsion. After visiting Vesta in 2011–2013 (Rayman and Mase, 2014), Dawn is now exploring the dwarf planet Ceres (Russell et al., 2016).

Examples of previous works on the design of asteroid tours divided the design process into different steps (Olympio, 2011): the first step consists in the definition of a shortlist of potential targets, based on their orbital elements, dimensions or scientific characteristics. In the sec-

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[1] http://ssd.jpl.nasa.gov/sbdb_query.cgi#x.
[2] http://dawn.jpl.nasa.gov/.

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ond step a sequence of target objects is selected using some form of global optimisation (Alemany et al., 2007) in combination with reduced models that provide a quick estimation of the cost of the transfer. The last step is the optimisation of the sequence with a local optimisation method. A recent work by Cuartielles et al. (2016) proposes a mission to fly-by 10 or more asteroids in 7 years in the timeframe 2029–2030, using a spacecraft equipped with a chemical engine launched by a Soyuz launcher. The study includes the possible use of a gravity assist of Mars. A branch and bound search method is used to identify an optimal sequence of asteroids under the assumption that all fly-by's with the asteroids occur at the point of Minimum Orbital Intersection Distance (MOID). The use of gravity assist to reach the main belt is studied also by Chen et al. (2014), who present the results of an analysis of accessibility for 200 asteroids in the main belt with diameter greater than 100 km. The global minimum of the cost of the transfer to these asteroids, using gravity assists with Mars or Earth, is sought. Results show that Mars is the most useful gravity-assist body and that dual gravity assists with Mars are the best type of trajectories to reach mid or outer belt asteroids and high-inclination ones. The low-thrust transfer to asteroid Flora is included in the analysis. The control profile for the low-thrust transfer is optimised with an indirect optimal control method and homotopy. Shang and Liu (2017) proposed a machine learning method based on Gaussian Process Regressions to study the accessibility of more than 600,000 main belt asteroids considering rendezvous realised through bi-impulsive or Mars gravity-assisted transfers. Mars' gravity assists to reach the main belt are also proposed by Yang et al. (2015). In this work, the transfer from a near-Earth asteroid to a main belt asteroid, using low-thrust propulsion and multiple gravity assists, is studied. Based on an analysis of the Tisserand graph, the Earth-Mars-Mars gravity assists sequence is found to be the best option to reach the main belt. A global solver is then used to obtain the event dates for the gravity assists and the deep space manoeuvres, using an impulsive model for the transfers. Finally, the optimal control problem for the design of the low-thrust trajectory is solved using an indirect method and homotopy.

In recent times, the problem of visiting multiple asteroids was part of the objective of some Global Trajectory Optimisation Competitions (GTOC).[3] In particular, in GTOC4 the problem was to identify the maximum number of asteroids' fly-bys from a given list of 1438 objects, considering a rendezvous with the last asteroid in the sequence and a total mission time of ten years. GTOC5 also proposed a mission to Near Eearth Asteroids (NEAs) (Bottke et al., 2000; Stuart, 2001), considering a database of 7073 objects, while GTOC7 presented a multi-spacecraft exploration of the asteroid belt and a database of 16,256 potential targets. For GTOC4, the first ranking team found a solution visiting 44 asteroids (Grigoriev and Zapletin, 2013). They solved the discrete part of the problem (the identification of the optimal sequence of asteroids to visit) using dynamic programming, performing the construction of the solution vector step by step and optimising time and mass consumption at each step. The trajectory was approximated with a solution of the Lambert problem. Lantoine and Russell (2012) used an algorithm called HDDP (Hybrid Differential Dynamic Programming), a variant of the classical Differential Dynamic Programming technique. The multi-phase formulation of HDDP was used by splitting the trajectory into several portions connected by the fly-by's at the asteroids. The initial guess was obtained from a ballistic Lambert solution that provided the asteroid sequence. The solution was characterised by 24 fly-by's and 1 rendezvous.

This paper presents some results for a possible tour of the main asteroid belt using solar electric propulsion. The particular problem presented in this paper is similar to the one proposed in Cuartielles et al. (2016) and differs from previous analyses of the accessibility of the main belt or asteroid tours considered in past GTOCs. More specifically, in order to limit mission time and total mass at launch, the strategy proposed in this paper is to fly-by as many asteroids as possible at their nodal points by traversing the asteroid belt with an elliptical orbit with perihelion at (or near) the Earth and aphelion at the main belt. Each asteroid is expected to be visited with one single fly-by only (see Di Carlo et al. (2017b) and Vroom et al. (2016)). The resulting combinatorial problem is solved with a combination of two simple pruning techniques over the space of possible fly-by's. The first pruning is on the MOID between the initial orbit and the asteroids in the database. After this first pruning a deterministic branch and prune algorithm is applied to a binary tree that incrementally constructs the optimal sequence of targets. Finally, the best solution is re-optimised with electric propulsion. A direct transcription method based on asymptotic analytical solutions to the accelerated Keplerian motion (Zuiani et al., 2012) is used to transcribe the optimal control problem that defines the optimal control profile of the engine. The transfer from the Earth to the initial elliptical orbit traversing the main belt is then optimised with the same transcription approach.

The length of the tour is constrained by a given total mission time and desirable launch capability. Two scenarii are considered: in the first scenario the database of target objects includes scientifically interesting bodies and tries to find the longest sequence of objects in a given time and ΔV budgets; in the second scenario, more than 100,000 objects are added to the previous database and the aim is find the longest sequence of asteroids that contains also some (more than 0) scientifically interesting targets. Note that the number of possible targets is, in this case, about one order of magnitude larger than the one of previous GTOCs. The analysis proceeds, as in the first

[3] https://sophia.estec.esa.int/gtoc_portal/.

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