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Formation flying for electric sails in displaced orbits. Part II: Distributed coordinated control

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Abstract

We analyze a cooperative control framework for electric sail formation flying around a heliocentric displaced orbit, aiming at observing the polar region of a celestial body. The chief spacecraft is assumed to move along an elliptic displaced orbit, while each deputy spacecraft adjusts its thrust vector (that is, both its sail attitude and characteristic acceleration) in order to track a prescribed relative trajectory. The relative motion of the electric sail formation system is formulated in the chief rotating frame, where the control inputs of each deputy are the relative sail attitude angles and the relative lightness number with respect to those of the chief. The information exchange among the spacecraft, characterized by the communication topology, is represented by a weighted graph. Two typical cases, according to whether the communication graph is directed or undirected, are discussed. For each case, a distributed coordinated control law is designed in such a way that each deputy not only tracks the chief state, but also makes full use of information from its neighbors, thus increasing the redundancy and robustness of the formation system in case of failure among the communication links. Illustrative examples show the effectiveness of the proposed approach.

Keywords: Electric solar wind sail; Displaced orbit; Formation flying; Distributed control

1. Introduction

In recent years, much effort has been devoted to the study of an Electric Solar Wind Sail (E-sail), an interesting propulsion system that uses the natural solar wind dynamic pressure to generate a continuous low-thrust, without the need of any reaction mass (Janhunen and Sandroos, 2007; Mengali et al., 2008; Sanchez-Torres, 2016). A potential and challenging mission scenario of an E-sail-based spacecraft is to generate a heliocentric closed trajectory, usually referred to as displaced orbit (McInnes, 1997; Gong and Li, 2014; Salazar et al., 2016), in which the continuous propulsive acceleration is used to shift the spacecraft orbital plane off the Sun's center-of-mass. A scientific application of this unusual trajectory is, for example, to continuously observe the polar region of a celestial body, such as a planet or an asteroid. However, the propulsive requirements for this kind of mission scenario, given in terms of maximum value of propulsive acceleration necessary to maintain the displaced orbit, could be beyond the technological capabilities of an E-sail propulsion system. A possible solution to this problem is to reduce the spacecraft launch mass (with a subsequent increase of the E-sail characteristic acceleration) by distributing the payload among different E-sail-based vehicles operating in a formation flight, where each functional module (spacecraft) of

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Nomenclature

a	orbital semimajor axis [au]
$a_\oplus$	spacecraft characteristic acceleration [$\mathrm{mm/s^2}$]
$\boldsymbol{a}$	propulsive acceleration [$\mathrm{mm/s^2}$]
B	celestial body
e	orbital eccentricity
$\boldsymbol{e}$	relative position errors [m]
$\mathcal{E}$	set of edges
f	true anomaly [rad]
$\mathcal{G}$	communication topology graph
H	displacement [au]
I	identity matrix
$\mathcal{L}$	Laplacian matrix (with entries $[l_{ij}]$)
N	number of deputy spacecraft
n	mean motion of displaced orbit [rad/day]
n_r	angular velocity of reference relative orbit [rad/day]
O	Sun's center-of-mass
o	focus of displaced orbit
$\boldsymbol{q}$	auxiliary vector
R	focus-spacecraft distance [au]
$\boldsymbol{r}$	position vector (with $r = \|\boldsymbol{r}\|$) [au]
S	spacecraft
t	time [days]
$\mathcal{T}_I$	inertial reference frame
$\mathcal{T}_R$	rotating reference frame
$\boldsymbol{u}$	control input of deputy
$\mathcal{V}$	set of vertices
$\hat{\boldsymbol{x}}, \hat{\boldsymbol{y}}, \hat{\boldsymbol{z}}$	unit vectors of coordinate axes

$\mathcal{W}$	weighted adjacency matrix (with entries $[w_{ij}]$)
α	cone angle [rad]
β	lightness number
γ	elevation angle [rad]
θ, φ	attitude angles [rad]
κ	dimensionless propulsive acceleration
$\mu_\odot$	Sun's gravitational parameter [$\mathrm{au^3/day^2}$]
ρ_x, ρ_y, ρ_z	components of relative position vector in chief's rotating frame [km]
$\boldsymbol{\rho}$	relative position vector [km]
υ	vertex
$\boldsymbol{\omega}$	angular velocity vector (with $\omega = \|\boldsymbol{\omega}\|$) [rad/s]

Subscripts

B	celestial body
C	chief
i	i-th deputy
max	maximum
S	spacecraft
$\odot$	Sun

Superscripts

$\star$	reference value
T	transpose
$\cdot$	time derivative
$\wedge$	unit vector

the formation takes the essential mass only (Mazal and Gurfil, 2013; Salazar et al., 2015).

So far, the control problem of different spacecraft flying around a heliocentric displaced orbit falls into two main categories, that is, control with single or leader-follower strategy. In the first case the concept is to distribute a number of sail-based (either photonic solar sail or E-sail) spacecraft into different displaced orbits and to control them separately, without the need of any real-time information about the position of each spacecraft with respect to the chief vehicle (Wang et al., 2016b,a). In a companion paper (Wang et al., in press) the same idea has been applied to a set of E-sail spacecraft in a formation flight. With such a simple control strategy, some typical formation geometries, as well as the bounds of the spacecraft relative motion, can be analytically estimated by selecting the displaced orbital elements. However, the robustness of the formation system cannot be guaranteed since no stability control is involved.

The second concept, instead, assumes the chief spacecraft to follow a prescribed displaced orbit, and the deputies to adjust their thrust vectors (that is, both the sail attitude and the characteristic acceleration) in order to track the desired relative trajectories with respect to the chief (Gong et al., 2007, 2011). This is the so called chief-deputy or leader-follower control strategy. Nevertheless, inherent limitations also exist in the latter system arrangement. For example, the unique chief spacecraft, which represents the only information source about the reference state for each deputy, is a single point of massive failure for the whole group (Ren, 2007). Another weakness associated with a chief-deputy strategy is the absence of a mutual feedback information flow throughout the formation structure. As a result, an unfavorable situation may arise if a fault happens in the chief-deputy communication links. A possible improvement consists in including the information exchange among the deputies into the feedback control. In addition, it has been proved that the mutual connection of agents also contributes to an accuracy enhancement during the transient motion (Ren, 2006).

Recognizing these issues, this paper concentrates on the problem of cooperative control for multiple E-sail formation flight around a heliocentric (elliptic) displaced orbit, by making full use of the measurable information among the formation structure. In particular, two qualitatively

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