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Multiple near-earth asteroid rendezvous mission: Solar-sailing options

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Abstract

The scientific interest in near-Earth asteroids (NEAs) and the classification of some of those as potentially hazardous for the Earth stimulated the interest in their exploration. Close-up observations of these objects will drastically increase our knowledge about the overall NEA population. For this reason, a multiple NEA rendezvous mission through solar sailing is investigated, taking advantage of the propellantless nature of this propulsion technology. Considering a spacecraft based on the DLR/ESA Gossamer technology, this work focuses on a method for searching possible sequences of NEA encounters. The effectiveness of the approach is demonstrated through a number of fully-optimised trajectories. The results show that it is possible to visit five NEAs within 10 years with near-term solar-sail technology. Moreover, a study on a reduced NEA database demonstrates the reliability of the approach used, showing that 58% of the sequences found with an approximated trajectory model can be converted into real feasible solar-sail trajectories. Overall, the study shows the effectiveness of the proposed automatic optimisation algorithm, which is able to find solutions for a large number of mission scenarios without any input required from the user.

Keywords: Automatic trajectory design; Solar sail; Tree-search algorithm; Multiphase trajectory optimisation; Gossamer; Near-earth asteroids; Multiple rendezvous

1. Introduction

In the last decades, near-Earth asteroids (NEAs) received considerable attention for planetary defence, science, human spaceflight and technology demonstration. From a technological point of view, NASA considers NEAs as a bridge toward the human exploration of Mars (Boden et al., 2015). A manned NEA mission offers similar challenges as a mission to the red planet (i.e. a relevant deep-space environment and a total mission duration similar to an Earth-Mars transit). On the other hand, the total mission duration and the required Δv (and, therefore, the launch costs) are below those needed for a full Mars return mission. As reported in Boden et al. (2015), however, for safety considerations, the asteroid selection for such a mission shall take into account several characteristics of the target objects (e.g. size, composition, rotation rate, etc.). Based on the observations taken from Earth, the characterisation of NEAs discovered to date often suffers from uncertainties in their physical, chemical and orbital properties. Moreover, some NEAs are defined as potentially hazardous asteroids (PHAs) and, especially for planetary defence scenarios, an accurate characterisation of their properties is needed (Sanchez et al., 2009). Sugimoto et al. (2013) underlined this need for deflection purposes. Even if methods exist to deal with NEA composition uncertainties (e.g. evidence theory), Sugimoto showed how some deflection methods – the ones that have a strong interaction with the target object (e.g. nuclear interceptor,

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Nomenclature

A	sail area, m^2
$\mathbf{A}(\boldsymbol{x})$	matrix of the dynamics
$\boldsymbol{a}$	solar-sail acceleration, mm/s^2
a	semi-major axis, AU
a_c	solar-sail characteristic acceleration, mm/s^2
$\boldsymbol{b}(\boldsymbol{x})$	vector of the dynamics
e	eccentricity
f, g	in-plane modified equinoctial elements
g_0	standard gravitational acceleration on Earth's surface, 9.81 m/s^2
H	asteroid absolute magnitude
$\hat{\boldsymbol{h}}$	orbital angular momentum unit vector
I_{SP}	specific impulse, s
j, k	out-of-plane modified equinoctial elements
L	true longitude, rad
m_0	total mass, kg
m_{dry}	spacecraft dry mass, kg
$\hat{\boldsymbol{N}}$	unit vector normal to the sail plane
$P_{\oplus}$	solar radiation pressure at Earth distance, 4.56 $\mu N/m^2$
p	semi-latus rectum, AU
$\boldsymbol{r}$	sun-spacecraft position vector ($r := \|\boldsymbol{r}\|$), AU
$\ddot{\boldsymbol{r}}$	acceleration
$r_{\oplus}$	mean Sun-Earth distance, 1 AU
t	time, s
t_0	departure date
U	quality code
$\boldsymbol{x}$	state vector in modified equinoctial elements
α	sail cone angle, deg
Δv	velocity increment, km/s
$\delta\varpi$	longitude of pericentre variation, rad
$\dot{\zeta}$	sail slew rate, deg/s
$\ddot{\zeta}$	sail angular acceleration, deg/s^2
θ	angle between two angular momenta, rad
λ	shaping parameter
μ	gravitational parameter of the Sun, 1.3271×10^{11} km^3/s^2
φ	phasing parameter, rad
ϖ	longitude of pericentre, rad

Superscripts

T	transpose

Subscripts

0	initial value
F	boundary conditions at the final time
fg	in-plane modified equinoctial elements
I	boundary conditions at the initial time
p	semi-latus rectum

solar sublimation or kinetic impactor) – are affected by uncertainties about asteroid composition (i.e. porosity, surface materials, precise shape, etc.) more than others. Furthermore, not only the chemical, physical and mineralogical composition but also the rotation of these objects can have an important role in the success of a mission, for both deflection and sample-return missions. Miller et al. (2015) gave an overview of the asteroid-characterisation priorities for planetary defence, pointing out the possible issues derived by a deflection mission to badly-characterised objects. Several survey and mitigation programs have been established for the purpose of a better knowledge of NEA characteristics (NEOWISE (Mainzer et al., 2012), JPL/NASA Near-Earth Object Program,[1] and NEOShield (Harris et al., 2013) are just three examples) but most of them deal with ground-based observations. Specifically regarding Europe, Koschny and Drolshagen (2015) showed the ongoing activities to mitigate the potential threat posed by NEAs. To date, few missions to small bodies have been successfully completed (e.g. NEAR (Cheng et al., 1997), Deep Impact (Blume, 2005), Hayabusa (Fujiwara et al., 2004, 2006), and Rosetta (Glassmeier et al., 2007; Pätzold et al., 2011)) and two spacecraft (OSIRIS-REx (Berry et al., 2013) and Hayabusa-2 (Tsuda et al., 2016)) are currently on their way to rendezvous two different NEAs (Bennu and 1999 JU_3, respectively). The Asteroid Impact and Deflection Assessment (AIDA) mission aims to demonstrate the kinetic-impact technique for asteroid deflection and consists of two spacecraft, the first of which is scheduled to be launched in late 2020 (Cheng et al., 2015). A further mission, the Asteroid Redirect Mission (ARM), is currently under study and is planned to capture and redirect a small NEA into an orbit accessible to a human crew (Gates et al., 2015). Nevertheless, a multiple NEA rendezvous mission can help the scientific community to improve our knowledge about these objects. A multiple-target mission is more desirable than a single-rendezvous mission due to the reduced cost of the single observation and the more extensive information returned. Moreover, within a multiple-target mission, it might be possible to change the targets in due course, if there is enough Δv available. This feature can be useful if new interesting objects are discovered after the launch. However, the large amount of possible sequences of objects that can be chosen to visit makes the optimal planning of such a mission very challenging. In fact, more than a billion of possible ordered sequences with three consecutive encounters exist, considering a database

[1] https://cneos.jpl.nasa.gov/orbits/elements.html (cited 08 August 2015).

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