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ScienceDirect

Advances in Space Research 60 (2017) 14–27

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Guidance of magnetic space tug

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Received 5 September 2016; received in revised form 3 March 2017; accepted 28 March 2017
Available online 5 April 2017

Abstract

Magnetic tugging of a target satellite without thrust capacity can be interesting in various contexts, as for example End-Of-Life management, or to complete launchers capabilities. The aim is to gradually modify the orbit of the target by constantly exerting on it a magnetic force. To do so, the chaser is assumed equipped with a steerable magnetic dipole, able to create both forces and torques on the magnetic torque rods carried by the target. The chaser is also supposed to carry electric thrusters, creating a continuous force which modifies the orbit of the whole formation composed of chaser and target.

The relative motions of both satellites are derived, in order to assess the feasibility of such a concept. Relative configuration (attitudes and position) trajectories are derived, which are compliant with the dynamics, and enable the chaser to tug the target.

Considering targets in Low Earth Orbit (LEO), the magnetic field of the Earth is taken into account, modeled by the International Geomagnetic Reference Field (IGRF). The position of the magnetic torque rod of the target may not be located at its center of mass. This lever-arm is taken into account in the dynamics.

As for every Electro-Magnetic Formation Flight concept developed in the literature, satellites involved in magnetic tugging are constantly subjected to torques, created by the Earth magnetic field and by the magnetic fields created by the other satellites in the formation. In this study, the solution chosen to face this problem is to take into account the attitude equilibrium of the satellites early in the guidance phase, in order to avoid having to wave the dipole, as it is generally done.

Promising results are presented for different types of orbit, showing that the concept could be feasible in many different scenarios.

Keywords: Space tug; Electromagnetic formation flying; Active debris removal

For a given vector $\mathbf{x}, x$ is the norm of the vector, and $\hat{\mathbf{x}}$ is the unitary vector associated. Scalar variables are never represented by bold letters. With the exception of $\mathbf{F}$ (a force) and $\mathbf{B}$ (a magnetic field), upper-case bold letters refer to non-vector matrices. $[\mathbf{x}]$ is the skew-symmetric matrix denoting the cross-product $\mathbf{x}\times$ and $\dot{\mathbf{x}}$ denotes the time derivation in the orbital frame: $\dot{\mathbf{x}} = \frac{d\mathbf{x}}{dt}|_{\mathcal{O}}$.

Subscripts are used to give precision on the variables. A maximum of four subscripts are used, in the order defined here: the first one defines the object concerned. The second one refers to the cause. The third one is the axis considered, and the fourth defines projection frame. For example, $F_{C_{th_{x_{\mathcal{O}}}}}$ is the projection of the thruster force applied on the chaser along the x-axis of the orbital frame. To lighten equations, this notation is reduced when the clarity is unaf-

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http://dx.doi.org/10.1016/j.asr.2017.03.042
0273-1177/

Nomenclature

Constants

μ_0	magnetic constant ($\mu_0 = 4\pi 10^{-7}$ N/A^2)
μ	standard gravitational parameter of the Earth ($\mu = 3.986\ 10^{14}$ m^3/s^2)

Variables

$\mathbf{F}$	force (N)
$\mathbf{f}$	force per unit of mass (N/kg)
$\mathbf{B}$	magnetic field (T)
$\boldsymbol{\tau}$	torque (Nm)
$\boldsymbol{\mu}$	magnetic dipoles, always with subscript (Am^2)
$\mathbf{d}$	vector from chaser dipole to target dipole (m)
$\mathbf{s}$	vector from target center of mass to the chaser center of mass (m)
$\mathbf{s}_i$	vector from formation center of mass to satellite i center of mass (m)
$\boldsymbol{\theta}$	vector of Euler angles describing the attitude of the target in orbital frame
$\mathbf{r}$	vector from Earth center to the point considered (m)
$\boldsymbol{\gamma}_{\mu_T}$	vector from target center of mass to the target dipole (m)
m	spacecraft mass (kg)
m_{CT}	reduced mass: $m_{CT} = \frac{m_C m_T}{m_C + m_T}$
$\boldsymbol{\omega}$	rotation vector from inertial to orbital frame
$\mathbf{J}$	spacecraft inertia matrix in spacecraft body frame
$\mathbf{I}_l$	identity matrix of size l
$\mathbf{P}_{\mathcal{O}\to\mathcal{T}}$	rotation matrix from frame $\mathcal{O}$ to $\mathcal{T}$: $\mathbf{x}_\mathcal{T} = \mathbf{P}_{\mathcal{O}\to\mathcal{T}}\mathbf{x}_\mathcal{O}$

Subscript

$\mathcal{I}$	inertial frame
$\mathcal{O}$	orbital frame
$\mathcal{C}$	chaser body frame
$\mathcal{T}$	target body frame
C	chaser satellite
T	target satellite
i	either C or T
CoM	center of mass of the formation
g	gravity or gravity gradient
$\epsilon\mu$	electromagnetic
E	due to the Earth
γ	due to the lever-arm $\boldsymbol{\gamma}_{\mu_T}$
th	thrusters
rw	attitude control system (e.g. reaction wheels)
d	created by the reaction wheels to desaturate them
p	perturbation

fected. For example, $\mathbf{F}_{T_{\epsilon\mu}}$ is the electromagnetic force exerted on the target.

Three frames are used in this article; $\mathcal{I}$, an inertial frame centered on the Center of Mass of the formation (CoM); $\mathcal{O}$, the orbital frame centered on the center of mass of the formation; $\mathcal{T}$, the target body frame. These reference frames are represented in Fig. 1. $\hat{\mathbf{z}}_\mathcal{O}$ is toward the Earth. $\hat{\mathbf{y}}_\mathcal{O}$ is perpendicular to the orbit, in opposition to the angular momentum. $\hat{\mathbf{x}}_\mathcal{O} = \hat{\mathbf{y}}_\mathcal{O} \times \hat{\mathbf{z}}_\mathcal{O}$. These definitions are summarized in Fig. 1.

1. Introduction

Satellite tugging can be motivated by various reasons. It can be for de-orbiting or re-orbiting: for example in the case of satellites having finished their mission, but being unable to do the maneuver by themselves. It can be for orbit management, in the case of a constellation composed of several satellites in which only one is equipped with thrusters for example. It can also be considered as a mean to finalize launches, in which case this maneuver would increase launchers capabilities.

Whatever the reasons, several means can be considered to achieve orbit modification of a satellite by tugging it with another satellite. Indeed, one could simply dock a chaser satellite to the target satellite. In the frame of Active Debris Removal (ADR), contactless solutions however could be more interesting. They could indeed provide a way to avoid the need for standardized interfaces and hazardous uncooperative docking phases, as well as reduce the risk of creating new debris. For example, Schaub and Sternovsky (2014) suggested to use electrostatic forces by charging the surfaces of the target and the chaser with ions of the other polarity, in order to create an attracting force between the two. However, charging satellite surfaces is generally problematic, and can even be hazardous, as pointed out by Garrett (1981). This solution seems therefore adapted mainly for dead satellites.

In this study, which has been briefly presentented in Fabacher et al. (2015), and in the same context as Voirin et al. (2012), solutions using magnetic forces to tug the target are detailed. Indeed many satellites, specially in Low Earth Orbit, are equipped with Magnetic Torque Bars (MTQ) which are devices used for attitude control. MTQ create magnetic fields, which could be used by a chaser equipped with a powerful steerable magnetic dipole, in order to create forces and torques on the target.

Electromagnetic Formation Flying (EMFF) is a concept studied since the beginning of the 21st century. It consists in flying satellites in formation, using magnetic forces and torques to control their relative positions and attitudes. Much theoretical work has already been done, giving this concept a solid framework. Schweighart (2005) solved the