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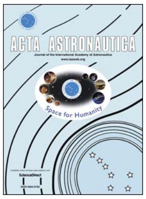

Asteroid retrieval missions enabled by invariant manifold dynamics

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ABSTRACT

Near Earth Asteroids are attractive targets for new space missions; firstly, because of their scientific importance, but also because of their impact threat and prospective resources. The asteroid retrieval mission concept has thus arisen as a synergistic approach to tackle these three facets of interest in one single mission. This paper reviews the methodology used by the authors (2013) in a previous search for objects that could be transported from accessible heliocentric orbits into the Earth's neighbourhood at affordable costs (or Easily Retrievable Objects, a.k.a. EROs). This methodology consisted of a heuristic pruning and an impulsive manoeuvre trajectory optimisation. Low thrust propulsion on the other hand clearly enables the transportation of much larger objects due to its higher specific impulse. Hence, in this paper, low thrust retrieval transfers are sought using impulsive trajectories as first guesses to solve the optimal control problem. GPOPS-II is used to transcribe the continuous-time optimal control problem to a nonlinear programming problem (NLP). The latter is solved by IPOPT, an open source software package for large-scale NLPs. Finally, a natural continuation procedure that increases the asteroid mass allows to find out the largest objects that could be retrieved from a given asteroid orbit. If this retrievable mass is larger than the actual mass of the asteroid, the asteroid retrieval mission for this particular object is said to be feasible. The paper concludes with an updated list of 17 EROs, as of April 2016, with their maximum retrievable masses by means of low thrust propulsion. This ranges from 2000 tons for the easiest object to be retrieved to 300 tons for the least accessible of them.

1. Introduction

Recently, significant interest has been devoted to the understanding of the minor bodies of the Solar System, including near-Earth and main belt asteroids and comets. NASA, ESA and JAXA have conceived a series of missions to obtain data from such bodies, having in mind that their characterisation not only provides a deeper insight into the Solar System but also represents a technological challenge for space exploration. Near Earth objects (NEOs), in particular, have also stepped into prominence because of two important aspects: they are among the easiest celestial bodies to reach from the Earth and they may represent a threat to our planet.

As witnesses of the early Solar System, NEOs could cast some light into the unresolved questions about the formation of planets from the pre-solar nebula, and perhaps settle debates on the origin of water on Earth or panspermian theories, among others (e.g., [1,2]). This scientific importance has translated into an increasing number of robotic probes sent to NEOs, and many more planned for the near future. Their low gravity wells have also identified them as the only “planetary” surface that can be visited by crewed missions under NASA's flexible path plan [3]. Science, however, is not the only interest of these objects and mission concepts exploring synergies with science, planetary protection and space resources utilization have started to be uttered. Examples of this are recent NASA and ESA studies on a kinetic impact demonstration mission on a binary object, DART and AIM [4].

Proposed technologies and methods for the deflection of Earth-impacting objects have experienced significant advances, along with increasing knowledge of the asteroid population. While initially devised to mitigate the hazard posed by global impact threats, the current impact risk is largely posed by the population of small undiscovered objects [5], and thus methods have been proposed to provide subtle changes to the orbits of small objects, as opposed to large-scale interventions such as the use of nuclear devices [6]. This latter batch of deflection methods, such as the low thrust tugboat [7], gravity tractor [8], ion beam [9] or small kinetic impactor [10] are moreover based on currently proven space technologies. They can therefore render the apparently ambitious scenario of manipulating asteroid trajectories a likely option for the near future.

On the other hand, the in-situ utilisation of resources in space has long been suggested as the means of lowering the cost of space

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missions, for example, by providing bulk mass for radiation shielding or manufacturing propellant for interplanetary transfers [11]. The development of technologies for in-situ resource utilisation (ISRU) could become a potentially disruptive innovation for space exploration and utilisation and, for example, enable large-scale space ventures that could today be considered far-fetched, such as large space solar power satellites, sustaining communities in space or geoengineering [12]. Although the concept of asteroid mining dates back to the early rocketry pioneers [13], evidences of a renewed interest in the topic can be found in the growing body of literature [14–16], as well as in high profile private enterprise ventures such as by Planetary Resources Inc. [17].

With regards to the accessibility of asteroid resources, recent work by Sanchez and McInnes [18] discusses how a substantial quantity of resources could potentially be accessed at relatively low energy; on the order of 10^{14} kg of material could be harvested at an energy cost lower than that required to access resources from the surface of the Moon. More importantly, asteroid resources could be accessed across a wide spectrum of energies, and thus, current technologies could be adapted to return to the Earth's neighbourhood small objects from 2 to 30 m diameter for scientific exploration and resource utilisation purposes [18].

Together with the availability of small objects in the Earth's orbital vicinity, recent advances in invariant manifold dynamics (e.g., [19]) provide the necessary tools to design surprisingly low energy trajectories, which may in turn enable the possibility to retrieve small celestial objects from their natural heliocentric trajectories. An asteroid retrieval mission envisages a spacecraft that rendezvous with an asteroid, lassos it and then hauls it back to Earth neighbourhood [20]. Current interplanetary spacecraft however have masses on the order of 10^3 kg, while an asteroid of 10 m diameter will most likely have a mass of the order of 10^6 kg. Hence, moving such a large object, with the same ease that scientific payload is transported today, would demand propulsion systems order of magnitudes more powerful and efficient; or alternatively, orbital transfers orders of magnitude less demanding than those to reach other planets in the Solar System. Hence, it is here that invariant manifolds associated with periodic and quasi-periodic orbits near the Sun-Earth L_1 and L_2 points provide important pathways to design extremely low energy transfers.

This paper reports on the latest results from AsteroidRetrieval Project (PIEF-GA-2012-330649[1]). The project aimed at gaining further understanding of the current and near-term capability to modify the asteroid's trajectory by judicious use of orbital mechanics. More particularly, the project focused on exploiting the subtle underlying dynamics of multi-body systems, in order to benefit from simultaneous gravitational interactions between the Sun, Earth and Moon to find effective means to transport asteroid material to the Earth's vicinity. The paper will also review the earlier work by García Yárnoz et al. [21], which presented a new sub-category of NEOs in an attempt to provide an objective and quantifiable classification of asteroids that could be transported from accessible heliocentric orbits into the Earth's neighbourhood at affordable costs.

Section 2 will briefly describe fundamental aspects of low energy transport phenomena in multi-body systems. The methodology used to distinguish between those asteroids that can be "*easily*" transported back to Earth vicinity and those that cannot is then discussed in Section 3, and was originally presented in García Yárnoz et al. [21]. The list of potential candidates for retrieval, as of 12th April 2016, is given in Section 4, together with their optimized impulsive capture trajectories. The latter set of solutions is then used as first guesses to solve the low thrust optimal control problem, which is described in Section 5. The opportunities and potential retrieval capability enabled by invariant manifold dynamics associated with periodic and quasi-periodic orbits in the Sun-Earth system is finally discussed and compared with published results from NASA's Asteroid Redirect Robotic Mission (ARRM) [22] (Section 6).

2. Low energy transport conduits

Solar system transport phenomena, such as the rapid orbital transitions experienced by comets Oterma and Gehrels 3, from heliocentric orbits outside Jupiter orbital radius to orbits enclosed by it [23], or the Kirkwood gaps in the main asteroid belt, are some manifestations of the sensitivities of multi-body dynamics. The hyperbolic invariant manifold structures associated with periodic orbits near the L_1 and L_2 collinear points of the Three Body Problem provide a mathematical representation of the mechanism that controls the aforementioned transport phenomena [23–25]. The same underlying principles that enable these transport phenomena allow also for excellent opportunities to design incredibly low energy transfers.

2.1. Periodic and quasi-periodic orbits

This paper thus focuses on the dynamics near the Sun-Earth L_1 and L_2 points, as they are the gate keepers for ballistic capture of asteroids in the Earth's vicinity. The paper assumes the motion of the spacecraft and asteroid under the gravitational influence of the Sun and Earth within the framework of the Circular Restricted Three Body Problem (CR3BP). Thus, in a synodic reference frame centred in the barycentre of the Sun-Earth system, the unpropelled motion of the asteroid-hauling spacecraft can be modelled by [26,27]:

$$\ddot{x} = 2\dot{y} + \frac{\partial \Omega}{\partial x}$$
$$\ddot{y} = -2\dot{x} + \frac{\partial \Omega}{\partial y}$$
$$\ddot{z} = \frac{\partial \Omega}{\partial y} \qquad (1)$$

where the potential function Ω is defined as:

$$\Omega = \frac{x^2 + y^2}{2} + \frac{1-\mu}{r_S} + \frac{\mu}{r_E} \qquad (2)$$

where r_S and r_E are the distances to the Sun and the Earth respectively and the mass parameter μ considered in the paper is $3.0032080443 \times 10^{-6}$, which neglects the mass of the Moon. Note that the usual normalised units are used when citing Jacobi constant values [26].

Together with the five well-known equilibrium positions of Eq. (1), from which L_1 and L_2 points are the two closest to the Earth, respectively defined as in Fig. 1, an extensive catalogue of bounded motion near these equilibria has also been comprehensively mapped (e.g., [28]). The principal families of these are planar and vertical families of Lyapunov periodic orbits, quasi-periodic Lissajous orbits, and periodic and quasi-periodic halo orbits [29]. Although, some other families of periodic orbits can be found by exploring bifurcations in the aforementioned main families [28]. This paper however presents capture or retrieval opportunities enabled by three classes of periodic motion near the Sun-Earth L_1 and L_2 points: These are planar and vertical Lyapunov and halo orbits, from now on referred to as a whole as libration point orbits (LPOs).

Ideally, an asteroid transported into one of these orbits would remain near the libration point for an indefinite time. In practice, however, these orbits are unstable, and an infinitesimal deviation

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[1] http://cordis.europa.eu/project/rcn/108052_en.html