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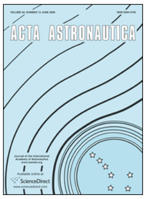

Collective trajectory planning for satellite swarm using inter-satellite electromagnetic force☆

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ABSTRACT

The inter-satellite electromagnetic force presents several significant advantages that help to expand its space applications to the multi-satellite missions gradually. For a satellite swarm, whether the electromagnetic force is applied to enable collective maneuver and how to provide a better performance and broader applications for such swarm highlight an important issue. Considering the trajectory planning problem of satellite swarm using inter-satellite electromagnetic force, a behavior-based collective planning scheme is developed by designing the desired velocity of each satellite as the sum of several different behavioral contributions, which are used to represent the internal and external interactions of the swarm. Therefore, the desired configuration is associated with the equilibrium points of the pre-designed kinematical field. Furthermore, the trajectory planning problem could be translated to a parameter optimization problem considering the swarm dynamics with inter-satellite electromagnetic force. Then based on the analysis of the applicability and advantages triggered by integrating the inter-satellite electromagnetic force into such behavior-based planning scheme, the collective trajectory planning problem with sole electromagnetic force actuation and hybrid actuation with thruster are studied respectively. Numerical simulations are carried out to verify the validity of the proposed algorithm, and the satellite swarm performance enhanced by inter-satellite electromagnetic force is discussed at last.

1. Introduction

The inter-satellite electromagnetic force presents an attractive novel operational approach for the relative motion control of satellites. Utilizing three orthogonal superconducting magnetic coils equipped on each satellite, the electromagnetic forces are electrically generated by the interaction of the magnetic fields to control the relative motion of satellites, and their quantity and orientation can be adjusted by changing the currents through the coils. Not only would the lifetime of the satellite be greatly extended due to no propellant consumption and effective avoidance of plume contamination, but also the control precision of relative motion could be improved because of the continuity and reversibility of the current control. Moreover, the electromagnetic forces apply on multiple satellites simultaneously, convenient for synchronous controllability as well. Both above prominent advantages have enabled a host of researches on the satellite formation flight [1,2] and docking [3] using inter-satellite electromagnetic force, and the potential applications would be likely to extend from preliminary two-satellite cases to multi-satellite cases in the future along with the growing requirement of space missions. As an emerging concept of distributed space system, satellite swarm is quite appealing

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over traditional monolithic satellite due to its flexibility, robustness, redundancy and cost-effectiveness. Many space applications have been extensively studied, for instance earth observation (SAMSON project [4]), optical interferometry (TPF mission [5]), as well as on-orbit assembly [6] etc., all of which would be likely to have significant improvements if the inter-satellite electromagnetic force is applied.

However, the inter-satellite electromagnetic force has come with several particular challenges such as limited feasible interaction range, coupled electromagnetic torque, troublesome interaction with Earth's magnetic field, as well as strong coupling and nonlinear control, which have extremely restricted its implementations. Moreover, the electromagnetic forces are internal to the system, which maintain the inertial linear and rotational momentum and cannot alter the motion of the center of mass. Especially, the superposition and coupling effects of multiple electromagnetic fields have potentially complicated the dynamics and relative motion of a multi-satellite system to a certain extent. How to utilize the inter-satellite electromagnetic force to provide a better performance, higher efficiency and broader applications for such a complex system highlight an important trend. Kong [7] analyzed the feasibility of electromagnetic force on spinning five-satellite arrays maintenance as needed for TPF. Ramirez-Riberos [8] and Su [9] introduced electromagnetic force into distributed control based on cyclic pursuit approach and artificial potential method respectively, and the configuration control problems of multi-satellite electromagnetic formation are addressed. Saaj [10] proposed a hybrid propulsion system using electrostatic force and electric thruster together for close formation flight. Hogan [11] investigated the two-spacecraft orbit corrections using electrostatic forces and inertial thrusters. These strategies have greatly expanded the applications of Coulomb force, and both are worthy for reference with respect to the electromagnetic force.

Cooperation is a key requirement of the satellite swarm while flying in a formation, which includes the spatial and temporal connotations. The spatial cooperation ensures that the satellites could maintain formation flight in a coordinated manner while being capable of avoiding collisions among each other and from external threats, and the temporal cooperation means that the swarm could reshape a desired geometry in finite time. In addition, the more satellites are required to execute maneuvers, the more difficult to achieve optimality and more burdensome for on board computers to perform the computation. Therefore, it is of great significance to design a distributed planning scheme to observe the cooperation among collective satellites. Many studies dealing with collective planning in space have been done and several approaches such as Hamilton–Jacobi–Bellman optimality [12], mixed integer nonlinear programming [13], pseudospectral method [14] and consensus algorithm [15] have been applied successfully. For the Coulomb formation flight, Felicetti [16] presented a comparison among several possible control strategies. Wang [17] developed a collision avoidance strategy depending on the measurements of the separation distances and the distance rates using internal Coulomb forces. Moreover, Scharf [18] summarized the characteristics of five basic cooperated architectures for formation flight, and showed that a behavior-based approach is simple and effective to apply in a swarm. Especially it performs better with a large number of satellites. Gazi [19] systematically investigated the stability and optimization of a swarm underlying collaborative behavior, and the potential functions [19,20] are used to model these behaviors and the environment effects. Tripp [21] introduced stigmergy as a mechanism for coordinating satellite clusters, and the feasibility and advantage of such behavioral approach are analyzed. Sabatini [22] defined the control of individuals in accordance with four behavior-based rules, thus the collective maneuvers of satellite swarm are determined accordingly. Izzo [23] proposed the “Equilibrium Shaping (ES)” scheme, defined three different high-level behavior velocities to conduct swarm aggregation and maneuver, and introduced the corresponding control feedbacks that are able to track the desired trajectories. Based on the ES scheme, Nag [24] further developed various strategies for scatter maneuvers. For the satellite swarm with propellant-free actuation such as Coulomb force and electromagnetic force, Pettazzi [25] studied the possibility of integrating the Coulomb force into the ES scheme, and discussed the trajectory planning and formation control problem with sole Coulomb force and hybrid actuation, respectively. Su [26] put forward a control law that simulates organism fish swarm motion for the electromagnetic satellite cluster, which has shown to be well-preformed.

With above considerations in mind, this paper presents a behavior-based collective planning approach for the satellite swarm to achieve a given configuration, and mainly studies the applicability and advantages triggered by integrating the inter-satellite electromagnetic force into this scheme, as well as the collective trajectory planning problem. The remainder is organized as follows. Firstly, after analyzing the swarm cohesion under behavior strategy, the desired kinematical field of satellites is designed based on “Equilibrium Shaping” and a distributed trajectory planning scheme is derived with the effects of external environment considered. Secondly, the dynamic model for a swarm with inter-satellite electromagnetic force is developed and its applicability to this problem is discussed. Thirdly, the trajectory planning problem with sole electromagnetic force actuation and hybrid actuation by electromagnetic forces and thrusters are analyzed respectively, and then numerical simulations are carried out to verify above analysis. Finally, some conclusions are safely put forward.

2. Behavior-based motion planning

During the formation flight or maneuver, it is very important for a satellite swarm to maintain the swarm aggregative while being capable of responding to the inter-satellite effects and external environment at the same time. Therefore, we would analyze the swarm cohesion before introducing a behavior-based planning strategy.

2.1. Swarm cohesion analysis

Considering a swarm composed of N individual agents (here satellite) in n-dimension Euclidean space, let $\boldsymbol{\rho}_i \in \mathbb{R}^n$ $(i = 1, \ldots, N)$ denote the relative position vector of the i-th