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ScienceDirect

Advances in Space Research 58 (2016) 619–634

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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# Sliding mode control of electromagnetic tethered satellite formation

Mohammad Amin Alandi Hallaj, Nima Assadian *

*Center for Research and Development in Space Science and Technology, Department of Aerospace Engineering, Sharif University of Technology, Tehran, Iran*

Received 24 February 2016; received in revised form 4 May 2016; accepted 12 May 2016
Available online 20 May 2016

**Abstract**

This paper investigates the control of tethered satellite formation actuated by electromagnetic dipoles and reaction wheels using the robust sliding mode control technique. Generating electromagnetic forces and moments by electric current coils provides an attractive control actuation alternative for tethered satellite system due to the advantages of no propellant consumption and no obligatory rotational motion. Based on a dumbbell model of tethered satellite in which the flexibility and mass of the tether is neglected, the equations of motion in Cartesian coordinate are derived. In this model, the $J_2$ perturbation is taken into account. The far-field and mid-field models of electromagnetic forces and moments of two satellites on each other and the effect of the Earth's magnetic field are presented. A robust sliding mode controller is designed for precise trajectory tracking purposes and to deal with the electromagnetic force and moment uncertainties and external disturbances due to the Earth's gravitational and magnetic fields inaccuracy. Numerical simulation results are presented to validate the effectiveness of the developed controller and its superiority over the linear controller.


*Keywords:* Tethered satellites formation; Electromagnetic formation; Electromagnetic far-field and mid-field models; Sliding mode control

## 1. Introduction

Nowadays, it is a proven fact that using a distributed satellite architecture with several small satellites instead of a large monolithic satellite can reduce the satellite manufacturing cost and complexity and increase the flexibility and reliability of the space missions (Alfriend et al., 2009). Using *Tethered Space System* (TSS) concept is one of the possible methods to achieve satellite formation flying with fewer required fuel and total mass (Alpatov et al., 2010). In literature, the term TSS is used for a system that composed of two or more satellites which are connected by low-mass cables, called tether. The main advantage of TSS is to prevent satellites from drifting apart without applying active control.

In the recent decades, one of the TSS applications that have attracted the most attentions is formation flight. Fundamental study on the tethered dynamics was done by Misra and Modi (1986). Beletsky and Levin (1993) studied the possible applications of TSS. Misra and Modi (1992) also investigated the dynamics of three dimensional N-satellite open chains and the in-orbit plane equilibrium of this configuration was examined by Guerman (2003). Several researches have been done on the disturbance effects on the dynamics of flying spacecraft such as gravity perturbation, aerodynamics heating and atmospheric drag. For example, Hurlbut and Potter (1991) studied the heating effect in TSS and dynamics of satellite formation flight by taking $J_2$ perturbation into account was studied by Hamel and Lafontaine (2007).

Most works of the TSS literature are based on dumbbell models of tethered satellite system. The dumbbell system model includes two massive bodies connected together by a taut mass-less tether (Beletsky and Levin, 1993).

* Corresponding author. Tel.: +98 (21) 6616 4607 (Office); fax: +98 (21) 6602 2731.
*E-mail addresses:* amin_hallaj@ae.sharif.ir (M.A.A. Hallaj), assadian@sharif.edu (N. Assadian).

http://dx.doi.org/10.1016/j.asr.2016.05.019
0273-1177/

However, there are interesting applications in which multi body tether system is required. Ring configurations were studied in Beletsky and Levin (1985), Anchored configurations were examined in Pizarro-Chong and Misra (2008) and Tragesser and Tuncay (2005), Hub-and-Spoke configurations were studied by Pizarro-Chong and Misra (2008) and Zhao and Cai (2008) and the triple-mass triple-tethered satellite system under the low Earth orbit perturbations of drag and Earth's oblateness was analyzed in Razzaghi and Assadian (2015). A detailed rich review of space tether researches was presented by Cartmell and McKenzie (2008).

Traditionally, satellite formation flight without any structural connection is controlled using conventional thrusters which involves continuous fuel consumption to maintain the formation geometry (Alfriend et al., 2009). Correspondingly, the fuel consumption could reduce the lifetime of the mission significantly. To alleviate these concerns, several propellant-less methods such as using non-contacting forces for controlling the space formations is offered in the past decade. Huang et al. (2014) studied the relative equilibrium conditions for general formation with non-contacting internal forces. LaPointe (2001) offered the microwave scattering formation flight method. King et al. (2002) applied Coulomb force and Shoer and Peck (2007) presented magnetic flux pinning forces to control a space formation.

One of the most attractive methods to maintain a satellite formation in the recent years is using electromagnetic sources. Feasibility of using electromagnetic foundations to maintain a satellite formation flight was examined by Ninomiya and Hashimoto (2001). Kong (2002) studied the initial estimation of required subsystem's physical specifications for *Electromagnetic Formation Flight* (EMFF). Schweighart and Sedwick (2002) investigated the maintaining possibility of the EMFF in LEO considering the geomagnetic field. General formulation of magnetic forces and moments of an N-satellite EMFF was investigated by Schweighart (2005). Ahsun and Miller (2006) presented the 2D dynamics of general N-satellites formation and proposed a nonlinear control law. Elias et al. (2007) demonstrated that two-satellite formation flying is fully controllable using three orthogonal coils and reaction wheels and designed a linear optimal controller using linearized dynamics. Ahsun et al. (2010) presented a nonlinear adaptive control law and Zeng and Hu (2012) have investigated a finite time control for the general N-satellites EMFF in LEO. Cai et al. (2013) have studied the optimal and sliding-mode control of two satellites EMFF.

Based on the fact that the EMFF has not any structural connection between satellites, continues energy expenditure is required to keep the configuration up in the Earth's orbit. In this way, Alandi Hallaj and Assadian (2015) addressed a novel non-rotating space tethered configuration in which the relative positions and satellites' orientations are controlled using electromagnetic forces and reaction wheels and presented a linear control law and an optimal control method for tether reorientation. Since using the steerable magnetic dipoles can generate desired forces and moments in any arbitrary direction, the proposed system is fully controllable and electromagnetic forces are the only actuation source that controls the tether length and orientation. As their claim, equipped space tethered system with electromagnetic actuators needs no centrifugal forces and rotational motion to keep the tether taut. Therefore, it does not restrict the mission lifetime due to fuel availability and consumption and guarantees the satellite proximity without using continues energy expenditure.

However, the linear control and used optimal control method in Alandi Hallaj and Assadian (2015) require an exact plant model. If the nonlinearities of the system are large enough, the linear control algorithms will only guarantee the local stability. Furthermore, the un-modeled dynamics due to the orbit perturbations, uncertainties in the Earth's magnetic field model and the approximation of the magnetic force and torque models can degrade the response of the system to the linear or off-line optimal control. Therefore, a nonlinear control law based on the inherent nonlinearities of the dynamics and robust characteristic for uncertainties and disturbances should be considered to guarantee the global stability of the system and improve its closed-loop response characteristics. Sliding mode control is one of the most common used nonlinear control methods which illustrates the robustness specification by dealing with the model uncertainties and disturbances. In this way, the boundary information of the uncertainties and disturbances is required.

The remaining of this paper is organized as follows. Section 2 gives some specifications to the dynamics model and coordinate systems, and then develops the nonlinear translational equations of relative motion of the tethered satellite formation in Cartesian form, and finally derives the attitude dynamics in the body frame. A nonlinear controller based on the sliding mode technique and the guidance scheme for the tether length, relative positions, and the satellites attitudes are introduced in Section 3. To validate the performance of the proposed controllers, the results of the nonlinear numerical simulations and the analyses are presented in Section 4. Finally, some useful conclusions of the present investigation are expressed in Section 5.

## 2. System model

A reasonable general model for electromagnetic dumbbell tether system consists of two massive bodies; $m_1$ and $m_2$, which are equipped with three orthogonal reaction-wheels and three electromagnetic coils and are connected by a straight massless tether $l$. In this paper, the tether flexibility is neglected and it is assumed that the attitudes of satellites are independent of the tether's motion. Fig. 1 shows the model configuration and the coordinate systems.