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Heliocentric trajectory analysis of Sun-pointing smart dust with electrochromic control

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Abstract

A smart dust is a micro spacecraft, with a characteristic side length on the order of a few millimeters, whose surface is coated with electrochromic material. Its orbital dynamics is controlled by exploiting the differential force due to the solar radiation pressure, which is obtained by modulating the reflectivity coefficient of the electrochromic material within a range of admissible values. A significant thrust level can be reached due to the high values of area-to-mass ratio of such a spacecraft configuration. Assuming that the smart dust is designed to achieve a passive Sun-pointing attitude, the propulsive acceleration due to the solar radiation pressure lies along the Sun-spacecraft direction. The aim of this paper is to study the smart dust heliocentric dynamics in order to find a closed form, analytical solution of its trajectory when the reflectivity coefficient of the electrochromic material can assume two values only. The problem is addressed by introducing a suitable transformation that regularizes the spacecraft motion and translates the smart-dust dynamics into that of a linear harmonic oscillator with unitary frequency, whose forcing input is a boxcar function. The solution is found using the Laplace transform method, and afterwards the problem is generalized by accounting for the degradation of the electrochromic material due to its exposition to the solar radiation. Three spacecraft configurations, corresponding to low, medium and high performance smart dusts, are finally used to quantify the potentialities of these advanced devices in an interplanetary mission scenario.

Keywords: Smart dust; Spacecraft-on-a-chip; Electrochromic control; Radial thrust

1. Introduction

Technological advances in the miniaturization process of components used for space applications make potentially possible the realization of micro spacecraft, characterized by dimensions comparable to that of a common microchip, that is, on the order of some centimeters or even some millimeters (Atchison and Peck, 2010). These devices have an area-to-mass ratio much greater than that of typical spacecraft, with the consequence that their orbital dynamics is highly influenced, and in some cases dominated, by a number of effects (including solar radiation pressure, atmospheric drag, electrostatic forces etc.) that are usually thought of as simple perturbative forces for conventional space vehicles (Colombo and McInnes, 2011; Colombo et al., 2012).

Micro spacecraft represent a very attractive option for future space missions (especially in a planetary mission scenario) due their unique characteristics, such as the low manufacturing costs, the cheap launch costs related to the possibility of deployment from a CubeSat or as piggy back on more conventional spacecraft, the high spatial coverage offered by the potential large number of objects that can be launched and operated simultaneously (Colombo and McInnes, 2012). To maximize their effectiveness, these devices should be equipped with suitable means, capable of

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Nomenclature

A	smart dust effective reflective area, [cm^2]
$\mathcal{A}, \mathcal{B}$	dimensionless auxiliary function, see Eqs. (17) and (18)
$\boldsymbol{a}_P$	acceleration due to radiation pressure, [mm/s^2]
a_c	spacecraft characteristic acceleration, [mm/s^2]
$\mathcal{E}$	specific mechanical energy of osculating orbit, [km^2/s^2]
H	Heaviside step function
m	smart dust total mass, [g]
O	Sun's center-of-mass
p	osculating orbit's semilatus rectum, [au]
P	solar radiation pressure, [Pa]
$\boldsymbol{r}$	position vector, with $r = \|\boldsymbol{r}\|$, [au]
s	complex variable
T	degradation half-life, [year]
$\mathcal{T}(O; r, \theta)$	polar heliocentric reference frame
$\boldsymbol{v}$	inertial velocity vector, [km/s]
β	lightness number, see Eq. (2)
ϵ	degradation parameter, [$year^{-1}$]
η	reflectivity coefficient
θ	polar angle, [deg]
$\mu_\odot$	Sun's gravitational parameter, [km^3/s^2]
ρ	dimensionless auxiliary variable, see Eq. (6)
ϕ	apse line rotation angle, [deg]

Subscripts

0	initial, parking orbit
$\oplus$	one astronomical unit
esc	escape
fin	final orbit
max	maximum
min	minimum

Superscripts

$\cdot$	time derivative
$'$	derivative w.r.t. θ
$\sim$	dimensionless variable

modifying their orbital dynamics. An interesting solution is to cover the micro spacecraft surface with electrochromic material (Lücking et al., 2012; Lücking et al., 2010; Colombo et al., 2013), which is able to change its optical properties on application of a voltage. Accordingly, and accounting for their microscopic dimensions, such devices are also termed Smart Dusts (SDs) (Colombo and McInnes, 2011).

The orbital dynamics of SDs have been studied by Colombo and McInnes (2011), Colombo and McInnes (2012) and Colombo et al. (2012) by investigating the combined effects caused by the solar radiation pressure, atmospheric drag and Earth's oblateness in a planetary mission scenario. In this context, SDs with electrochromic coatings have also been suggested as a solution to extend the mission lifetime. In particular, a simple control law with a bang-bang control, similar to the time-optimal control of a linear oscillator, is discussed by Lücking et al. (2012) and Colombo et al. (2013), while Lücking et al. (2010) propose an artificial potential field control algorithm that uses a reflectivity change twice per orbit.

The use of micro spacecraft, and so of SDs, is potentially a feasible option also within a heliocentric mission scenario. In this respect the original paper by Atchison and Peck (2010) contains some interesting ideas on possible practical application of those small spacecraft. For example, Atchison and Peck (2010) point out that a micro spacecraft could be used to maintain suitable non-Keplerian (or even displaced) orbits in the vicinity of Earth, or to reach a Solar System escape condition. Note, however, that the use of either a single or multiple micro spacecraft for a deep space mission implies that the characteristic distances between the SDs are at least an order of magnitude greater than those necessary within a planetocentric range. This may represent a serious problem due to the limited capabilities of data transmission (in terms of maximum allowable range) between two SDs or one SD and the Earth (or the mothership used for orbital deployment).

In this paper the heliocentric orbital dynamics and control of a SD is investigated from a new viewpoint, aimed at obtaining analytical expressions for its deep space trajectory. To this end the SD is designed to be passively Sun-pointing, while its orbital dynamics exploits the propulsive effect of the solar radiation pressure to produce a purely (outward) radial thrust, i.e. a propulsive thrust aligned with the Sun-spacecraft direction. The analysis is conducted under the assumption that the reflectivity coefficient of the electrochromic material, which covers the SD surface, can take two values only. The SD dynamics is first described using an extension of the Bürdet-Ferrándiz regularization method. As a result, the SD heliocentric trajectory can be calculated analytically for a generic control law in the form of a boxcar function. Finally the degradation effect of the material is accounted for by means of a simplified model in which the SD reflectivity reduces with time according to an exponential decreasing law. A closed form solution to the SD trajectory is found even in this more complex case.

2. Smart dust heliocentric dynamics

Consider a SD spacecraft, characterized by a mass m and an effective area A, the latter being equal to the projection of the surface exposed to the solar radiation onto a