Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 54 (2014) 2318–2335

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Optimal spacecraft formation establishment and reconfiguration propelled by the geomagnetic Lorentz force

Xu Huang *, Ye Yan, Yang Zhou

College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China

Received 5 April 2014; received in revised form 14 July 2014; accepted 11 August 2014
Available online 23 August 2014

Abstract

The Lorentz force acting on an electrostatically charged spacecraft as it moves through the planetary magnetic field could be utilized as propellantless electromagnetic propulsion for orbital maneuvering, such as spacecraft formation establishment and formation reconfiguration. By assuming that the Earth's magnetic field could be modeled as a tilted dipole located at the center of Earth that corotates with Earth, a dynamical model that describes the relative orbital motion of Lorentz spacecraft is developed. Based on the proposed dynamical model, the energy-optimal open-loop trajectories of control inputs, namely, the required specific charges of Lorentz spacecraft, for Lorentz-propelled spacecraft formation establishment or reconfiguration problems with both fixed and free final conditions constraints are derived via Gauss pseudospectral method. The effect of the magnetic dipole tilt angle on the optimal control inputs and the relative transfer trajectories for formation establishment or reconfiguration is also investigated by comparisons with the results derived from a nontilted dipole model. Furthermore, a closed-loop integral sliding mode controller is designed to guarantee the trajectory tracking in the presence of external disturbances and modeling errors. The stability of the closed-loop system is proved by a Lyapunov-based approach. Numerical simulations are presented to verify the validity of the proposed open-loop control methods and demonstrate the performance of the closed-loop controller. Also, the results indicate the dipole tilt angle should be considered when designing control strategies for Lorentz-propelled spacecraft formation establishment or reconfiguration.

Keywords: Electrostatically charged spacecraft; Lorentz force; Spacecraft formation flying; Trajectory optimization; Sliding mode control

1. Introduction

Compared to a traditional monolithic spacecraft, spacecraft formation flying (SFF) that consists of a cluster of spacecraft, has been identified as a key enabling technology for future space missions due to its advantages of decreased cost and risk, increased flexibility and reliability, enhanced performance and so on (Guibout et al., 2006; Huntington et al., 2008). Generally, to achieve spacecraft formation establishment or formation reconfiguration, thrusters on board using chemical fuels are utilized to perform relative orbital control. The durations of most space missions are therefore constrained by the amount of propellant on board. To extend the lifetime of on-orbit spacecraft, it would be preferable and advantageous to use propellantless propulsion, such as the geomagnetic Lorentz force acting on an electrostatically charged spacecraft.

Such a charged spacecraft, which we shall call a Lorentz spacecraft, is a conceptual space vehicle that could generate a net charge on its surface to induce the Lorentz force via interaction with the surrounding planetary magnetic field (Gangestad et al., 2009; Peck et al., 2005). The induced Lorentz force could be utilized as a new means

* Corresponding author. Tel.: +86 15574868148; fax: +86 073184573187.
E-mail addresses: xunudt@gmail.com (X. Huang), yynudt@gmail.com (Y. Yan), yznudt@gmail.com (Y. Zhou).

http://dx.doi.org/10.1016/j.asr.2014.08.010
0273-1177/

of propellantless electromagnetic propulsion for orbital maneuvering. Despite the fact that the Lorentz force could only act in the direction that is perpendicular to the direction of the local magnetic field and that of the vehicle's velocity relative to the local magnetic field, active modulation of the specific charge (i.e., charge-to-mass ratio) of Lorentz spacecraft could still perform effective orbital control, such as propellantless rendezvous (Huang et al., 2014a; Pollock et al., 2011), spacecraft hovering (Gangestad et al., 2009; Huang et al., 2014b,c), formation flying (Peck et al., 2007; Peng and Gao, 2012; Tsujii et al., 2013), orbital inclination change (Pollock et al., 2010), planetary capture and escape (Gangestad et al., 2010, 2011) and so on. A Lorentz spacecraft is more effective in low Earth orbit (LEO) where the spacecraft travels faster and the magnetic field is intenser than high Earth orbit (HEO) to generate the Lorentz force. Due to a lack of relative velocity with respect to the Earth's magnetic field, the Lorentz spacecraft is less effective in the vicinity of geostationary or geosynchronous orbits (GEOs).

Natural charging levels may reach to 10^{-8} C/kg, which are insufficient to perturb the orbit significantly (Vokrouhlicky, 1989). To allow efficient Lorentz-propelled orbital maneuvering, a charging level on the order of 10^{-5} C/kg or even higher is necessary (Pollock et al., 2010). Obviously, higher charging levels would lead to increased efficiency, but also raise more challenging technical requirements on the charge generation device, charge storage mechanism, and power system. Peck et al. (2005) presented that a specific charge of 0.03 C/kg may be the near-term feasible maximum within current material limits, and charging levels higher than the order of 0.1 C/kg may lie in the future (Gangestad et al., 2010). Therefore, a specific charge no greater than 0.03 C/kg is assumed in this paper. Note that 0.03 C/kg is a theoretical value, which is obviously many orders of magnitude larger than natural charging levels and the experimental study of Lorentz spacecraft is ongoing (Gorman, 2007; Gangestad et al., 2009, 2010). Several technical challenges remain to be overcome before the realization of a Lorentz spacecraft.

Several previous works deal with the Lorentz-propelled spacecraft formation problem. Peck et al. (2007) designed a triangular formation with one uncharged chief spacecraft in an equatorial circular orbit and another two charged deputy spacecraft hovering around the chief based on the absolute orbital equation of a charged Lorentz spacecraft. By assuming that the spacecraft are in close proximity and the Lorentz force generally acts in the radial direction, a closed-loop PD controller was also designed to achieve formation reconfiguration that the two deputies exchange their positions. Peng and Gao (2012) incorporated the Lorentz acceleration into Gauss variational equations and designed a Lorentz-augmented J_2-invariant formation by using the average classical orbital elements. When computing the average changes in classical orbital elements in a single orbital period, the magnetic dipole orientation is assumed to be constant, which is to some extent less representative of the actual Earth's magnetic field since the tilted magnetic dipole corotates continuously with Earth. Thus, modeling errors are inevitably introduced. Based on the assumption that the Earth's magnetic field could be modeled as a perfect magnetic dipole with its south pole aligned with the geographic north pole, Tsujii et al. (2013) studied the dynamics and control of Lorentz-propelled spacecraft formation flying by including the Lorentz acceleration into the Hill–Clohessy–Wiltshire (HCW) equations and Tschauner–Hempel (TH) equations, respectively. HCW equations, a set of linearized ordinary differential equations, have been widely used to describe the orbital motion of a spacecraft with respect to a near-circular reference orbit (Clohessy et al., 1960) and TH equations are generally used to describe the relative motion in the vicinity of an elliptic orbit (Tschauner and Hempel, 1965). Based on the developed dynamical models, Tsujii et al. (2013) designed Lorentz-propelled relative transfer orbits using stepwise charge control and presented new types of Lorentz-propelled periodic relative orbits by sequential quadratic programming method. However, the Earth's magnetic dipole is tilted by nearly 11.3° with respect to the Earth's rotation axis, which is not sufficiently small to be neglected. Therefore, the accuracy of the results for Earth's orbits may be influenced due to the assumption of a nontilted dipole. Sobiesiak and Damaren (2012, 2013) proposed optimal hybrid control methods for Lorentz-augmented formation flying using a linearized dynamical model in terms of relative orbit elements. By modeling the Earth's magnetic field as a tilted magnetic dipole, a nonlinear dynamical model that characterizes the relative motion of Lorentz spacecraft is developed in this paper. Based on the proposed dynamical model, the optimal control trajectories for Lorentz-propelled spacecraft formation establishment and reconfiguration are derived via Gauss pseudospectral method (GPM), a direct transcription method that belongs to the category of pseudospectral method, which has been widely used in trajectory optimization. Furthermore, the effect of the dipole tilt angle on the solution of the optimal control trajectories is also numerically analyzed.

Wu et al. (2009, 2011) designed a fuel-optimal maneuver strategy to reconfigure spacecraft formations using a low-thrust propulsion system by Legendre pseudospectral method (LPM) and also presented an energy-optimal low-thrust maneuver method for formation reconfiguration in the presence of J_2 perturbations by LPM. Huntington et al. (2008) investigated the fuel-optimal reconfiguration problem for a tetrahedral formation using GPM. Inampudi and Schaub (2012) designed the optimal reconfigurations of a two-craft coulomb formation under different optimality criteria by LPM. In this paper, GPM is used to solve the open-loop optimal control trajectories for Lorentz-propelled formation establishment and reconfiguration problems with two kinds of final conditions constraints, namely, the fixed and free final conditions constraints, which will be elaborated in Section 3. Furthermore,