Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 56 (2015) 837–847

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Low-cost transfer between asteroids with distant orbits using multiple gravity assists

Hongwei Yang, Jingyang Li, Hexi Baoyin *

School of Aerospace Engineering, Tsinghua University, Beijing 100084, People's Republic of China

Received 2 February 2015; received in revised form 5 May 2015; accepted 6 May 2015
Available online 16 May 2015

Abstract

Low-cost transfer trajectories are significant to explore asteroids with distant orbits in a multiple targets' mission. Methods for designing these trajectories optimally are proposed. The sequence of gravity-assists is evaluated by the Tisserand graph. Then, an optimization method combining the particle swarm optimization (PSO) and the indirect method is used to optimize the low-thrust trajectories with gravity assists. The Bang–Bang control problem in the indirect method is overcome by a smooth technique. The whole transfer trajectories solving process by the shooting method is divided into several steps to overcome the difficulty and improve the efficiency. Numerical simulations are carried out for validating the proposed method.

Keywords: Asteroid; Gravity assist; Optimization; Low-thrust trajectory; Indirect method

1. Introduction

Both near-Earth asteroids and main-belt asteroids have attracted space agencies to carry out explorations. Several spacecrafts have explored these asteroids successfully, including NEAR Shoemaker (Dunham et al., 2002), Hayabusa-1 (Kawaguchi et al., 2008), Dawn (Russell et al., 2007), etc. The first two spacecrafts executed near-Earth asteroids' missions (Dunham et al., 2002; Kawaguchi et al., 2008) and the third one has finished rendezvousing the main-belt asteroid Vesta and is on its way to the Ceres (Russell et al., 2007). Several other future missions, such as MarcoPolo (Barucci et al., 2012), OSIRIS-REx (Lauretta and Team, 2012), Hayabusa 2 (Tsuda et al., 2013), etc., are proposed in the past years as well.

Near-Earth asteroids includes three types which are Apollo ($a \geqslant 1.0$ AU; $q \leqslant 1.0167$ AU), Aten ($a < 1.0$ AU; $q > 0.983$ AU) and Amor (1.0167 AU $< q \leqslant 1.3$ AU) (Morbidelli et al., 2002). Accessibility of exploring the near-Earth asteroids by direct transfer or using the Earth gravity assist has been studied and evaluated (Lau and Hulkower, 1987; Qiao et al., 2006). Different from the near-Earth asteroids, the orbits of the main-belt asteroids are distant to the Earth. These asteroids are usually divided into three groups according to the semimajor axis: the inner belt asteroids (2.1 AU $\leqslant a \leqslant$ 2.5 AU), the middle belt asteroids (2.5 AU $< a \leqslant$ 3.0 AU) and the outer belt asteroids ($a > 3.0$ AU) (Chen et al., 2014). Due to the orbits of the main-belt asteroids are distant, single and multiple gravity assists are studied to lower the mission cost and the accessibility is evaluated (Chen et al., 2014). Dual Mars gravity assists are shown to be the best via the analysis (Chen et al., 2014) and the dual Mars gravity assists are used twice in the sample return mission (Dankanich et al., 2010).

* Corresponding author.
E-mail addresses: yang.hw.thu@gmail.com (H. Yang), lijingyang10@mails.tsinghua.edu.cn (J. Li), baoyin@tsinghua.edu.cn (H. Baoyin).

http://dx.doi.org/10.1016/j.asr.2015.05.013
0273-1177/

Visiting multiple asteroids during one mission can reduce costs and increase the scientific results obviously (Olympio, 2011). Sears et al. and Morimoto et al. studied a mission of sampling return of multiple near-Earth asteroids (Sears et al., 2004; Morimoto et al., 2004). Olympio derived the transversality conditions for the optimal control of missions in which the multiple asteroids are visited by rendezvous or flyby (Olympio, 2011). Besides, visiting multiple asteroids is one of the main subjects of the global trajectory optimization competition (GTOC). In the recent 7th edition GTOC, a mission with multiple spacecrafts for visiting the asteroid belt is proposed (Casalino and Colasurdo, 2015). Actually, this is a multiple targets mission with several important features such as the simultaneous optimization of trajectories, cooperation between mothership and probes, etc. (Casalino and Colasurdo, 2015). Visiting near-Earth asteroids and main-belt asteroids in one mission can achieve scientific aims of studying both these two kinds of asteroids and lower the cost. One key part of designing such a mission is the transfer orbits between the near-Earth asteroids and main-belt asteroids.

Due to the orbits of a near-Earth asteroid and a main-belt asteroid is distant, the gravity assists are necessary to lower the cost significantly. Besides, the electric propulsion, which provides the low thrust, gives higher specific impulse and thus is more efficient compared with the traditional chemical propulsion (Jiang et al., 2012). Actually, the electric propulsion has already been used in the asteroid's mission for visiting the Itokawa (Kuninaka et al., 2007). So far, many works have been carried out for dealing with low-thrust trajectory design to outer planets combined with gravity assists (Armellin et al., 2010; Casalino et al., 1999; Jiang et al., 2012; McConaghy et al., 2003; Rasotto et al., 2013; Woo et al., 2006). McConaghy et al. (2003) proposed a two-step approach including the broad search and the parameter optimization. In the broad search, a simplified shape-based trajectory model is used and the best trajectories are selected by a heuristic cost function. Woo et al. (2006) employed the genetic algorithms and proposed automatic searching procedure. The methods developed by McConaghy et al. (2003) and Woo et al. (2006) are regarded as direct methods to deal with the optimal control problems. Different with their works, the fuel optimal low-thrust trajectories using multiple gravity assists are studied by the indirect method in this paper. In the indirect method, the optimal control problem is transformed into a boundary value problem with the help of the Pontryagin's Maximum theory and then solved by a shooting method (Rao, 2009). In the study of Casalino et al. (1999), the indirect method is used and both cases of free-height and minimum-height flybys are studied. Besides, the method proposed by Casalino et al. (1999) is able to deal with both cases of constant and variable exhaust velocity as well. Jiang et al. (2012) proposed a practical homotopic method which can be applied to solve the low thrust trajectories combined gravity assists. Both the studies of Casalino et al. (1999) and Jiang et al. (2012) dealt with single gravity-assist problems. In the current paper, a multiple gravity-assist problem is to be studied. Rasotto et al. (2013) has proposed a method for dealing with the multiple gravity-assist problems using the multiple-shooting technique (Olympio, 2011). An intermediate point is selected within the arc between two planets to increase the robustness (Rasotto et al., 2013). Indeed, the multiple-shooting technique can greatly improve the convergence of solving the boundary value problems. But the number of the variables will increases quickly with number of the intermediate points as well. Besides, the boundary value problems may be hard to converge without proper guessed initial values when the number of the unknown variables is too large. Different with the approach of Rasotto et al. (2013), the method proposed in this paper is developed from the practical homotopic method (Jiang et al., 2012). The method proposed by Jiang et al. (2012) becomes very fast and effective in its solving process by involving two key techniques: (1) normalization of the initial costate vector; (2) switching detection. Actually, the practical homotopic method (Jiang et al., 2012) has shown its excellent efficiency for optimizing the low-thrust trajectories in the 5th edition GTOC (Jiang et al., 2014). The idea herein is to divide the whole low-thrust trajectories into several sub-trajectories and each contains only one gravity assist for the purpose of decreasing the number of the unknown variables. In this way, the practical homotopic method (Jiang et al., 2012) can be applied simply and effectively for optimizing each sub-trajectory. The whole low-thrust trajectories are then obtained by a three-step solving process. Although only the optimality of the sub-trajectories can by guaranteed by the method in the current paper, the proposed method is easy to converge and can be simply extended for low-thrust trajectory optimizations with more than three gravity assists.

As for the fuel optimal control problem, there always exists a Bang–Bang control problem which leads the convergence of the shooting process to be difficult (Bertrand and Epenoy, 2002). Bertrand and Epenoy (2002) proposed a smoothing technique in which an index homotopy is built to overcome this difficult. This method has been used and developed in many studies (Chen et al., 2014; Jiang et al., 2012; Olympio, 2011; Rasotto et al., 2013; Caillau et al., 2012; Yang and Baoyin, 2015). Specifically, Rasotto et al. (2013) proposed two kinds of smoothing approximations which are the exponential approximation and arctangent approximation. Besides, Rasotto et al. (2013) and Caillau et al. (2012) applied the smoothing technique to the optimal control problems with three-body dynamics; Yang and Baoyin (2015) dealt with the optimal control problems in irregular gravity fields. However, it is difficult to determine the switching points only by the smoothing technique. Switching time optimization methods are regarded as an efficient ways to determine the optimal Bang–Bang switching points (Lin et al., 2014; Loxton et al., 2014). In these methods, the key technique is the time-scaling transformation by which the existence of the partial derivatives of the