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Relative control of an ion beam shepherd satellite using the impulse compensation thruster

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ABSTRACT

The “ion beam shepherd” is a recently proposed concept for removing space debris in a contactless manner. A shepherd satellite must be controlled to move at a certain small distance in front of a space debris object during the de-orbiting phase. Because of the considerable duration of this phase, the propellant consumption is a key requirement for the control design. In this paper, the in-plane relative position of the shepherd is maintained using a small thrust variation of the compensation thruster. The controller is designed and analyzed considering the time-varying and parametric uncertain plant in the presence of the ion beam and orbital perturbations, sensor noise, actuation errors, taking into account limitations on the controller output. The system robustness and specified requirements are confirmed both by a formal criteria and numerical simulations. The estimations show that this control strategy is more efficient in terms of propellant consumption than the conventional approach with chemical thrusters.

1. Introduction

The space community has been investigating techniques and technologies that have the potential to support debris removal from Earth orbit. A concept of contactless removal of space debris objects named “ion beam shepherd” (IBS) [1] has a number of advantages in comparison with other technologies, namely: acceptable de-orbiting performance, a low risk level, reusability (multimission) capabilities, and technological readiness.

According to the IBS concept, a shepherd satellite (SS) is equipped with an impulse transfer thruster (ITT) and an impulse compensation thruster (ICT). The ion plume from the ITT is pointed towards a space debris object (SDO) and used for transferring the de-orbiting momentum. The nozzle of the ICT is pointed in the opposite direction to compensate the reaction force created by the ITT (Fig. 1).

For efficient contactless de-orbiting, the SS has to fly on a sufficiently small distance in front of the SDO of the order of a few SDO diameters. To maintain this distance, it is not enough just to compensate the ITT force because the SS-SDO relative dynamics are unstable. Therefore, the SS must have a system to control its position relative to the SDO [1].

Relative motion control systems are used on spacecraft performing rendezvous and docking operations are examples of such control systems. Conventional approaches to construct such systems are presented in Refs. [2,3]. Both studies assume that the actuators for formationkeeping are chemical thrusters. Thrust is available along all three translational axes to control the position of the spacecraft. However, the specific impulse of such thrusters is much less than that of the electric ones. This feature and the duration of the de-orbiting phase implies that, depending on the specific design, the mass of hydrazine to control the SS relative position may be an important share of the total propellant consumption of the mission.

In this paper, we investigate another control strategy to reduce the propellant consumption. To maximize the de-orbiting rate of the SDO, it is desirable to maintain a maximum magnitude ITT thrust. At the same time, the thrust of the ICT can be varied to control the relative motion of the SS.

A recent work [4] shows that a quite smooth and accurate thrust control for an ion propulsion assembly can be achieved. Spacecraft formation control using no radial thrust has been examined in several studies [5–7]. Leonard et al. [5] applied along-track input in the form of differential drag by changing ballistic coefficients of both satellites of the formation. However, these results cannot be used for an ion beam debris removal problem since space debris objects unable to cooperate with the SS. The study [6] considers linear-quadratic regulators with no radial axis inputs using a Cartesian coordinate model. The stability analysis is not undertaken and the stability conditions are not stated. Starin et al. [7] present the design and analysis of a simple linear

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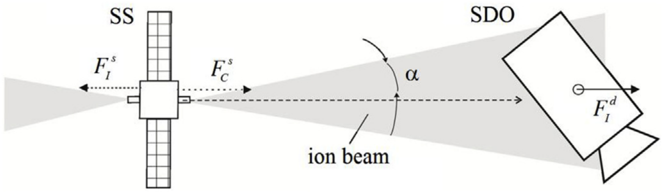

Fig. 1. IBS concept.

regulator for formation flying of satellites using thrust in along-track direction. The ability to provide the relative position error below the meter level is confirmed by numerical simulation. However, these papers do not consider the effects of several factors, which are relevant for the IBS concept. For example, there is a disturbing effect from the ion beam; the controller output is limited since only one thruster is used as the actuator; measurements of the state vector are corrupted by noise; the SDO mass is not exactly known; the model of the relative dynamics is time-variant. These issues are examined in this paper.

Since the IBS concept is relatively new, the literature devoted to it is still small. In the IBS seminal paper [1], the problem of SS relative control was just mentioned and its complexity and importance was emphasized. An original method to determine the force transmitted by an ion beam to a SDO was proposed in Ref. [8]. The method allows determining this force on the SS board using a visual camera [9]. The influence of the ion beam forces on the stability of the relative motion of the SS was studied in Refs. [10,11]. It was shown that the open-loop in-plane dynamics are always unstable and the motion out of the orbital plane is stable only for the case when the radial destabilizing effect of the beam does not prevail against the gravity gradient restoring force in the direction normal to the orbit plane. A three-axis thruster-based proportional derivative feedback control system to control the SS-SDO relative motion was designed and investigated in Ref. [10], but such issues as sensor noise and control costs were not addressed.

Since the controllers without radial output simplify the architecture of the control system and may improve its fuel efficiency [6], in this paper we investigate the feasibility of maintaining the predetermined SS relative position using only a small variation of the ICT thrust. The robust stability/performance tradeoff is achieved for the time-varying and parametric uncertain plant in the presence of the ion beam and orbital perturbations, sensor noise, actuation errors, taking into account limitations on the controller output.

The remainder of this paper is organized as follows. The problem statement and the data used for the study are presented in Section 2. Section 3 describes the equations of the relative dynamics. Some background on the ion beam perturbation is given in Section 4. Section 5 presents the uncertainty model of the plant. The controller is designed in Section 6. Section 7 analyses robust stability and performance of the system. Section 8 validates the proposed approach numerically. Finally, conclusions are gathered in Section 9.

2. Problem statement and system data

In this paper, we consider the de-orbiting of a SDO from a low Earth orbit using the IBS technology. The thrust of the ITT is held constant. The ICT is used as an actuator to maintain the SS predetermined position with respect to the SDO. It is assumed that the ICT thrust can be varied around its nominal value within a certain range.

The control system has some sensors that can measure the coordinates of the vector that determines a SDO position with respect to the SS. These measurements are corrupted by noise.

Only the relative dynamics parallel to the orbital plane is considered in this study, assuming that the accuracy required for the SS positioning in the direction perpendicular to the orbital plane is provided in some other way. Such assumption is made due to the following reasons: on the one hand, the relative in-plane dynamics are always unstable, more difficult to control, and decoupled from the out-of-plane ones [10,11], the accelerations in the tangent direction can guarantee the controllability only the in-plane motion of the formation.

Table 1
System data.

Parameter	Values
Initial altitude of the orbit [km]	640
Final altitude of the orbit [km]	340
Inclination of the orbit [deg]	90
Eccentricity of the orbit	≤ 0.05
Mass of the SS [kg]	500 ± 50
Mass of the SDO [kg]	1575 ± 315
Errors of the determination of the SDO relative position (in x, y, and z directions) [m]	≤ 0.1
Actuation errors (in x, y, and z directions) [N]	$\le 1{\cdot}10^{-4}$

The main aim of this study is to design a controller to maintain the SS relative position using the ICT as an actuator during the SDO de-orbiting. The controller must guarantee the closed-loop robustness to all the disturbing effects relevant for the de-orbiting stage.

The controller was designed and the relative dynamics of the SS was analyzed for the data presented in Table 1.

3. Equations of motion

A Local-vertical/local-horizontal frame $Oxyz$ (LVLH) is used to determine the position of the SS with respect to the SDO. The frame origin is at the center of mass of the SS. The x -axis points along the position vector of the SS, with respect to the Earth. The z -axis is taken along the direction normal to the plane defined by the orbital position and velocity vectors, and pointing towards the positive values of the orbital angular momentum. The y -axis forms a right-handed coordinate system.

The in-plane relative dynamics for the SDO-SS formation can be described using the following system of linearized equations [12]:

$$\ddot{x} - \omega^2 x - 2\omega\dot{y} - \dot{\omega}y - kx = \frac{f_x^d}{m^d} - \frac{f_x^s}{m^s},$$
$$\ddot{y} - \omega^2 y + 2\omega\dot{x} + \dot{\omega}x + ky = \frac{f_y^d}{m^d} - \frac{f_y^s}{m^s}, \tag{1}$$

where x, y are the coordinates of the position vector that represents the position of the center of mass of the SDO with respect to the origin of the LVLH; m^s and m^d are the masses of the SS and SDO, respectively; f_x^s and f_y^s are the forces applied to the SS in the x and y directions, respectively; f_x^d and f_y^d are the forces applied to the SDO in the x and y directions, respectively.

The parameters of equation (1) are calculated as follows:

$$\omega = \sqrt{\frac{Gm}{p^3}}(1 + \varepsilon\cos\upsilon),\ \ p = a(1-\varepsilon^2),$$
$$\dot{\omega} = -2\varepsilon\sqrt{\frac{Gm}{p^3}}\sin\nu(1+\varepsilon\cos\upsilon)\omega,$$
$$k = \frac{Gm}{R^3},\ \ R = \frac{a(1-\varepsilon^2)}{1+\varepsilon\cos\upsilon}, \tag{2}$$

where Gm is the Earth gravitation constant; υ is the true anomaly; ε is the eccentricity of the orbit; a is the semi-major axis.

The system (1) is time-varying. In fact, the altitude of the SDO orbit is getting smaller with time due to the ion beam de-orbiting force. The mass of the SS is also decreasing as propellant is consumed. In addition to that, for elliptic orbits, the parameters of the model (1) are also functions of the true anomaly.

We represent the ICT thrust using two components as follows:

$$f_c = f_c^n + f_c^v \tag{3}$$

where f_c^n and f_c^v are the nominal and variable component of the ICT thrust, respectively.