Acta Astronautica 104 (2014) 450–457

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Optimal nodal flyby with near-Earth asteroids using electric sail

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ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form
4 February 2014
Accepted 13 February 2014
Available online 22 February 2014

Keywords:
Electric Solar Wind Sail
NEA exploration
Trajectory optimization

ABSTRACT

The aim of this paper is to quantify the performance of an Electric Solar Wind Sail for accomplishing flyby missions toward one of the two orbital nodes of a near-Earth asteroid. Assuming a simplified, two-dimensional mission scenario, a preliminary mission analysis has been conducted involving the whole known population of those asteroids at the beginning of the 2013 year. The analysis of each mission scenario has been performed within an optimal framework, by calculating the minimum-time trajectory required to reach each orbital node of the target asteroid. A considerable amount of simulation data have been collected, using the spacecraft characteristic acceleration as a parameter to quantify the Electric Solar Wind Sail propulsive performance. The minimum time trajectory exhibits a different structure, which may or may not include a solar wind assist maneuver, depending both on the Sun-node distance and the value of the spacecraft characteristic acceleration. Simulations show that over 60% of near-Earth asteroids can be reached with a total mission time less than 100 days, whereas the entire population can be reached in less than 10 months with a spacecraft characteristic acceleration of 1 $\mathrm{mm/s^2}$.

1. Introduction

The interest of the scientific community in studying Near Earth Asteroids (NEAs) is emphasized by the increasing number of papers that have been devoted to this matter, especially in the last decade. A detailed review about NEAs and their possible threat to our planet, including an up-to-date and extensive bibliography, is given in the recent review paper by Perna et al. [1] to which the interested reader is referred for further information. After the pioneering successes of the American mission Near Earth Asteroid Rendezvous – Shoemaker [2] and the more recent conclusion of Japanese Hayabusa mission [3,4], the two proposed European missions Don Quijote [5] and Marco Polo [6,7] are expected to represent a fundamental step forward in the knowledge of these interesting celestial bodies of the Solar System.

In general terms, an orbital rendezvous with a NEA using a robotic mission is a rather involved problem, due to the typical non-negligible orbital inclination of those (minor) celestial bodies [8,9]. For example, about 49% of the currently known NEAs (that is, over 9500 asteroids at the beginning of the 2013 year), have a heliocentric orbital inclination greater than 10 deg. Such a characteristic, especially when coupled with a non-negligible value of orbital eccentricity, in most cases requires the need of a large ΔV to perform a classical rendezvous mission with a high-thrust propulsion system as, for example, a chemical rocket. A substantial reduction of the necessary ΔV can be obtained by relaxing the constraints regarding the terminal phase of the mission, for example by performing a close encounter with the asteroid instead of an orbital rendezvous. Within the context of flyby missions toward

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http://dx.doi.org/10.1016/j.actaastro.2014.02.012
0094-5765

Nomenclature

a_c	spacecraft characteristic acceleration
$a_\oplus$	Earth's orbit semimajor axis
$e_\oplus$	Earth's orbit eccentricity
$\mathcal{H}$	Hamiltonian function
$\mathcal{J}$	set of NEAs
r	Sun-spacecraft distance ($r_\oplus \triangleq 1$ au)
$\mathcal{T}(r,\theta)$	polar reference frame
t	time (t_f is the total flight time)
v	spacecraft velocity modulus
α	sail cone angle
α_λ	reference angle, see Eq. (12)
θ	polar angle
λ_i	adjoint to variable i
$\mu_\odot$	Sun's gravitational parameter
ν	true anomaly
τ	switching parameter

Subscripts

0	initial
f	final, target
r	radial
θ	transverse
max	maximum

Superscripts

$\cdot$	time derivative
-	mean value over ν_0

NEAs, Ref. [10] discusses an interesting approach, referred to as nodal flyby, in which the target asteroid is reached at one of its two orbital nodes using an impulsive transfer. A similar idea has been subsequently exploited in Ref. [11] to accomplish a preliminary mission analysis toward long-period comets with high orbital inclination and using a photonic solar sail, that is, a spacecraft with a propellant-less (primary) propulsion system that provides a continuous, low, propulsive acceleration. For example, Table 6 of Ref. [11] shows that the flight time required to reach the descending node of comet Hale–Bopp ranges between about 200 and 660 days depending on the photonic solar sail performance.

The aim of this work is to apply the nodal flyby concept to a mission analysis using a spacecraft whose propulsion system is constituted by an Electric Solar Wind Sail (E-Sail) [12,13]. The E-sail is an innovative propulsion concept, which uses the solar wind dynamic pressure for generating a propulsive acceleration without the need for reaction mass. As such, it represents an interesting option for robotic missions toward NEAs, especially when a small scientific payload mass is considered [14].

In this paper all NEAs in the set of known asteroids (evaluated at mid-January 2013) have been considered as potential targets in a robotic mission scenario. The analysis of each mission case has been performed within an optimal framework, by calculating the minimum-time trajectory necessary to reach one orbital node of the target asteroid. This amounts to finding the optimal mission performance irrespective of the initial and final E-sail positions at both the parking orbit and the target node. The use of such a simplified mission scenario, in which the ephemeris constraints are not taken into account, is a common choice in a preliminary mission analysis [15], and is necessary to accomplish a thorough investigation involving the whole population of NEAs with reasonable simulation times. For each target the optimal problem has been solved with an indirect approach, using different values of the spacecraft characteristic acceleration. The mathematical model, which is briefly described in the next section, has been adapted from that discussed in Ref. [15].

As a result of the study, a database with the outputs of nearly 19 000 optimal transfers has been created. In this sense, this work is an extension of a previous paper [16] presented at the 7th Symposium on Realistic Advanced Scientific Space Missions (Aosta, 2011) and completes the analysis of Ref. [15] regarding an E-sail based mission towards potentially hazardous asteroids. The collected simulation data are sufficient for obtaining a first order estimation of the performance required by an E-sail to fulfil a mission toward a NEA.

2. Mathematical model

According to the most recent studies [12], the E-sail propulsive acceleration modulus depends on the Sun-spacecraft distance r as $a_c(r_\oplus/r)$, where a_c is the spacecraft characteristic acceleration, that is, the maximum propulsive acceleration at a reference distance $r_\oplus \triangleq 1$ au.

Assuming a two-dimensional transfer, the heliocentric equations of motion for an E-sail in an ecliptic polar reference frame $\mathcal{T}_\odot(r,\theta)$ are (see Fig. 1):

$$\dot{r} = v_r \tag{1}$$

$$\dot{\theta} = \frac{v_\theta}{r} \tag{2}$$

$$\dot{v}_r = \frac{v_\theta^2}{r} - \frac{\mu_\odot}{r^2} + a_c \tau \frac{r_\oplus}{r} \cos\alpha \tag{3}$$

$$\dot{v}_\theta = -\frac{v_r v_\theta}{r} + a_c \tau \frac{r_\oplus}{r} \sin\alpha \tag{4}$$

where the polar angle θ is measured anticlockwise from the Sun-spacecraft position at the beginning of the transfer phase, the thrust angle $\alpha \in [-\alpha_{\max}, \alpha_{\max}]$ coincides with the angle between the Sun-spacecraft line and the thrust direction, $\alpha_{\max}$ is the maximum cone angle (in this paper it is assumed that $\alpha_{\max} = 30$ deg, see Ref. [15]), and the switching parameter $\tau = (0,1)$ models the E-sail on/off condition.

The following analysis is performed assuming a circular Earth's heliocentric orbit and an E-sail deployment on