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Output feedback control of Lorentz-augmented spacecraft rendezvous

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ABSTRACT

A Lorentz spacecraft is an electrostatically charged space vehicle that could modulate the surface charge to induce Lorentz force as propellantless electromagnetic propulsion for orbital maneuvering. Modeling the Earth's magnetic field as a tilted dipole corotating with Earth, a dynamical model of Lorentz-augmented spacecraft relative motion about arbitrary elliptic orbits is developed, based on which the optimal open-loop trajectory of Lorentz-augmented rendezvous is solved by Gauss pseudospectral method. To track the open-loop trajectory in the presence of external perturbations and without velocity measurements, a reduced-order observer and an output feedback controller are designed, ensuring the stability of the closed-loop system by a Lyapunov-based approach. Numerical simulations verify the validity of both the open-loop and closed-loop controllers.

1. Introduction

Spacecraft are naturally to be charged in the ambient plasma environment, which is generally undesirable due to its deleterious effects on electronics on board [10]. Differently from traditional researches on the passive mitigation of spacecraft charging, a new conception of Lorentz spacecraft that actively generates electrostatic charge on its surface to induce the Lorentz acceleration for orbital maneuvers via interaction with surrounding magnetic field has been proposed by Peck [11]. This kind of propellantless electromagnetic propulsion is preferable and promising in a series of applications, such as spacecraft rendezvous [14,19,7], spacecraft hovering [2,5,8], formation flying [12,16,15,6], planetary capture and escape [3,4], orbital inclination control [13] and so on. Despite the distinct advantages over traditional spacecraft in saving propellant, the space mission design of Lorentz spacecraft is complicated by the fact that the Lorentz force could only act in the direction perpendicular to the local magnetic field and the vehicle velocity relative to the local magnetic field. Meanwhile, a Lorentz spacecraft is more effective in low Earth orbit (LEO) where the magnetic field is much intenser and the spacecraft travel faster to induce Lorentz force.

Natural charging levels may reach to the order of 10^{-8} C/kg, and the resulting Lorentz acceleration may not perturb the orbit in a significant way [17]. Efficient orbital control in LEO necessitates charging levels higher than 10^{-5} C/kg [13]. A specific charge of 0.03 C/kg seems to be the near-term feasible maximum [11]. Though insufficient for absolute orbital control such as LEO inclinations control, it is adequate to the relative orbital control such as spacecraft rendezvous.

Several previous researches have dealt with Lorentz-propelled spacecraft rendezvous problems based on the linearized models that describe the relative motion of Lorentz spacecraft. Modeling the Earth's magnetic field as a tilted dipole corotating with Earth, Pollock et al. [14] derived approximate analytical solutions to the linearized equations of Lorentz spacecraft relative motion about circular orbits, based on which a rendezvous strategy was designed that the chaser initially locates in the in-track direction of the target in a circular equatorial orbit with zero relative velocity. Then, maintaining a constant specific charge could achieve rendezvous at the final time which should equal an integer number of orbit periods and an integer number of days. Such constraints on the initial relative states and the maneuver time arise from the characteristics of linearized Lorentz spacecraft relative motion. Similarly, by assuming that the Earth's magnetic dipole is nontilted, Yamakawa et al. [19] investigated the relative dynamics of Lorentz spacecraft about elliptic reference orbits, and designed propellantless planar rendezvous strategies in equatorial orbits. Actually, the Earth's magnetic dipole is tilted by nearly 11.3° with respect to the rotation axis of Earth. Considering this fact, Huang et al. [8] developed a nonlinear dynamical model of Lorentz spacecraft relative motion about arbitrary elliptic Earth orbits, and applied it to solve the optimal trajectory of Lorentz-propelled spacecraft rendezvous with no similar aforementioned constraints on initial relative states or maneuver duration by Gauss pseudospectral method (GPM) [9]. However, nearly all of the aforementioned strategies are open-loop

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control methods. To fulfill rendezvous in the presence of external perturbations, closed-loop controllers remain to be designed.

Previous researches on closed-loop Lorentz spacecraft relative motion control indicate that the relative motion is not fully controllable by using the Lorentz force alone [15,6]. To render the relative motion fully controllable, other kind of propulsion requires to be supplemented, such as the thruster-generated control acceleration. Due to this reason, in solving the optimal open-loop rendezvous trajectory which will be tracked by the closed-loop controller, hybrid control inputs consisted of the specific charge and the thruster-generated control acceleration of Lorentz spacecraft are considered, and the resulting trajectory is a Lorentz-augmented one but not a Lorentz-propelled one in our previous works that singly uses Lorentz force as propulsion for open-loop rendezvous [9]. Nevertheless, by choosing appropriate objective function, a nearly propellantless rendezvous could also be achieved that the magnitude of the required thruster-generated control acceleration is nearly the same order as that of the external perturbations or even smaller. Present closed-loop controllers for Lorentz-augmented spacecraft relative motion are almost all full-state feedback controllers [8,6], which are thus inapplicable to cases without relative velocity measurements. Since eliminating velocity sensors could reduce the cost and mass for control system [18], to handle the relative motion control without velocity measurements, an output feedback controller is designed in this paper.

The organization of this paper proceeds as follows. A nonlinear dynamical model for Lorentz-augmented spacecraft relative motion is developed in Section 2, followed by the description of open-loop control method in Section 3. Section 4 elaborates the design of a reduced-order velocity observer and a closed-loop output feedback controller. Numerical simulations are presented in Section 5, and Section 6 concludes the paper.

2. Dynamical model

2.1. Equations of relative motion

Consider two spacecraft subjects to the Earth's gravity field, which are referred to as the chaser and target spacecraft, respectively. The chaser is assumed to be a charged Lorentz spacecraft while the target is an uncharged one. As illustrated in Fig. 1, $O_E X_I Y_I Z_I$ is an Earth-centered inertial (ECI) frame with its origin locating at the center of Earth, O_E. $O_T xyz$ is the relative motion (RM) frame located at the center of mass (c.m.) of the target spacecraft, O_T, where x axis is aligned with the radial direction, z axis is along the normal direction of the target's orbital plane, and y axis completes the Cartesian right-handed frame. And O_L is the c.m. of the Lorentz spacecraft.

The equations of orbital motion of the Lorentz spacecraft and the target spacecraft are, respectively, given by

$$\frac{\mathrm{d}^2\mathbf{R}_L}{\mathrm{d}t^2} = -\frac{\mu}{R_L^3}\mathbf{R}_L + \mathbf{a}_L + \mathbf{a}_C \tag{1}$$

$$\frac{\mathrm{d}^2\mathbf{R}_T}{\mathrm{d}t^2} = -\frac{\mu}{R_T^3}\mathbf{R}_T \tag{2}$$

where $\mathbf{R}_L$ and $\mathbf{R}_T$ are, respectively, the orbital radius vector of the Lorentz and target spacecraft. $\mathbf{a}_L = [\,a_x \quad a_y \quad a_z\,]^{\mathrm{T}}$ and $\mathbf{a}_C = [\,a_r \quad a_s \quad a_w\,]^{\mathrm{T}}$ refer to the Lorentz acceleration and the thruster-generated control acceleration acting on the Lorentz spacecraft, respectively. μ is the gravitational parameter of Earth.

Denote by $\boldsymbol{\rho} = \mathbf{R}_L - \mathbf{R}_T = [\,x \quad y \quad z\,]^{\mathrm{T}}$ the position vector of the chaser with respect to the target expressed in RM frame, then, the governing dynamics of Lorentz spacecraft relative motion can be described in RM frame as [5]

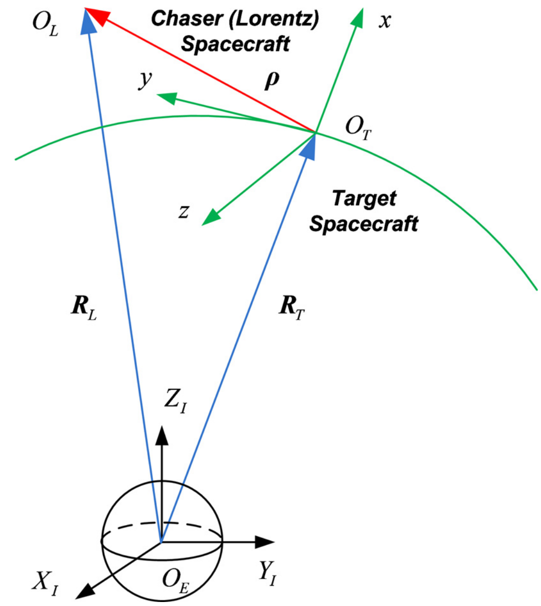

Fig. 1. Definition of coordinate frames.

$$\ddot{\boldsymbol{\rho}} = [\,\ddot{x} \quad \ddot{y} \quad \ddot{z}\,]^{\mathrm{T}} = \mathbf{M}(\boldsymbol{\rho}, \dot{\boldsymbol{\rho}}) + \mathbf{a}_L + \mathbf{a}_C \tag{3}$$

with

$$\mathbf{M}(\boldsymbol{\rho}, \dot{\boldsymbol{\rho}}) = \begin{bmatrix} 2\dot{u}_T\dot{y} + \dot{u}_T^2 x + \ddot{u}_T y + n_T^2 R_T - n_L^2(R_T + x) \\ -2\dot{u}_T\dot{x} + \dot{u}_T^2 y - \ddot{u}_T x - n_L^2 y \\ -n_L^2 z \end{bmatrix} \tag{4}$$

where $n_T = \sqrt{\mu/R_T^3}$ and $n_L = \sqrt{\mu/R_L^3}$, with $R_L = [(R_T + x)^2 + y^2 + z^2]^{1/2}$ being the orbital radius of the Lorentz spacecraft. u_T is the argument of latitude of the target, thus, $\dot{\mathbf{u}}_T = [\,0 \quad 0 \quad \dot{u}_T\,]^{\mathrm{T}}$ and $\ddot{\mathbf{u}}_T = [\,0 \quad 0 \quad \ddot{u}_T\,]^{\mathrm{T}}$ are, respectively, the orbital angular velocity and acceleration vector of the target. $\dot{\boldsymbol{\rho}} = [\,\dot{x} \quad \dot{y} \quad \dot{z}\,]^{\mathrm{T}}$ denotes the relative velocity vector.

2.2. The Lorentz acceleration

By assuming that the Lorentz spacecraft could be regarded as charged point mass and that the Earth's magnetic field could be modeled as a tilted dipole corotating with Earth, the Lorentz acceleration acting on the Lorentz spacecraft is given by

$$\mathbf{a}_L = \lambda\mathbf{V}_r \times \mathbf{B} \tag{5}$$

where $\lambda = q/m$ is the specific charge of Lorentz spacecraft, with q and m being the charge and the mass of Lorentz spacecraft, respectively. $\mathbf{V}_r$ refers to the velocity of Lorentz spacecraft relative to the local magnetic field $\mathbf{B}$.

Based on the assumption of a tilted dipole, the local magnetic field at the Lorentz spacecraft can be described as [14]

$$\mathbf{B} = [\,B_x \quad B_y \quad B_z\,]^{\mathrm{T}} = \left(B_0/R_L^3\right)\left[3\left(\mathbf{n}^0 \cdot \mathbf{R}_L^0\right)\mathbf{R}_L^0 - \mathbf{n}^0\right] \tag{6}$$

where $B_0 = 8.0 \times 10^{15}$ T m^3 is the Earth's magnetic dipole moment. The superscript 0 represents a unit vector in that direction. For example, the unit orbital radius vector of the Lorentz spacecraft can be expressed in RM frame as

$$\mathbf{R}_L^0 = (1/R_L)\,[\,R_T + x \quad y \quad z\,]^{\mathrm{T}} \tag{7}$$

$\mathbf{n}^0$ is the unit magnetic dipole moment vector, which can be described in ECI frame as

$$\mathbf{n}^0 = -\cos\Omega_M \sin\alpha\mathbf{X}_I^0 - \sin\Omega_M \sin\alpha\mathbf{Y}_I^0 - \cos\alpha\mathbf{Z}_I^0 \tag{8}$$