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Fast solar sail rendezvous mission to near Earth asteroids

Xiangyuan Zeng*, Shengping Gong, Junfeng Li

Department of Aerospace Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

The concept of fast solar sail rendezvous missions to near Earth asteroids is presented by considering the hyperbolic launch excess velocity as a design parameter. After introducing an initial constraint on the hyperbolic excess velocity, a time optimal control framework is derived and solved by using an indirect method. The coplanar circular orbit rendezvous scenario is investigated first to evaluate the variational trend of the transfer time with respect to different hyperbolic excess velocities and solar sail characteristic accelerations. The influence of the asteroid orbital inclination and eccentricity on the transfer time is studied in a parametric way. The optimal direction and magnitude of the hyperbolic excess velocity are identified via numerical simulations. The found results for coplanar circular scenarios are compared in terms of fuel consumption to the corresponding bi-impulsive transfer of the same flight time, but without using a solar sail. The fuel consumption tradeoff between the required hyperbolic excess velocity and the achievable flight time is discussed. The required total launch mass for a particular solar sail is derived in analytical form. A practical mission application is proposed to rendezvous with the asteroid 99942 Apophis by using a solar sail in combination with the provided hyperbolic excess velocity.

1. Introduction

Since the first launch of the manned satellite, most of planets in our solar system have been explored and some human probes even aimed to escape the solar gravitational field and go beyond the heliopause, such as the Voyager 1 and Voyager 2 launched by NASA in 1977 [1]. Besides the continuous interest in planetary missions, Near Earth Asteroids (NEAs) are being considered as new targets with full science and resource survey objective. NEAs are small celestial bodies with a perihelion distance of not more than 1.3 AU ($1\ \text{AU} \approx 1.496 \times 10^8$ km). On the one hand, these rocky objects are believed to be left over from the beginning of the solar system and deserve to be explored to widen our knowledge [2]. On the other hand, it has been proven that asteroids have many planetary resources which can be mined and then possibly brought to the Earth or be used in space as in-situ resource utilization. A novel concept was proposed by NASA named asteroid retrieval mission [3]. The mission goal is to send a robotic spacecraft to a selected NEA and tow it back to a parking orbit near the moon. If the mission can be successfully carried out in the near future, it should be significant for further deep space explorations, such as a manned mission to NEAs.

Collisions between the Earth and NEAs recently draw the attention of scientists again after the falling meteor over the Russian mountains in February 2013.[1] Small objects with a diameter of 50 mm usually burn up and get destroyed through the atmosphere, but NEAs with

* Corresponding author.
E-mail addresses: zxy0985@gmail.com (X. Zeng), gongsp@tsinghua.edu.cn (S. Gong), lijunf@tsinghua.edu.cn (J. Li).

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non-ignorable dimensions can penetrate the atmosphere and cause substantial damages on a regional or global scale [4]. A number of strategies have been proposed to deflect a potentially hazardous object on a course of collision with Earth [5]. In 2005, a demonstrative mission named "Don Quijote" developed by ESA was designed to access the technology in case one day needed to deflect a dangerous NEA. Most of these strategies or missions require accurate physical and orbital data of NEAs. The ground-based observation and laboratory analysis could only provide a rough estimation of the above required data. Thus, in-situ measurements or close flybys are necessary to some extent in the determination of the risk and deflection execution.

Both practical and academic advances have been made in the area of small celestial bodies in the past decades. Spacecraft with conventional impulsive rockets have accomplished a few flybys or rendezvous missions with asteroids, such as the Galileo (1989–2003), NEAR (1996–2001) and Deep Impact (launched in 2005) launched by NASA [6]. Due to the relatively low specific impulse of the chemical rocket, the planetary gravity assist is usually employed to decrease the initial launch mass for the mission requiring a high launch energy, consequently with an increase of the mission time, such as the ROSETTA [7] launched by ESA in 2004. In order to reduce the flight time and total mission costs, continuous low-thrust propulsion systems have been widely utilized in scientific spacecraft, such as the Deep Space-1, Dawn and Hayabusa [8]. At the meantime, a large number of research papers on asteroids have been published, working on the asteroids' distribution and composition [9], rendezvous transfer trajectories [10] and deflection strategies for dangerous asteroids [5].

Due to the irregular shape and rotation of the asteroid, near-asteroid orbital dynamics are considerably different from classical Keplerian orbits around major planets of the solar system in the two-body problem [11]. For most cases, a continuous low thrust control is required for near-asteroid operations, like station-keeping or transfer between equilibrium points. Moreover, because of orbital uncertainties affected by gravitational perturbations, the Yarkovsky effect and sometimes collisions, the orbit of an asteroid is difficult to be accurately predicted in long term propagation [12]. Hence, fast transfer trajectories are of great importance to intercept or rendezvous with an asteroid. Additionally, multiple target exploration of NEAs with a single spacecraft is a likely scenario for future missions to reduce the mission costs and maximize the benefits. With the increasing requirement of shorter transfer time and lower costs, alternative propulsion systems, i.e., solar photonic, electric and magnetic sails, are being considered and developed in addition to current continuous low-thrust propulsion systems.

The successful flight of IKAROS and Nano Sail-D2 in 2010 has made solar sail technology to be the most mature propulsion system without consumption of on-board propellant mass. A solar sail is a large reflective surface that can be accelerated by momentum transfer from solar photons. It can offer unique opportunities for the NEA exploration, such as providing wide launch windows [13], long-term multiple-objective missions [14] and hovering positions out of the equatorial plane [15]. Although solar sail is a new type of propulsion, its concept has been known for nearly a century. Before the study of comet Halley rendezvous mission proposed by NASA/JPL in the late 1970s, solar sail has never been considered as a feasible propulsion technology [16]. With the development of micro-technologies and thin films, plenty of practical experiments have been carried out, including Znamya-2, COSMOS-1, and Nano Sail-D. Theoretical analyses have been improved from the simple heliocentric transfer [17] to current highly non-Keplerian orbits [18]. Since there are no onboard supplies of fuel, the time optimal trajectory design is usually in the focus for solar sails [19]. To the authors' knowledge, up to date the majority of those trajectories are designed with a conservative estimation [20,21], assuming that a solar sail is directly inserted into a heliocentric orbit with zero hyperbolic excess velocity ($v_\infty = 0$ km/s, i.e., $C_3 = 0$ km^2/s^2). The non-zero v_∞ mission scenario has only been addressed briefly by Hughes et al. [22] and Dachwald et al. [23,24]. In fact, a non-zero v_∞, representing the characteristic of the launch system, could be appropriately used for a fast rendezvous mission to a NEA [25].

The subject of this paper is to investigate the effect of a non-zero v_∞ on NEA rendezvous missions by using a solar sail. The analysis will extend the time optimal control framework for interplanetary transfers reported by Sauer [19,21]. The rest of the content is organized as follows, with three main sections and the conclusion part. A time optimal control problem with a non-zero v_∞ is presented in Section 2 and then transformed to a two point boundary value problem (TPBVP) by using an indirect method. A parametric study regarding the transfer time is performed in Section 3 by varying the value of v_∞ in the range of [0, 9] km/s. The simple coplanar circular orbit rendezvous scenario is investigated using a solar sail in characteristic accelerations of [0.5, 2.0] mm/s^2. The influence of the orbital inclination and eccentricity of the target asteroid on the fast rendezvous mission is discussed and analyzed. For the coplanar circular rendezvous scenario, a comparison is made in terms of the fuel consumption between using v_∞ for the solar sail transfer and a bi-impulsive transfer of the same flight time, but without using a solar sail. The fuel consumption tradeoff between the total launch mass and the flight time is investigated. A practical mission example is given in Section 4 taking asteroid 99942 Apophis as a candidate to validate the proposed concept of fast solar sail missions including the hyperbolic launch excess velocity.

2. Time optimal control model for rendezvous missions

The time optimal transfer trajectory using a solar sail with an initial hyperbolic excess velocity from Earth to the target asteroid is considered in this study. An ideally reflecting flat sail model is adopted by ignoring the wrinkles of the sail surface caused by the sail deployment or prolonged exposure in the deep space. The sail attitude control is supposed to be implemented instantaneously without tracking error. A solar sail in a heliocentric orbit is