RECONFIGURATION MANEUVERS FOR SWARMS OF HIGH AREA-TO-MASS RATIO SPACECRAFT

Giorgio Mingotti(1) and Colin McInnes(2)
(1)(2)*Advanced Space Concepts Laboratory, Department of Mechanical & Aerospace Engineering, University of Strathclyde, 75 Montrose Street, G1 1XJ Glasgow, United Kingdom.*
e-mail: giorgio.mingotti@strath.ac.uk, colin.mcinnes@strath.ac.uk

Keywords: *Relative Motion, Solar Radiation Pressure, Femto-Spacecraft, Electrochromic Control.*

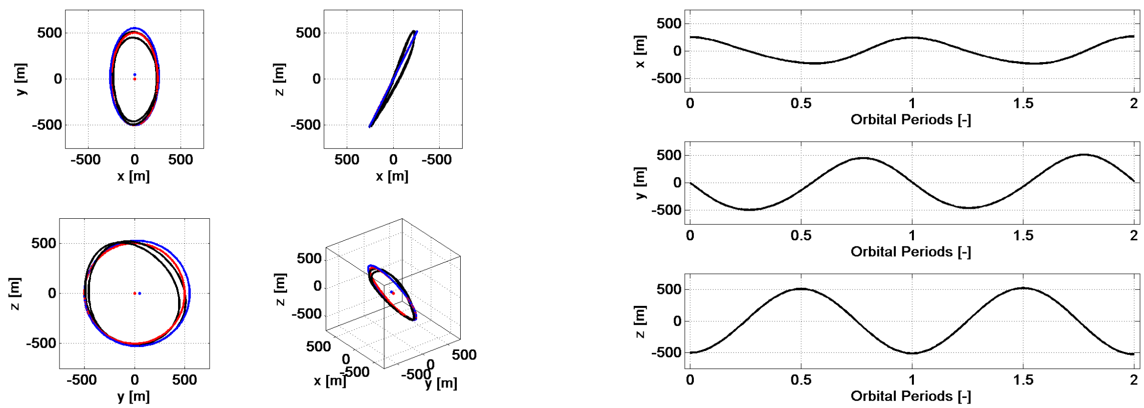
ABSTRACT

Reconfiguration maneuvers for relative motion are investigated in this work, assuming High Area-to-Masso Ratio (HAMR) femto-spacecraft. Considering the exact J_2 nonlinear relative dynamics, an optimal control problem is formulated to accomplish the maneuvers. A continuous control acceleration is applied to the system orbital- and attitude- dynamics via a propellant-free approach, which exploits differential solar radiation pressure by means of electrochromic coating. Thanks to the advances in miniaturised technology, a great number of electromechanical devices can be manufactured and deployed at low cost with active sensors on-board.

The recent developments in spacecraft design exploiting miniaturised electromechanical systems with sensing, computing, bi-directional communicating and micro-power functions have enabled a new class of low-cost, low-weight micro-scale spacecraft suitable for use in swarm applications. Current concepts for functional devices in space have been designed by exploiting existing capabilities, such as satellite-on-a-chip [1]. Distributed devices for Earth observation and communication, autonomous on-orbit self-assembly, diagnostic or environmental detection in the proximity of a large satellite are among the prospective missions that may be enabled. The concept of a swarm of separated elements cooperating coherently enables, for example, the implementation of extremely large aperture radio frequency or optical antennae. These elements would be free-flying in space, either controlled by active or natural forces for each element to stay within a prescribed volume.

The last few decades have seen a growing interest in space missions for remote sensing of the Earth. Numerous missions carrying active and passive sensors for military and civil applications have been implemented. Different kinds of sensors are currently available to obtain a complete set of information useful for a plethora of applications (i.e., atmospheric gas monitoring, landslide control, polar ice monitoring, harbour monitoring, etc.). However, due to the high overall system complexity of space missions, the raw data products can only be obtained at a relatively high cost. This reduces the diffusion and the exploitation of such raw data, especially for civil applications, where Earth-based solutions often result to be cheaper (i.e., terrestrial monitoring of the environment). The aim of this paper is to propose a novel concept for cost effective space missions in order to make remote sensed data accessible to a broader user community.

The exploitation of orbital dynamics at small-length scale and so high area-to-mass ratio requires entirely new techniques for modelling and relative motion control. Solar radiation pressure and aerodynamic drag may become dominant with respect to the Earth's gravity [2]. Assuming the femto-devices are coated with an electrochromic material, the relative motion within the swarm is continuously controlled via the modulation of differential solar radiation pressure $dc_r a_{srp}$: the optical properties of the elements change when an electrical current is applied [3]. A propellant-free



(a) Deputy spacecraft trajectory, controlled dynamics. (b) Relative coordinates evolution, controlled dynamics.

Figure 1. Orbit amplitude and centre shift reconfiguration maneuver.

control method is developed to design and maintain the relative orbits of the swarm. The dynamics is initially based on the linearised formulation of the relative motion of - for a sake of clarity - only two femto-spacecraft flying in close proximity, assuming they are in low, circular orbits around a spherical Earth. Then the dynamical model is extended to include the perturbation caused by the Earth's oblateness[4] and to consider multiple spacecraft; therefore, the exact nonlinear J_2 relative dynamics for for each spacecraft is assumed as follows:

$$\begin{aligned}
\ddot{x}-2\dot{y}\omega_z+x(\eta_d^2-\omega_z^2)+y\alpha_z+z\omega_x\omega_z+(\xi_d-\xi)s_i s_\theta-r(\eta_d^2-\eta^2) &= +\sigma d c_r a_{srp}\cos(\alpha)\cos(\delta)\\
\ddot{y}+2\dot{x}\omega_z-2\dot{z}\omega_x+x\alpha_z+y(\eta_d^2-\omega_z^2-\omega_x^2)-z\alpha_x+(\xi_d-\xi)s_i c_\theta &= -\sigma d c_r a_{srp}\sin(\alpha)\cos(\delta)\\
\ddot{z}-2\dot{y}\omega_x+x\omega_x\omega_z+y\alpha_x+z(\eta_d^2-\omega_x^2)+(\xi_d-\xi)c_i &= +\sigma d c_r a_{srp}\sin(\delta)
\end{aligned}$$

An optimal control problem has been formulated via an indirect approach, with the aim of finding the optimal control law history expressed in polar coordinates.

A preliminary reconfiguration maneuver with the aim of changing the amplitude and of shifting the centre of a PCO is shown in Figure 1. Starting from an amplitude of 500 m, the deputy micro-spacecraft is driven to a larger relative orbit, with an amplitude of 525 m. Moreover, starting from an initial location of the centre along the y axis, the deputy femto-spacecraft is driven to a relative orbit, with a centre location shifted by 25 m. The maneuver time is set equal to 2 orbital periods.

References

[1] Atchison, J. A. and Peck, M. "A Millimeter-Scale Lorentz-Propelled Spacecraft." "Proceedings of the AIAA Guidance, Navigation, and Control Conference," Vol. 5. 2007.

[2] Hamilton, D. P. and Krivov, A. V. "Circumplanetary Dust Dynamics: Effects of Solar Gravity, Radiation Pressure, Planetary Oblateness, and Electromagnetism." Icarus, Vol. 123, No. 2, pp. 503–523, 1996.

[3] Lucking, C., Colombo, C., and McInnes, C. R. "Electrochromic Orbit Control for Smart-Dust Devices." Journal of Guidance, Control, and Dynamics, Vol. 35, 2012.

[4] Xu, S. and Wang, D. "Nonlinear Dynamic Equations of Satellite Relative Motion Around an Oblate Earth." Journal of Guidance, Control, and Dynamics, Vol. 31, No. 5, 2008.