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Review

Collision avoidance of Coulomb spacecraft formations using multi-mode hall thrusters

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ABSTRACT

A great number of abandoned satellites and satellite constellations that cannot maintain their precise positions by orbital control are wandering in geostationary Earth orbits, and these represent significant collision risk with functioning satellites. Collision avoidance for a Coulomb satellite formation (CSF) is a major problem that remains to be solved. However, internal Coulomb forces cannot alter the inertial momentum of the CSF center of mass. Thus, collision avoidance cannot be implemented employing purely Coulomb-based control. In this paper, multi-mode Hall thrusters are proposed to supply CSF propulsion in collision avoidance. To avoid plume contamination between close-proximity satellites in a CSF, the low-thrust mode of the Hall thruster is initially employed to gradually transform a close-proximity CSF to a formation with an appropriate security distance between nearby satellites. The security distance is selected to avoid the impact of plume contamination while employing the high-thrust mode of the Hall thruster to maneuver the CSF around an obstacle. Both stages apply optimal control based on a linear quadratic regulator. Subsequently, a CSF may be reconfigured to its initial formation. Meanwhile, the satellites maintain their original charges throughout the entire process. Simulations are employed to verify the effectiveness of the proposed scheme.

1. Introduction

Coulomb satellite formation (CSF) technology has emerged in recent years. A satellite in a geostationary Earth orbit (GEO) exists in a plasma environment with varying densities of positively and negatively charged particles. By controlling the buildup of charged particles on the surfaces of satellites, the configurations of CSFs can be controlled through the Coulomb electrostatic forces (attraction and repulsion) acting between the formation members [1]. This method of controlling the relative motion of satellites functions essentially in the absence of a propellant, and, hence, without deposition [2], making it an extremely clean and fuel-efficient method. By exerting the appropriate control, a CSF can be maintained relatively stable in space, and can even perform some maneuvering [3]. Because Coulomb electrostatic forces are relatively short range, the method can be applied to close-proximity formation flying (i.e., inter-satellite distances of 10–100 m) missions in the future [4]. Owing to its many advantages, such as non-deposition, high specific impulse, and low energy consumption, CSF technology has been the subject of in-depth study by numerous researchers.

An abundance of abandoned satellites and satellite constellations continue to occupy their original GEOs, although they cannot maintain their positions by precise orbital control. These waste satellites represent significant collision threats to functional satellites in GEOs [5]. Hence, it is essential to study the means of reconfiguring and maneuvering CSFs to avoid collision. The majority of studies focused on CSF reconfiguration have employed approaches based solely on Coulomb electrostatic force propulsion, and several examples are cited as follows. The authors in [6], have designed a nonlinear model-predictive controller to stabilize a three-body CSF in a triangular configuration. Shuquan and Hanspeter [7] developed a two-stage stable charge feedback control strategy based on Lyapunov's direct method for a three-craft CSF restricted to a single dimension. While the control strategy employed provided globally stable saturated control, the resulting control was not asymptotically stable. Authors in [8] explored a linear control design approach for a pair of satellites. The Coulomb force acting between the two satellites was controlled by adjusting multiple charge surfaces on the chief satellite to ensure the deployment of the deputy satellite to specified end states. While control methods employing Coulomb forces have been shown to be capable of accurately controlling the relative motion of satellites in a CSF, Coulomb electrostatic attraction and repulsion are strictly internal forces, and, as such, the primary weakness of all such methods is that Coulomb

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forces are unable to alter the inertial momentum of the CSF center of mass. Therefore, collision avoidance cannot be implemented using Coulomb electrostatic propulsion alone.

The maneuvering required in actual collision avoidance processes necessitates an ability to alter the inertial momentum of the CSF center of mass. Saaj [9] firstly proposed a hybrid propulsion scheme for CSF flying using electrostatic force propulsion in conjunction with standard electric thrusters. Here, the collision avoidance of a close-proximity CSF was developed using a sliding mode control (SMC) strategy in coordination with an artificial potential field (APF) method. While this previous work provides the theoretical basis for the present study, it neglected the impact of plume deposition due to the emission of impurities by electric propulsion systems.

It is well known that electrostatic discharges between the sensitive components of satellites are detrimental to their functionality. As such, the distance between satellites in a CSF must be sufficient to avoid electrostatic discharge, and differential spacecraft charging must also be avoided. Investigation has shown that, under the densest plasma conditions in a GEO, the naturally distributed charge on a pair of satellites would generate about 0.1 mN at a 10 m separation distance [10]. Moreover, the collision avoidance process may require several spacecraft charging cycles when relying solely on Coulomb electrostatic force propulsion. The small forces involved, in conjunction with the potentially long charging period, increase the danger of overly close approach. In addition to the danger of discharge associated with differential spacecraft charging, the control of satellite motion can also be affected [11]. Although substantial effort has been devoted to eliminating spacecraft differential charging [12–14], considerable effort remains before electrostatic propulsion can be applied in actual CSF missions. As an alternative for close-proximity formations, electric propulsion (EP) methods, such as Hall thrusters, can provide thrust levels ranging from micro-Newton to milli-Newton [9]. Various electric thrusters have already been employed in practical CSF flying applications, and have been the subject of increasing attention [4,15,16]. In 1971, engineers in the former Soviet Union were the first to employ a pair of SPT-60 Hall thrusters to provide for orbital station-keeping on the Meteor satellite. Presently, more than 238 Hall thrusters are servicing 48 orbital spacecraft [17]. The European Space Agency (ESA) also successfully implemented the PPS-1350G Hall thruster as the main propulsion system in the lunar detector mission [18].

The plumes of EP systems emit impurities that may be deposited on the surfaces of neighboring satellites in close-proximity formations, changing their surface properties and incurring potential satellite damage. However, this situation can be avoided by employing a multi-mode Hall thruster capable of low-thrust and high-thrust modes of operation. For close-proximity formations, the Hall thruster is operated in the low-thrust mode, employing a low supply voltage and current in conjunction with low neutral gas injection. Accordingly, the total plume is very small, and the deposition range is less than the distance between nearby satellites in the CSF. Therefore, the present work applies a multi-mode Hall thruster to the collision avoidance process of CSFs. In addition, we also define a security formation, where the distance between nearby satellites is greater than the maximum plume deposition range under the high-thrust mode of the Hall thruster (i.e., high supply voltage and current in conjunction with high neutral gas injection). As such, plume deposition can be neglected once the inter-satellite distances of the CSF are equal to or greater than those of the security formation, and the Hall thruster can then operate in the high-thrust mode to provide sufficient force for CSF maneuvering. The control process proposed in this work involves two stages in sequence: a reconfiguration stage followed by a formation maintenance stage. In the reconfiguration stage, the CSF is reconfigured from its initial compact formation to the security formation employing the low-thrust mode of the Hall thruster. Then, in the formation maintenance stage, the CSF is maintained in the security formation while maneuvering around obstacles employing the high-thrust mode of the Hall thruster. All satellites of the CSF maintain their initial charge throughout the entire process. Both stages employ an optimal control method based on the linear quadratic regulator (LQR).

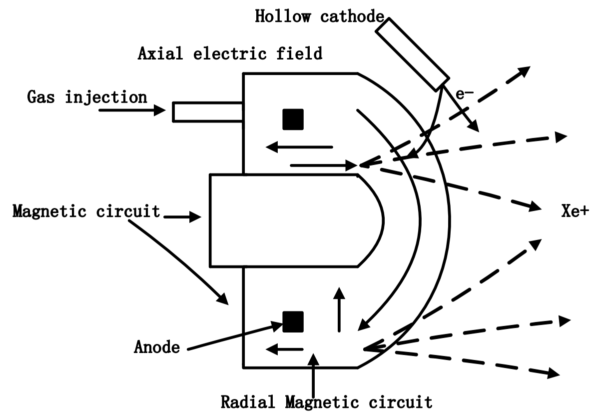

Fig. 1. Operating principle of the Hall thruster.

The remainder of this paper is organized as follows. Section 2 analyzes the effect of operating parameters on the performance of the multi-mode Hall thruster. Section 3 introduces the dynamic CSF equation, and describes the two-stage collision avoidance process in detail. Section 4 presents the reconfiguration stage employing an improved LQR optimal control method, and the performance is verified by means of simulations. Section 5 presents the formation maintenance stage employing LQR optimal control, and the performance of this stage is also verified by means of simulations. Conclusions and future work are given in Section 6.

2. Analysis of a multi-mode hall thruster

2.1. Hall thruster model

Presently, Hall thrusters are one of the most widely employed thrusters in EP systems. Representative models are the Russian SPT-100, the ESA PPS-1350, and the United States BPT-4000. The Hall Thruster has a very long life and simple structure.Compared with other plasma thrusters, the Hall thruster has an outstanding advantage that it provides a very wide range mode of operation which can be easily switched by fuzzy control. Even the extreme low mode operation can achieve accurate control. Therefore, the Hall thruster has excellent prospects for promoting the future development of astronautics.

The operating state of a Hall thruster is illustrated in Fig. 1. Firstly, the hollow cathode is heated to its operating temperature, whereupon it begins emitting electrons. A portion of the electrons enter into the ceramic discharge channel, and move toward the anode under the influence of an axial electric field. While passing through the radial magnetic field of the ceramic discharge channel, electrons undergo Larmor rotation. The combined axial electric field and radial magnetic field causes the electrons to drift in the azimuthal direction at a given velocity, producing a current denoted as the Hall current. These electrons collide with a neutral gas injected near the anode, producing ions and more electrons, and continue their azimuthal drift until discharging at the anode. To improve the overall performance, EP systems typically select an inert gas with a relatively large atomic mass, such as xenon (X_e), which is assumed for the remainder of this discussion. Because the xenon ion (X_e^+) mass is much greater than the electron mass, its