Planetary and Space Science 123 (2016) 4–15

Contents lists available at ScienceDirect

Planetary and Space Science

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

Rendezvous missions to temporarily captured near Earth asteroids

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ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
25 September 2015
Accepted 17 December 2015
Available online 21 January 2016

Keywords:
Temporarily captured objects
Three and four-body problem
Optimal control
Indirect numerical methods

ABSTRACT

Missions to rendezvous with or capture an asteroid present significant interest both from a geophysical and safety point of view. They are key to the understanding of our solar system and are stepping stones for interplanetary human flight. In this paper, we focus on a rendezvous mission with 2006 RH_{120}, an asteroid classified as a Temporarily Captured Orbiter (TCO). TCOs form a new population of near Earth objects presenting many advantages toward that goal. Prior to the mission, we consider the spacecraft hibernating on a Halo orbit around the Earth–Moon's L_2 libration point. The objective is to design a transfer for the spacecraft from the parking orbit to rendezvous with 2006 RH_{120} while minimizing the fuel consumption. Our transfers use indirect methods, based on the Pontryagin Maximum Principle, combined with continuation techniques and a direct method to address the sensitivity of the initialization. We demonstrate that a rendezvous mission with 2006 RH_{120} can be accomplished with low delta-v. This exploratory work can be seen as a first step to identify good candidates for a rendezvous on a given TCO trajectory.

1. Introduction

In this paper we compute delta-v minimal spacecraft transfers from an Earth–Moon (EM) L_2 Halo orbit to rendezvous with temporarily captured Earth orbiters (TCO). All computed transfers are for a 350 kg spacecraft with 22N maximum thrust and 230 s specific impulse, and we impose that the trajectory utilize three or less max thrust boosts.

The only documented Earth TCO, known as 2006 RH_{120}(or from now on simply RH_{120} for brevity) serves as an important test target for our calculations. In addition, rendezvous missions are computed to several simulated TCOs from Granvik et al. (2012).

All transfers are designed using one of the two different gravitational models:

1. First, transfers are computed using the EM circular restricted three-body problem (CR3BP) for the gravitational dynamics, which is justified since Earth TCOs are naturally evolving near the Earth and Moon. For these calculations, the transfer time and precise Halo departure point are treated as free variables to be optimized.
2. Second, the influence of the Sun is included in the dynamics using the Sun-perturbed CR3BP, sometimes known as the Earth–Moon–Sun circular restricted four-body problem (CR4BP). In this case an exact location of the spacecraft is assumed at the moment of asteroid capture, so that a choice of rendezvous location and transfer time determines exactly the departure point from the Halo orbit (dubbed the *synchronization problem* and discussed in detail within).

Many methodologies have been developed over the past decades to design optimal transfers in various scenarios. Due to the complexity of the TCO orbits and the nature of the mission, techniques based on analytical solutions such as in Kluever (2011) for circular Earth orbits are not suitable and we use a numerical approach such as in Chyba et al. (2014a,b). A survey on numerical methods can be found in Conway (2012), and for reasons related to the specifics of our problem we choose to use a deterministic approach based on tools from geometric optimal control versus an heuristic method such as in Besette and Spencer (2006), Pontani and Conway (2013), Vaquero and Howell (2014), and Zhu et al. (2009). All computations are carried out using classical indirect methods based on the Pontryagin Maximum Principle, combined with sophisticated numeric methods and software. The well-known sensitivity to initialization for this type of approach is addressed via a combination of direct methods and continuation techniques.

Validation of our approach can be seen by comparing our work to Dunham et al. (2013), in which the authors develop a low delta-v asteroid rendezvous mission that makes use of a Halo orbit around Earth–Moon L_2. Their situation is different from ours in that they have carefully chosen a idealized asteroid for rendezvous. With a one-year transfer time, the delta-v value they realize is 432 m/s, which is

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http://dx.doi.org/10.1016/j.pss.2015.12.013

comparable to the delta-v values presented here in a less-ideal scenario.

Analysis of all computed transfers strongly suggests that the CR3BP energy may play a role in predicting suitable departure and rendezvous points for low delta-v TCO rendezvous missions. Moreover, we present evidence that TCOs with more planar and more circular orbits tend to yield lower delta-v transfers.

2. Temporarily captured orbiters (TCO), RH_{120}

The motivation for our work is to study asteroid capture missions for a specific population of near Earth objects. The targets, Temporarily Captured Orbiters (TCO), are small asteroids that become temporarily captured on geocentric orbits in the Earth–Moon system. They are characterized as satisfying the following constraints:

- the geocentric Keplerian energy $E_{\text{Earth}} < 0$;
- the geocentric distance is less than three Earth's Hill radii (e.g., $3R_{H,\oplus} \sim 0.03$ AU);
- it makes at least one full revolution around the Earth in the Earth–Sun co-rotating frame, while satisfying the first two constraints.

In regard to the design of a round trip mission, the main advantage of the TCOs lies in the fact that those objects have been naturally redirected to orbit the Earth; which contrasts with recently proposed scenarios to design, for instance, a robotic capture mission for a small near-Earth asteroid and redirect it to a stable orbit in the EM-system, to allow for astronaut visits and exploration (e.g. the Asteroid Redirect Mission (ARM)).

RH_{120} is a few meter diameter near Earth asteroid, officially classified as a TCO. RH_{120} was discovered by the Catalina Sky Survey on September 2006. Its orbit from June 1, 2006 to July 31, 2007 can be seen in Figs. 1 and 2, generated using the Jet Propulsion Laboratory's HORIZONS database which gives ephemerides for solar-system bodies. The period June 2006–July 2007 was chosen to include the portion of the orbit within the Earth's Hill sphere with a margin of about 1 month. We can also observe that RH_{120} comes as close as 0.72 lunar distance (LD) from Earth–Moon barycenter (Fig. 3).

In Granvik et al. (2012), the authors investigate a population statistic for TCOs. Their work is centered on the integration of the

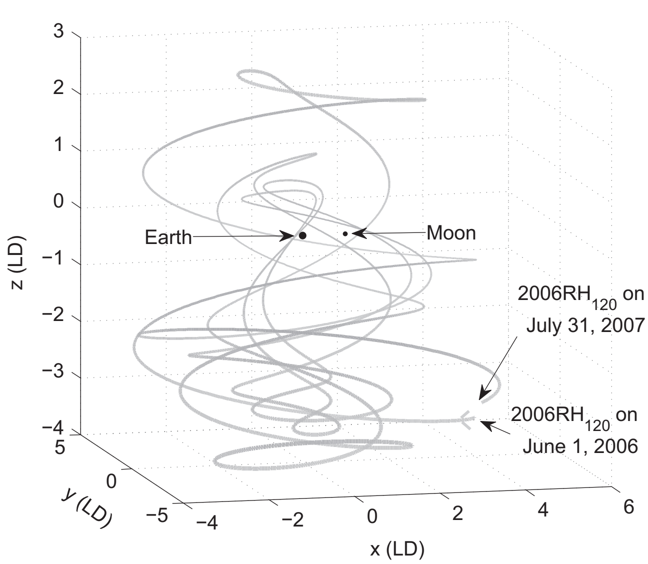

Fig. 1. Orbit of RH_{120} in the Earth–Moon CR3BP rotating reference frame.

trajectories for 10 million test-particles in space, in order to classify which of those become temporarily captured by the Earth's gravitational field – over eighteen-thousand of which do so. Their results suggests that RH_{120} is not the only TCO and that it is relevant to compute a rendezvous mission to RH_{120} to gain insight whether TCOs can be regarded as possible targets for transfers with small fuel consumption, and thus cost.

The choice of targets for our rendezvous mission sets us apart from the existing literature where transfers are typically designed between elliptic orbits in the Earth–Moon or other systems (Caillau et al., 2012; Mingotti et al., 2011) and (Mingotti et al., 2010), or to a Libration point (Folta et al., 2013; Picot, 2012) and (Ozimek and Howell, 2010; Vaquero and Howell, 2014). Rendezvous missions to asteroids in the inner solar system can be found in Dunham et al. (2013) and Kuninaka (2005) but they concern asteroids on elliptic orbits which is not the case for us since TCOs are present complex orbits and therefore require a different methodology.

Our assumption on the hibernating location for the spacecraft, a Halo orbit around the Earth–Moon unstable Libration points L_2, is motivated in part from the successful Artemis mission (Russell and Angelopoulos, 2013; Sweetser et al., 2011) and in part from the constraint on the duration of the mission, mostly impacted by the time of detection of the asteroid. Indeed, the Artemis mission demonstrated low delta-v station keeping on Halo orbits around L_1 and L_2.

3. Optimal control problem and numerical algorithm

3.1. Equations of motion

We introduce two models, the circular restricted three-body problem (CR3BP) (Koon et al., 2011) is first used to approximate the spacecraft dynamics and then we refine our calculations with a Sun-perturbed model (CR4BP). The first approximation is justified by the fact that a TCO can be assumed of negligible mass, and that the spacecraft evolving in the TCO's temporary capture space is therefore attracted mainly by two primary bodies, the Earth and the Moon.

The CR3BP model is well known, and we briefly recall some basic properties and notation which is useful for the remainder of the paper. We denote by $(x(t), y(t), z(t))$ the spatial position of the spacecraft at time t. In the rotating coordinates system, and under proper normalization (see Table 1), the primary planet identified here to the Earth, has mass $m_1 = 1-\mu$ and is located at the point $(-\mu, 0, 0)$; while the second primary, identified to the Moon, has a mass of $m_2 = \mu$ and is located at $(1-\mu, 0, 0)$. The distances of the spacecraft with respect to the two primaries are given by $\varrho_1 = \sqrt{(x+\mu)^2+y^2+z^2}$ and $\varrho_2 = \sqrt{(x-1+\mu)^2+y^2+z^2}$ respectively. The potential and kinetic energies, respectively V and K, of the system are given by

$$V = \frac{x^2+y^2}{2} + \frac{1-\mu}{\varrho_1} + \frac{\mu}{\varrho_2} + \frac{\mu(1-\mu)}{2}, \quad K = \frac{1}{2}(\dot{x}^2+\dot{y}^2+\dot{z}^2). \tag{1}$$

We assume a propulsion system for the spacecraft is modeled by adding terms to the equations of motion depending on the thrust magnitude and some parameters related to the spacecraft design. The mass of the spacecraft is denoted by m and the craft's maximum thrust by $T_{\max}$. Under those assumptions, we have the following equations of motion:

$$\ddot{x} - 2\dot{y} = \frac{\partial V}{\partial x} + \frac{T_{\max}}{m} u_1, \quad \ddot{y} + 2\dot{x} = \frac{\partial V}{\partial y} + \frac{T_{\max}}{m} u_2, \quad \ddot{z} = \frac{\partial V}{\partial z} + \frac{T_{\max}}{m} u_3 \tag{2}$$

where $u(\cdot) = (u_1(\cdot), u_2(\cdot), u_3(\cdot))$ is the control, and satisfies the