Acta Astronautica 89 (2013) 154–165

Contents lists available at SciVerse ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Optimal satellite formation reconfiguration actuated by inter-satellite electromagnetic forces

Wei-wei Cai *, Le-ping Yang, Yan-wei Zhu, Yuan-wen Zhang

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

ARTICLE INFO

Article history:
Received 19 December 2012
Received in revised form
3 April 2013
Accepted 10 April 2013
Available online 18 April 2013

Keywords:
Satellite formation
Inter-satellite electromagnetic force
Euler–Lagrange equation
Trajectory optimization
Robust control

ABSTRACT

The inter-satellite electromagnetic forces generated by the magnetic dipoles on neighboring satellites provide an attractive control actuation alternative for satellite formation flight due to the prominent advantages of no propellant consumption or plume contamination. However, the internal force nature as well as the inherent high nonlinearity and coupling of electromagnetic forces bring unique dynamic characteristics and challenges. This paper investigates the nonlinear translational dynamics, trajectory planning and control of formation reconfiguration actuated by inter-satellite electromagnetic forces. The nonlinear translational dynamic model is derived by utilizing analytical mechanics theory; and analysis on the dynamic characteristics is put forward. Optimal reconfiguration trajectories of electromagnetic force actuated formation are studied by applying optimal control theory and the Gauss pseudospectral method. Considering the high nonlinearity and uncertainty in the dynamic model, an inner-and-outer loop combined control strategy based on feedback linearization theory and adaptive terminal sliding mode control is proposed with finite-time convergence capability and good robust performance. Theoretical analysis and numerical simulation results are presented to validate the feasibility of the proposed translational model, reconfiguration trajectory optimization approach and control strategy.

1. Introduction

As compared with conventional large single satellites, satellite formation flight (SFF) is an attractive prospect in many future space missions due to its prominent advantages such as reduced cost, redundancy, upgradeability and performance improvement. Much work has been conducted on the relative motion dynamics, formation configuration design and formation control for SFF [1–3]. To date, many conventional SFF-based space missions have been designed with propellant based control actuators, resulting in a limited lifetime for the formation system and potential plume contamination to the optical payload of the neighboring satellite. An alternative for the relative motion control is to make use of non-contacting inter-satellite forces, such as Coulomb forces [4], magnetic flux-pinning forces [5] and electromagnetic forces [6]. Not only would the lifetime be greatly extended and plume contamination effectively avoided, but also the precision of formation control could be improved due to the continuity and reversibility of these non-contacting interaction forces. Moreover, these forces act on all the member satellites simultaneously, thus any changes of the forces would affect the whole formation system, bringing new control characteristics. However, the concept of coulomb formation flying is only applicable to GEO or higher altitudes, where the plasma environment is less dense; and external thrusters are required for the reorientation of a coulomb formation since the coulomb forces are aligned with the relative separation, resulting in increased complexity of system design [7]. As for the magnetic flux-pinning force, its unique characteristics and limited action

---

* Corresponding author. Tel.: +86 13786137751.
E-mail address: tsaiweiwei@hotmail.com (W.-w. Cai).

0094-5765/$ - see front matter © 2013 IAA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actaastro.2013.04.009

range make it more suitable for on-orbit modular spacecraft assembly and station-keeping applications [8]. Different from the other two categories of non-contacting inter-satellite forces, the electromagnetic forces which are imparted by two steerable three-dimensional magnetic dipoles can be used to control the relative separation, relative attitude, and inertial rotation. Utilizing three orthogonal coils on each satellite with high temperature superconducting (HTS) wire, the feasible interaction range of electromagnetic forces can be enlarged to tens or hundreds of meters [6]. These advantages enable the close-proximity electromagnetic formation flight (EMFF) with promising applications as space aperture arrays [9], fractionated spacecraft [10] and proximity inspector system [6], as well as electromagnetic docking [11].

Some of the early research on the concept and challenges of EMFF have been carried out by the MIT Space Systems Laboratory and the University of Tokyo. Schweighart investigated the exact and approximate models for the electromagnetic force and torques, and studied the magnetic dipole solution planning approaches [12]. Ahsun studied control problems of EMFF for near-Earth operations, and proposed a reasonable angular momentum management strategy [13]. Considering the inherent coupling of EMFF, Ramirez-Riberos performed a preliminary research on the decentralized control of EMFF based on cyclic pursuit approaches [14]. Ground experiments were carried out on a two-dimensional testbed consisting of two EMFF vehicles with HTS wire and reaction wheels [15]. A research group at the University of Tokyo proposed to drive the superconducting coils with differently phased sinusoidal current so as to counteract the geomagnetic disturbance torques [16]. In addition, a Polish researcher Wawrzaszek studied the application of EMFF to interferometer missions which include two or three aligned satellites rotating around the array's mass center [17]. Su investigated the gathering problem for fractionated electromagnetic satellites cluster, and proposed a control law which simulates organism swarm motion [18].

Different modeling ideas are required for the relative translational dynamics of EMFF due to the internal force nature of electromagnetic forces. Elias's effort to derive the dynamic equations with the multi-body system theory was a significant attempt in this area, though the linearization of the dynamic model was conducted in further research [19]. In terms of the modeling of such complex systems, analytical mechanics has great advantages in that it analyzes the plant from the perspective of energy and constraint. Its successful application to tethered satellites systems provides exciting inspiration for the relative translational motion modeling of EMFF [20].

In some applications of SFF, different missions may require different formation configurations, highlighting the need of formation reconfiguration maneuvers. When it comes to the system like EMFF, it is believed that the trajectory planning problem is coupled with the system design for any given mission, due to the fact that sub-optimal reconfiguration trajectories may result in underutilization of a designed system [6,13]. Moreover, the electromagnetic forces are coupled with the relative states, thus the optimal reconfiguration trajectory must differ from conventional SFF trajectories. Ahsun investigated the time-optimal in-plane reconfiguration trajectory for EMFF with linear translational dynamics [14]; however, the optimal trajectories for out-of-plane reconfigurations and with distinct performance criteria have not yet been systematically studied.

In the field of satellite formation maneuvers control, various approaches have been studied in the past years, such as sliding mode control [21], linear quadratic regulator control [22] and adaptive control [13]. However, most of these control approaches only guarantee an asymptotic stability with the convergence time approaching infinity. The time duration for any optimal reconfiguration trajectories obtained are specified, thus the reference trajectory tracking errors must converge to zero in finite-time. Additionally, EMFF is a highly nonlinear system with modeling errors and external disturbances in a realistic environment, leaving the control for EMFF a tough issue. The exact feedback linearization approach could convert a nonlinear system into an equivalent linear one by utilizing system states and control inputs transformation [23]. However, this approach requires an exact plant model because modeling uncertainties would degrade the control performance. By switching the control structure around the nonlinear sliding manifold, the terminal sliding mode (TSM) control method performs well in guaranteeing finite time convergence of system states to equilibrium, and great robust capability for model uncertainties and external disturbances, providing an alternative to address the control problem of optimal reconfiguration trajectory tracking [24]. However, the TSM controller is not drawback-free. The system states slowly converge when far from the equilibrium, and super-boundary information of the uncertainties or disturbances is required to improve the efficiency. Inspired by the rapid convergence of the linear super-plane based sliding mode controller, the global convergence performance of conventional TSM controller is greatly improved by modifying the sliding manifold. Besides, an on-line adaptive estimation for the super-boundaries of unknown disturbances could be introduced to the closed-loop system to improve the control performance.

The remainder of this paper is organized as follows. First, the nonlinear relative translational dynamic model for satellites actuated by the inter-satellite electromagnetic force is developed, then the dynamics property and formation reconfiguration challenge are briefly analyzed. Second, the reconfiguration trajectory optimization problem is formulated utilizing optimal control technique, and solved via the Gauss pseudospectral method. Third, an inner-and-outer loop combined control strategy based on feedback linearization theory and adaptive terminal sliding mode control approach is proposed in detail. Finally, numerical simulation is presented to validate the performance of the proposed reconfiguration trajectory optimization approach and combined control strategy. Some useful conclusions are put forward in the end.

2. Dynamic model and characteristics analysis

2.1. Relative translational dynamics

An electromagnetic formation usually contains several satellites, and the electromagnetic force acting on each member is generated by all the others in the formation. We only take two electromagnetic satellites *Sat*A and *Sat*B in