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Two-tangent-impulse flyby of space target from an elliptic initial orbit

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Abstract

The problem of two-tangent-impulse space target flyby is drawn in this paper. Unlike the traditional method, the transfer orbit is divided into two parts, i.e. the phasing orbit and the approaching orbit, considering the temporal and the spatial constraint respectively. The method of the phasing orbit and approaching orbit determination is formulated firstly. Then, the attainable target areas from a given position on the initial elliptic orbit, the feasible impulse position for approaching to a given point in space and the optimal approaching orbit to a given point are analyzed. Based on the optimal approaching orbit, the optimal solution for target flyby is provided in the time free case, and a suboptimal solution for the case of time-constrained. Numerical simulations demonstrate the application of the solutions to space target flyby in different scenarios.

Keywords: Space target flyby; Tangent-impulse maneuver; Phasing maneuver; Approach maneuver; Optimal orbit maneuver

1. Introduction

Space Target Flyby (STF) is a novel technology, and makes significant contributions to exploration of near Earth space and even the solar system. China's Chang'e-2 satellite flew-by Toutatis, the No. 4179 asteroid in 13th December 2012 (Zhao et al., 2014). NASA's New Horizons mission, aimed at carrying out scientific exploration of Pluto and the Kuiper Belt objects (Guo and Robert, 2005), successfully flied-by Pluto with closest approach in 14th July 2015. Though different in method of orbit realization, the flyby technique could be applied to fast approaching of an on-orbit artificial spacecraft, and execute the missions such as photographing, failure detecting, and information acquisition, etc. The key point of this technology is to determine the transfer orbit with optimal fuel and time assumption.

The problem of two-impulse transfer between two coplanar elliptic orbits has been studied since 1960 s. The equations governing the transfer orbit leading to minimum-cost has been found (Lawden, 1962; Lawden, 1963) and possible solutions discussed in time-open case (Lawden, 1992). The time-closed problem has also been studied (Prussing, 1969; Prussing, 1970; Prussing and Chiu, 1986) and the optimizing equations presented later (Lawden, 1993). Lambert theorem provides a good foundation for orbital determination (Sconzo, 1962). Many researchers have paid attention to Lambert's problem (Battin, 1977; Battin et al., 1978; Battin and Vaughan, 1984; Nelson and Zarchan, 1992). A solution procedure is outlined for the multiple-revolution Lambert problem (MRLP), based on which the minimum-cost, fixed time transfer between two fixed points on coplanar circular orbits is studied (Prussing, 2000). However, the minimum-cost solution is obtained only after calculating all the possible candidate of orbits by Prussing's method. To overcome this deficiency, an algorithm that quickly and efficiently determines the optimal solution has been

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provided (Shen and Tsiotras, 2003). Later, a less mathematically demanding and physically intuitive solution method to Lambert's problem is discussed (Avanzini, 2008), in which the transverse component of eccentricity vector has been used to identify the admissible orbits. Following Avanzini's work, the solution method has been extended to the case of multiple revolutions (He et al., 2010). Another algorithm is developed to find the optimal two-impulse solutions for rendezvous in non-coplanar elliptic orbits, where the cases of between two fixed endpoint and with moving target are considered. This algorithm uses the flight path angle as the iterative parameter for solving a MRLP, and results in computation of at most two points before getting the optimal solution by comparison(Arlulkar and Naik, 2014). Apart from these algorithms based on numerical iteration, a semi-analytical method to solve Lambert's problem by inverting Lagrange flight time equation is provided, in which the problematic 180° transfer is well supported (Wailliez, 2014).

Different from Lambert Problem, with two tangent impulses, a problem of optimal rendezvous between two coplanar elliptic orbits is studied (Zhang and Zhou, 2012; Zhang et al., 2012, 2013, 2014). The transfer orbit is tangent to the initial orbit and the final orbit together in Zhang's work. Based on MRLP, the problem of single-impulse orbit transfer for reaching with a circular orbit target by elliptic orbit chaser is studied (Tan et al., 2010). In the same background, the problem of visiting multiple targets in circle orbit with an elliptic orbit chaser is studied (Zhou et al., 2015). Unlike Tan's work, Zhou divides the trajectory in two parts, phasing and approaching, and imposes that both pulses are executed along track and at the perigee. Besides, the dynamics, control methods and collision avoidance of maneuvering satellites are also researched (Wang and Zhang, 2007; Jiang et al., 2015; Dang et al., 2015; Zhang and Wang, 2015).

In this paper, an engineering practical method is developed to find the optimal solution for the problem of two-tangent-impulse flyby of a space target. Inspired by Zhou's work, the transfer trajectory is divided into two parts, i.e. phasing and approaching. However, the two impulses are not executed at the perigee of the initial orbit, but optimized to minimize the total delta V. The optimal position is determined by mathematical analysis given the condition of long enough flight time. However, the numerical method should be adopted to search the optimal impulse position when the flight time is restricted very short. The organization of this paper is as follows: Section 2 states the problem to be studied; Section 3 provides the method to determine the phasing orbit and approaching orbit as well as the attainable target area and the feasible maneuver position by elliptic approaching orbit. The optimal schemes to arrange the phasing orbit and the approaching orbit are discussed in Section 4. Finally, the simulation study is given in Section 5, followed by conclusions in Section 6.

2. Problem statement

The problem of space target flyby is introduced in this section. A Chaser is arranged on an initial elliptic orbit awaiting order to execute a flyby mission at any time. To realize this mission, the final approaching orbit of the Chaser should pass one point beside the Target's orbit at a given distance, while strict intersection and coplanarity of the two orbits is not a necessary condition. Since this article is aimed at finding the fuel-minimal orbit scheme with tangent impulses, the results will not change if the distance how far the Chaser flies-by the Target be ignored. Therefore, the flyby distance will not be considered in the following context.

Assume that the Target is traveling on its own orbit under the action of gravity, and the Chaser is traveling on an elliptic initial orbit before any maneuver impulses are executed. Before the Chaser flying-by the Target, the Chaser goes through three stages of orbital traveling, i.e. the initial coasting, the phasing and the approaching, along with two impulses are executed when the Chaser switches to the phasing orbit and the approaching orbit respectively. On the purpose of simplicity, the impulse direction is restricted forward or backward along-track, and the two impulses are imposed on the Chaser at the common point of the three orbits, i.e. initial orbit, the phasing orbit and the approaching orbit.

The initial position of the Chaser and the Target are denoted by M_0 and S_0 respectively. Let M be the position where the two impulses are executed, R (R_o or R_i) be that the Chaser flies by the Target, S and K be that the Target passes when the first and the second impulse are executed respectively. The argument of M and R relative to the perigee of the initial orbit are denoted by $f_{M,0}$ and φ_R respectively, and the geocentric transfer angle between them is denoted by ϕ. To describe the local inclination angle of velocity as well as the impulse direction, the local vertical and local inclination (LVLH) frame $oxyz$ is defined. The origin is attached to the mass center of the Chaser, ox is along the vector from Earth center to the mass center of the Chaser, oy is along the circumference of Chaser's orbit, and oz is obtained by taking cross product $x \times y$. Then, the orbital velocity vector lies in xy plane and the local inclination angle of velocity at M, which is denoted by Θ, can be measured from oy axis of the LVLH frame. Fig. 1 shows the geometric sketch map of phasing orbit and approaching orbit.

The phasing guarantees that the Chaser arrives at M while the Target passes K, and approaching guarantees that the Chaser and the Target arrive at the flyby point (i.e. R) together. Table 1 shows the orbital traveling process of the Chaser and the Target.

Obviously, the fuel cost varies with the maneuver position (i.e. M), and this paper is aimed to find an optimal position to minimize the total fuel cost. The phasing and the approaching will be studied independently firstly, and then be taken into consideration together. An optimization