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Control of asteroid retrieval trajectories to libration point orbits

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ABSTRACT

The fascinating idea of shepherding asteroids for science and resource utilization is being considered as a credible concept in a not too distant future. Past studies identified asteroids which could be efficiently injected into manifolds which wind onto periodic orbits around collinear Lagrangian points of the Sun-Earth system. However, the trajectories are unstable, and errors in the capture maneuver would lead to complete mission failure, with potential danger of collision with the Earth, if uncontrolled. This paper investigates the controllability of some asteroids along the transfers and the periodic orbits, assuming the use of a solar-electric low-thrust system shepherding the asteroid. Firstly, an analytical approach is introduced to estimate the stability of the trajectories from a dynamical point of view; then, a numerical control scheme based on a linear quadratic regulator is proposed, where the gains are optimized for each trajectory through a genetic algorithm. A stochastic simulation with a Monte Carlo approach is used to account for different perturbed initial conditions and the epistemic uncertainty on the asteroid mass. Results show that only a small subset of the considered combinations of trajectories/asteroids are reliably controllable, and therefore controllability must be taken into account in the selection of potential targets.

1. Introduction

Recent studies have suggested that near-Earth asteroids (NEAs) could be harvested and exploited for resources [1]. It is in fact well known that some NEAs are potentially full of strategic resources for in-space utilization (e.g., future in-orbit construction of space components) or even precious metals that may find interest in terrestrial commodity markets [2]. Harvesting asteroids will without doubt be costly; however more and more space companies have shown interest in this idea, as the benefit might overcome the cost in a relatively near-term [3].

A scenario that seems, arguably, as directly borrowed from the sci-fi, that of a rendezvous with an asteroid, to lasso it and haul it back to Earth neighborhood, was recently announced as a mission concept under serious consideration by NASA[1]. However, evidence on the interest of the concept can also be found in the preceding growth of scientific output on the concept [4–8].

A scenario which was investigated in the last few years consists of modifying the NEA's orbit such as to capture it into a libration orbit of the Sun-Earth system [9] – halo, planar or vertical Lyapunov. The asteroid motion may then remain indefinitely on a periodic orbit near a libration point, which is relatively accessible from Earth, or alternatively transferred to other regions of the cislunar space (e.g., Moon orbit [7]).

Recently, García et al. [9] identified asteroids which could be injected into manifolds which wind onto periodic orbits around collinear Lagrangian points of the Sun-Earth system, by means of two low-cost capture maneuvers.

However, it is known that the considered periodic orbits as well as the associated manifolds are highly unstable, and small errors in the capture maneuver would bring to departure of the asteroid from the reference trajectory in a short time. The intrinsic risk of this scenario is the possibility to divert the asteroid's trajectory in a way that it could impact the Earth.

This paper therefore aims to provide a more accurate account of the towing maneuver required to place an asteroid on a libration point orbit near the Sun-Earth L_1 or L_2 points. The paper investigates the optimal control of the towing spacecraft during two distinct phases: firstly, at Earth approach, when the asteroid is still far but slowly approaching the Earth following a stable invariant manifold trajectory; secondly, after the insertion into a target libration orbit, as station keeping is still necessary in order to keep the asteroid from drifting away and causing any potential concern for the Earth. By means of a Monte-Carlo analysis, we quantify the control margins necessary to ensure that the asteroid does not divert irreparably on a different trajectory, and hence becomes a risk for the Earth. In addition, a range of potentially useful target orbits near the libration points are analyzed in terms of

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[1] http://www.nasa.gov/sites/default/files/files/AsteroidRedirectMission_FS_508_2.pdf [retrieved 4 Sep 2013]

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0094-5765/

Nomenclature

$\mathbf{A}$	Matrix of partial derivatives of the dynamical system with respect the states (i.e. Jacobian)
$\mathbf{B}$	Matrix of partial derivatives of the dynamical system with respect the controls
g_0	Standard gravity acceleration, m/s^2
H	Absolute magnitude
$\mathbf{I}$	Identity matrix
I_{sp}	Specific impulse, s
I_{tran}	Change of linear momentum
J	Cost function
$\mathbf{K}$	Control gain matrix
$\mathbf{M}$	Monodromy matrix
m	Mass, kg
m_{ast}	Asteroid mass, kg
$m_{s/c}$	Spacecraft mass, kg
N	Number of trials
$P_{SEP,max}$	Spacecraft power, kW
p	Success rate
p_v	Asteroid's albedo
$\mathbf{Q}$	State weights in cost function
$\mathbf{R}$	Control weights in cost function
$\mathbf{r}$	Position vector in the synodic frame
r_E	Distance to the Earth
r_S	Distance to the sun
$\mathbf{s}$	State vector of a reference trajectory
t	Time
t_0	Initial time
T	Period of a periodic orbit
T_{max}	Maximum thrust, N
T_x, T_y, T_z	Thrust components, N
$\mathbf{u}$	Control vector
$\mathbf{v}$	Velocity vector in the synodic frame
$\delta\mathbf{s}$	Error in state $\mathbf{s}$, km and km/s
Δv	Change in velocity, m/s
δm_{ast}	Error in the asteroid mass, kg
δv_{tran}	Error in velocity
η	Average expansion of a hyperbolic trajectory
η_{PO}	Average expansion of a periodic orbit
η_{SEP}	Efficiency of the solar electric propulsion system
x, y, z	Components of position vector in synodic frame
$\lambda_{\mathbf{B}}$	Eigenvalue of matrix $\mathbf{B}$
μ	Mass parameter of the circular restricted three-body problem
ρ	Asteroid density, kg/m^3
σ	Standard deviation
$\mathbf{\Phi}$	State transition matrix
Ω	Potential function of the circular restricted three-body problem

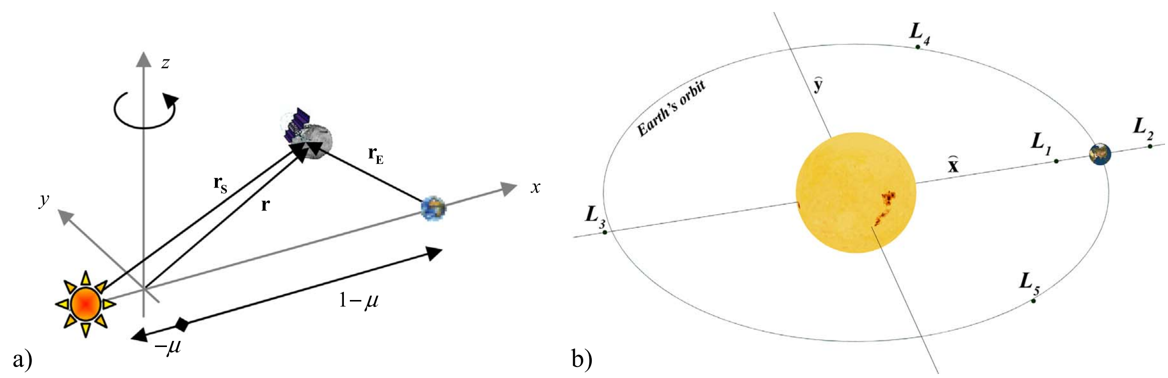

Fig. 1. Schematic of (a) the CR3BP and (b) its equilibrium points.

station-keeping costs and safety.

In this paper, we will quantify the uncertainties of the state vector of the asteroid-spacecraft system, after the capture maneuvers, due to epistemic uncertainty on the mass of the asteroid. Given these perturbed states, a feedback control based on a linear quadratic regulator will be used to pilot a low-thrust engine to bring the system on the reference trajectory towards the final periodic orbit. A Monte Carlo approach will be used to generate a variety of different initial perturbed states and obtain some statistical results on the controllability of each combination of asteroid and trajectory.

2. Asteroid retrieval trajectories

2.1. Equations of motion

The trajectories in this paper are modeled through the equations of motion of the normalized circular restricted three-body problem [10] (CR3BP) in a Sun-Earth synodic reference frame:

$$\begin{aligned} \ddot{x} &= 2\dot{y} + \frac{\partial \Omega}{\partial x} + \frac{T_x}{m} \\ \ddot{y} &= -2\dot{x} + \frac{\partial \Omega}{\partial y} + \frac{T_y}{m} \\ \ddot{z} &= \frac{\partial \Omega}{\partial y} + \frac{T_z}{m} \end{aligned} \tag{1}$$

with:

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

where $\mathbf{r} = [x \;\; y \;\; z]^T$ is the position vector with respect to the origin in the synodic frame, r_S, r_E are the distances to the Sun and the Earth respectively and $\mu = 3.0032 \times 10^{-6}$ for the Sun-Earth system. $\mathbf{u} = \left[T_x \;\; T_y \;\; T_z\right]^T$ is the control (i.e. thrust) vector, and m is the mass of the spacecraft and the asteroid, which are supposed to be tightly connected as a single point mass (Fig. 1a).

As is well known, when the thrust vector is zero, the system in Eq. (1) has five equilibrium positions (see Fig. 1b). The Sun-Earth L_1 and L_2 points are of particular interest for us, since they are the