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Switch programming of reflectivity control devices for the coupled dynamics of a solar sail

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Abstract

As demonstrated in the Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS), reflectivity control devices (RCDs) are switched on or off independently with each other, which has nevertheless been ignored by many previous researches. This paper emphasizes the discrete property of RCDs, and aims to obtain an appropriate switch law of RCDs for a rigid spinning solar sail. First, the coupled attitude–orbit dynamics is derived from the basic solar force and torque model into an underdetermined linear system with a binary set constraint. Subsequently, the coupled dynamics is reformulated into a constrained quadratic programming and a basic gradient projection method is designed to search for the optimal solution. Finally, a circular sail flying in the Venus rendezvous mission demonstrates the model and method numerically, which illustrates approximately 10^3 km terminal position error and 0.5 m/s terminal velocity error as 80 independent RCDs are switched on or off appropriately.

Keywords: Solar sail; Coupled attitude–orbit dynamics; Reflectivity control devices; Gradient projection method

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1. Introduction

Due to its capability of generating propulsion without fuel consumption, the solar sail has been envisioned to enable or enhance a wide range of mission applications throughout the solar system (Macdonald and McInnes, 2011). Some previous literature (Gong and Li, 2014; Zeng et al., 2014) mainly focused on the orbit design of a solar sail and assumed that the attitude can change instantaneously. However, the propulsion exerted by solar radiation pressure (SRP) is related to the angle between the sunlight and the normal vector of the sail surface, so the orbit dynamics and attitude dynamics are not completely independent of each other (Gong et al. 2009; Zhang and Wang, 2013). Thus, neither the attitude maneuver process nor the attitude–orbit coupled effects can be neglected.

Starting from the above idea, Gong et al. (2009) developed the coupled attitude–orbit dynamics for displaced solar orbits and discussed the stability of its motion. Zhang and Wang (2013) considered the flexibility of the sail membrane and derived a coupled dynamical equation for a flexible displaced solar orbiter. Nevertheless, neither of these authors discussed the physical realization of the desired trajectories in both orbit and attitude. An interesting implementation of reflectivity control devices (RCDs)

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on the attitude adjustment of a solar sail was demonstrated by the Japanese sail "interplanetary kitecraft accelerated by radiation of the sun" (IKAROS) (Tsuda et al., 2011a,b, 2013). RCD is a thin film attached to the surface of the sail that can switch its reflectivity between the specular and diffusive states versus electricity power being switched on or off. Different reflectivity states can result in different SRP. By adjusting the total amount and distribution of switched-on RCDs, the propulsion and torque acting on the sail can be controlled to follow the desired orbit and attitude. Compared to other methods for attitude control utilizing the gimbaled control boom (Wie 2004a,b), sail control vanes (Wie 2004a,b), or sliding masses (Scholz et al., 2011), the application of RCDs is obviously propellantless, much simpler in structure and has lower cost (Tsuda et al., 2011a,b).

Such benefits have prompted increasing research interest in the utilization of RCDs in solar sail missions. Mu et al. (2013, 2015a,b) extended the coupled attitude–orbit dynamics to formation flying for a GeoSail mission. The reflectivity modulation ratio and its distribution on the sail are used as continuous control variables, while RCDs consist of finite panels so that the achievable magnitudes of solar propulsion and torque are actually discrete rather than continuous. This point was noticed by Aliasi et al. (2013) in their exploration of the active stabilization of L_1-type artificial equilibrium points (AEPs) for a solar sail using RCDs. They considered the discretization and saturation effect and successfully generated AEPs by switching on or off the RCDs, which are symmetrically distributed on the sail.

This paper naturally extends the application of finite discrete RCDs to the coupled attitude–orbit control of a spinning rigid solar sail in a Venus rendezvous mission. The paper aims to determine the switch law of RCDs, i.e., which part and when the devices should be switched on to follow the desired orbit and attitude. The coupled attitude–orbit dynamical equation is derived from the SRP force model of RCDs implemented in IKAROS. A type of gradient projection algorithm is successfully developed to efficiently calculate the optimal switch sequences of RCDs, which is verified in the application to a Venus rendezvous mission.

This paper are outlined as follows. In Section 2, the model of coupled attitude–orbit dynamics of spinning solar sail using RCDs is derived. Section 3 rearranges the derived linear form into an underdetermined linear system (ULS) with a binary set constraint (BSC), converts the formulated multi-objective least squares estimation (MLSE) and l_1–l_2 hybrid optimization into a classical quadratic programming (QP), and develops a type of basic gradient projection (BGP) method. As numerical verifications, switch regulations of RCDs are programmed applying previously proposed methods to accomplish the Venus rendezvous mission in Section 4. Section 5 draws conclusions of this paper.

2. Coupled attitude–orbit dynamics model of spinning solar sail utilizing reflectivity control devices

2.1. Configuration and coordinates of solar sail

As depicted in Fig. 1, the solar sail is assumed to be an ultra-thin (zero thickness) rigid sheet with arbitrary contour shape and a total mass m_s. To maintain the stability and deployment, the sail is spinning along its normal axis at a constant angular rate Ω. On the surface of the sail, RCDs are fixed with $\boldsymbol{r}_{pi}$ as the vector from the mass center of the sail to the ith unit.

A series of right-handed orthogonal reference coordinates are established. The J2000 ecliptic coordinates are chosen as the inertial coordinates $o_I x_I y_I z_I$ to describe the

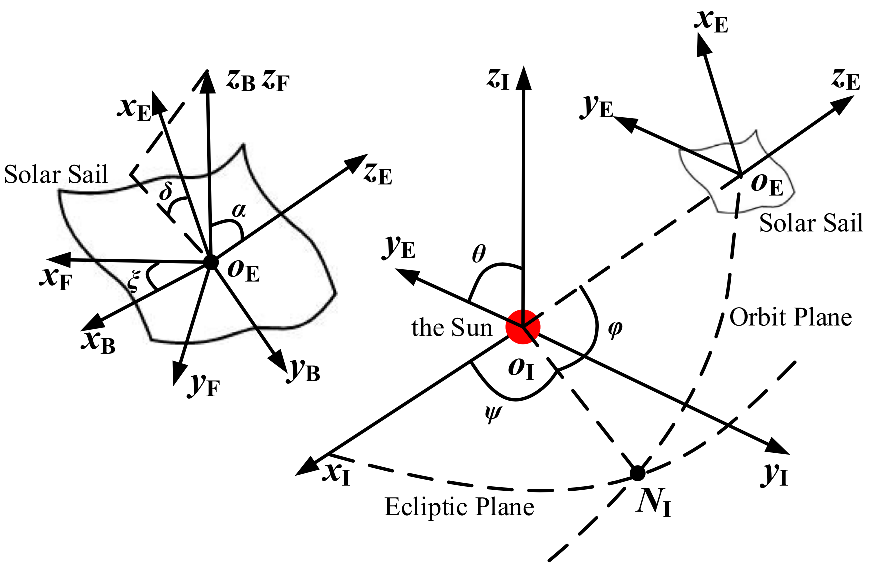

Fig. 1. Configuration (left) and coordinates (right) of solar sail.