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Analytical and numerical investigations on spacecraft formation control by using electrostatic forces

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ABSTRACT

The paper investigates some analytical and numerical aspects of the formation control exploited by means of inter-spacecraft electrostatic actions. The analysis is based on the evaluation and check of the stability issues by using a sequence of purposely defined Lyapunov functions. The same Lyapunov approach can also define a specific under-actuate control strategy for controlling selected "virtual links" of the formation. Two different selection criteria for these links are then discussed, showing the implications on the control chain. An optimal charge distribution strategy, which assigns univocally the charges to all the spacecraft starting from the charge products computed by the control, is also presented and discussed. Numerical simulations prove the suitability of the proposed approach to a formation of 4 satellites.

1. Introduction

The electrostatic control of the spacecraft formations' configuration, obtained by means of purposeful satellite surface charging to generate attractive or repulsive actions, is a technique facing increasing interest, with the significant advantage of a quite high precision at a moderate cost [1]. Missions involving two or more spacecraft flying in very strict formation are allowed, with very limited consumption (low amount of required power) and a "gentle" behavior with respect to payload, with no plume impingement on the satellite bus: optical interferometry missions or distributed remote sensing system observing the Earth from higher orbits can be some of the applications of this control technique [2].

This concept of formation control presents some peculiar characteristics which strongly affect the resulting maneuvers and the formation behavior. Specifically, the magnitude of the electrostatic actions depends on the inverse of the square of the distance and their effects are attenuated by the surrounding plasma, meaning that electrostatic maneuvers are applicable only for the acquisition and maintenance of close formations in high orbits. Electrostatic forces are internal ones, implying that it is not possible to move collectively the formation. Furthermore they act only along the directions connecting each pair of spacecraft, so that only the inter-spacecraft spacing can be directly commanded. It is also important to notice that an unstable behavior results from the electrostatic control applied in an open-loop strategy, and a feedback is therefore required to acquire or maintain a desired configuration. The magnitude of control actions is defined by the product of the involved spacecraft charges, and not by their individual values and sign, generating some issues on the formation control implementation [3]. Specifically,

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global control strategies applied to the system could provide a set of charges' products which cannot be implemented: see the case of the three spacecraft formation represented in Fig. 1, where a simultaneous reduction of the sides of the triangle is not attainable [4].

Issues concerning the feasibility on the distribution of the charges to the spacecraft have been firstly addressed by Wang and Schaub [5], showing that control may require imaginary charges which cannot be physically implemented, and finding the necessary conditions leading to a feasible solution. The approach has been extended [4,6,7], to the case of three-craft planar formations, suggesting a strategy based on sequential, selective switches among the sides to be controlled. On the other hand, these studies have also remarked that further analytical researches are needed to improve the performance in terms of power consumption and to ensure larger stability boundaries, even when the number of the satellites belonging to the formation increases.

Indeed, the present paper aims to discuss these stability issues and to extend these techniques to formations involving more than three spacecraft. After a brief recall of the leading equations of motion that characterize the electrostatic control of the formations (Section 1), a new approach, based on the definition of virtual links, is suggested to face the problem (Section 2). The following paragraph (Section 3) presents the global control strategy adopted in this paper: a sequence of appropriate Lyapunov functions to be evaluated at fixed time steps allows the selection of the sides of formation to be controlled. Then (Section 4) two different selection criteria are discussed: the first and simplest one provides to charge sequentially only two out of N spacecraft of the formation, while the second one addresses the problem of the simultaneous charging of all the spacecraft. Therefore, an ad-hoc built non-linear controller permits to obtain the required charge products which must be distributed to the spacecraft (Section 5). An analytical approach allows to optimize the partition of these charges' products among the spacecraft, extending previous results limited to three platforms (Section 6). The suggested overall process is validated by means of a numerical simulation campaign (presented in Section 7), evaluating the advantages and the drawbacks of the two different possible selection criteria (single and multiple links) implemented in the control strategy. Conclusions finally provide a brief summary of the main results obtained by this analysis. An appendix is also included to recall the phenomena that occur during the spacecraft charging and the laws ruling them.

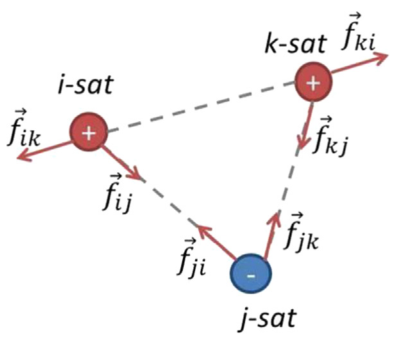

Fig. 1. Issues on the selection of the charge distribution.

2. Proximity equations of motion forced by electrostatic actions

The aim of this study is to analyze how is possible to control N spacecraft by means of the electrostatic forces. It is therefore needed to define a model which characterizes the electrostatic force acting to the spacecraft and which takes main environmental interactions into account. The problem has already been addressed in literature [8–10], facing the different aspect of spacecraft charging and interactions with the surrounding plasma. A brief resume of the charging model adopted in this paper is presented in Appendix A.

Modeling of the interactions among spacecraft simply by means of Coulomb law may produce inaccurate results: the space plasma exponentially reduces the magnitude of the force [10]. The scaling parameter is represented by the Debye length, which takes electron temperature (T_e) and electron density (n_e) of the space plasma into account and can be computed as:

$$\lambda_d = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e q^2}} \tag{1}$$

where $\varepsilon_0 = 8.854 \cdot 10^{-12}\, F/m$ is the vacuum dielectric constant, $q = 1.602 \cdot 10^{-19} C$ is the elementary charge and $k_B = 1.38 \cdot 10^{-23} J/K$ is the Boltzmann constant.

The resulting force acting on the i-th spacecraft and generated by the remaining members of the formation reads as:

$$\vec{f}_i = \frac{k_c}{m_i}\left[\sum_{\substack{j=1\\ j\neq i}}^{N} \frac{q_i q_j}{d_{ij}^2} e^{-\frac{d_{ij}}{\lambda_d}}\left(1+\frac{d_{ij}}{\lambda_d}\right)\hat{d}_{ij}\right] \tag{2}$$

where m_i is the spacecraft mass, q_i and q_j are respectively the charges of the i-th and the j-th spacecraft, and the vector $\vec{d}_{ij}$:

$$\vec{d}_{ij} = d_{ij}\hat{d}_{ij} = \vec{d}_i - \vec{d}_j \tag{3}$$

indicates the distance between these two spacecraft, with $\hat{d}_{ij}$ the relevant unit vector. The position vectors $\vec{d}_i$ and $\vec{d}_j$ are defined with respect to the Local Vertical Local Horizontal (LVLH) frame, whose origin is coincident with the center of mass of the formation F, and with $\hat{r}_R$, $\hat{\vartheta}_R$ and $\hat{h}_R$ axes representing the radial, the in-track and the orbit normal unit vectors respectively, as depicted in Fig. 2.

In Table 1 the typical values of the Debye length are reported for three different environmental conditions at different altitudes from the Earth. By considering that the electrostatic actions are effective only if the inter-spacecraft distances are below the Debye length, it is evident that the geostationary orbit (GEO) altitude range – and the geosynchronous at large – is eligible for exploiting this kind of control.