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Three spacecraft formation control by means of electrostatic forces

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ABSTRACT

This paper focuses on electrostatic orbital control in formation flying by using switching strategies for charge distribution. Natural and artificial charging effects are taken into account, and limits in charging technology and in power requirements are also considered. The case of three spacecraft formation, which is intrinsically different and more difficult than the two spacecraft problem often analyzed in literature, has been investigated. A Lyapunov based global control strategy is presented and applied to perform formation acquisition and maintenance maneuvers, producing as output the required overall charge. Then, a selective and optimized charge distribution process among the satellites is discussed for avoiding charge breakdowns to surrounding plasma, for reducing the power requirements and the number of charge switches. The results of numerical simulations show the advantages and drawbacks of the selected control technique.

0. Introduction

The use of electrostatic forces has been recently proposed for formation acquisition, maintenance and reconfiguration [1]. This new concept of formation control is based on the idea of generating attractive or repulsive actions among spacecraft by charging the satellites' surfaces, in order to control their mutual distances. The use of electrostatic forces allows new kind of missions, involving two or more spacecraft in very strict formation, with a considerably low amount of required power to perform the formation-keeping and maintenance maneuvers. The applications which can primarily benefit from this control technique are optical interferometry missions like planetary detectors or distributed remote sensing system observing the Earth from high orbits (MEO and GEO) [2].

With respect to the classical formation control the most suitable advantages are [2]: (a) no risk of plume impingement or contamination of neighboring spacecraft, which is especially important for optical payload, (b) high equivalent specific impulse (up to 6000 s) [3], despite limited electrical power requirements and (c) very high precision in control. Classic chemical propulsion systems cannot provide so fine and continuous thrust. On the other hand, electric thrusters allow for strict formation position tolerances, but the generated ion fluxes pollute the environment in a way which is especially dangerous in case of optical payloads. Instead, the Coulomb force based control concept allows for continuous, fine-resolution maneuverability, which will greatly improve formation acquisition and maintenance maneuvers, because of the rapidity at which the Coulomb forces can be continuously varied [2].

A limit of the technique is represented by the effectiveness of the electrostatic action that is related to the Debye length parameter, quantifying the shielding effect generated by space plasma. As a result, electrostatic control seems better suitable for high altitude orbits and close distances among the spacecraft [4].

It is worth to notice that formation dynamics present an unstable behavior if controlled by means of electrostatic forces applied in an open-loop strategy. Therefore, a feedback law is needed to gain a suitable behavior. The extensive research effort by Schaub et al. produced significant advances on modelling and control formations of two [5–7], three [8–10] and more [11] spacecraft. These studies clearly demonstrated the possibility to acquire and to precisely maintain desired distances between spacecraft.

This paper is then focused on the strategies to distribute the charges in formations involving three platforms, with the goal to attain the desired configuration in a fast and efficient way. It is worth to notice that, in the case of three spacecraft a global convergence of the applied controls is not always assured. Some

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Table 1
Models of charge exchanges between the spacecraft and the space environment.

Current	$V_{sc} > 0$	$V_{sc} \le 0$	Relations
Plasma electron current	$I_e = I_{e0}(1 + \frac{qV_{sc}}{T_e})$	$I_e = I_{e0}\exp(\frac{qV_{sc}}{T_e})$	$I_{e0} = -\frac{qn_e A_{sc}}{2}\sqrt{\frac{2T_e}{\pi m_e}}$
Plasma ion current	$I_i = I_{i0}\exp(-\frac{qV_{sc}}{T_i})$	$I_i = I_{i0}(1 - \frac{qV_{sc}}{T_i})$	$I_{i0} = \frac{qn_i A_{sc}}{2}\sqrt{\frac{2T_i}{\pi m_i}}$
Photoelectron current	$I_{ph} = I_{ph0}\exp(-\frac{qV_{sc}}{T_{ph}})$	$I_{ph} = I_{ph0}$	$I_{ph0} = J_{ph0}A_{\perp}$

charge products, which are given as output by the controllers, can lead to imaginary charge values which are not feasible in reality [9]. This issue has been avoided in [8–10] by selectively re-designing the control schemes and considering only few tasks on the basis of a priority criteria. These schemes however do not lead to a global convergence of the formation and involve repetitive switches among the controllers. With respect to the previous studies [8–10], we propose to use an unique global control scheme, which computes first the necessary charge products and then, by selecting only some of those products, evaluates the commands for the formation. The selection of the product charge is dictated by an optimized distribution strategy that assigns the charges to spacecraft in order to minimize a cost function and by taking into account the constraints in charge and current limits due to the charging technology. The problem of charge chattering is also addressed by introducing dead-zones in the controller which define the precision whereby the formation can be acquired and maintained.

Following material begins with the description of the governing equations of spacecraft charging in presence of the environmental ion/electron fluxes and of the currents produced by the actuators (in Section 1). Then the equations of motion describing the dynamics of the three spacecraft formation forced by electrostatic actions is presented in Section 2. The overall control scheme adopted is described in Section 3. Then a selection criteria, the switching strategy for the case of three spacecraft formation as well as optimal charge distribution laws satisfying a part of the charge products obtained from the global controller are presented in Section 4. The introduction of the dead-zones for the controller is proposed in Section 5. The numerical results for the three-spacecraft formations are reported in the last section (Section 6) before the conclusion. The results, in terms of possible formation behaviors and energy consumptions, prove the interest of the proposed technique.

1. Spacecraft charging model

The space plasma, interacting with the spacecraft surfaces, naturally generates charging effect in the outer surfaces of the spacecraft [4]. The phenomenon depends upon the local plasma temperature of electrons/ions, the solar flux and the voltage reached by the spacecraft. The spacecraft charge dynamics results from the equilibrium between fast electrons and slower ions fluxes from/to the spacecraft and the neighbor space plasma: if the spacecraft is charged with positive charges, it will attract electrons coming from the surrounding plasma, vice-versa a flux of positive ions from the plasma will occur if the spacecraft charge is negative. An additional flux – the photoelectric one – is due to the impinging solar radiation which produces an emission of electrons from the surface.

In order to take these phenomena into account, the resulting electron (I_e), ion (I_i) and photoelectric (I_{ph}) currents can be modelled by means of laws, which can be found in literature [12–14], summarized briefly in Table 1.

In Table 1 V_{sc} is the spacecraft potential (in volts, V), $q = 1.602 \cdot 10^{-19}$ C is the elementary charge, T_e and T_i are the plasma electron and ion energies (in joules, J), m_e and m_i are the electron and ion masses (in kilograms, kg), n_e and n_i are the densities of the plasma electrons and ions (m^{-3}), J_{ph0} and T_{ph} are the photoelectron flux (A/m^2) and the energy of the emitted electrons (in joules, J[4]) respectively, A_{sc} is the spacecraft external surface and $A_{\perp}$ is the spacecraft surface exposed to the sun light (m^2).

Specific devices as the hollow cathodes, electron guns [15], or the ion emitters [16], are commonly adopted for neutralizing the electrostatic charge of the spacecraft with respect the neighbor environment. The possibility to use these devices for actively controlling the charge of the spacecraft with respect to the neighbor plasma potential has been experimentally demonstrated by SCATHA [17] and ATS [18] missions.

The control current I_c is due to the actuators and can be modelled as follows:

$$I_c = \begin{cases} +I_{s+} & \text{if } I_{rq} > I_{s+} \\ k_c I_{rq} & \text{if } I_{s-} < I_{rq} < I_{s+} \\ -I_{s-} & \text{if } I_{rq} < I_{s-} \end{cases} \tag{1}$$

where I_{rq} is the requested current (which will be computed by a dedicated controller) and the I_{s+} and I_{s-} are the saturation currents of the hollow cathodes and ion emitters respectively.

The fundamental physical process for the spacecraft charging is based on the following charging equation:

$$\frac{dq_{sc}}{dt} = I_e + I_i + I_{ph} + I_c \tag{2}$$

where q_{sc} is the spacecraft charge.

The resulting spacecraft potential V_{sc} with respect to the surrounding environment is computed by means of the following relation:

$$V_{sc} = \frac{q_{sc}}{C_{sc}} \tag{3}$$

where C_{sc} is the resulting electric capacitance of the external spacecraft surfaces that, in the simplest case of a spherical shape (radius R_{sc}) spacecraft, reads as $C_{sc} = 4\pi\varepsilon_0 R_{sc}$, with $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m.

In order to avoid uncontrolled breakdowns between the spacecraft and the outer plasma, a condition concerning the differences between their potentials must be satisfied during all the maneuvers. Such a condition can be roughly written as $V_{sc} - V_{pl} < \Delta V_{br}$, where V_{pl} is the potential of the plasma and ΔV_{br} is the maximum admissible potential ensuring that no destructive breakdown current occurs. In order to take into account this problem, a saturation limit on spacecraft charge is included by adding the following relation:

$$q_{s-} \le q_{sc} \le q_{s+} \tag{4}$$

where q_{s-} and q_{s+} are the lower and upper limits of the spacecraft charges calculated by taking into account Eq. (3) and the breakdowns potential limits.

The power needed to charge the spacecraft can be computed by the following relation [1]:

$$P_{sc} = I_c V_{sc} \tag{5}$$

[4] The plasma energy is generally measured in electronvolts (eV), but the authors preferred to refer all quantities to the International System of Units. Conversion factor is 1 eV = $1.60 \cdot 10^{-19}$ J.