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Deployment dynamics and control of large-scale flexible solar array system with deployable mast

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Abstract

In this paper, deployment dynamics and control of large-scale flexible solar array system with deployable mast are investigated. The adopted solar array system is introduced firstly, including system configuration, deployable mast and solar arrays with several mechanisms. Then dynamic equation of the solar array system is established by the Jourdain velocity variation principle and a method for dynamics with topology changes is introduced. In addition, a PD controller with disturbance estimation is designed to eliminate the drift of spacecraft mainbody. Finally the validity of the dynamic model is verified through a comparison with ADAMS software and the deployment process and dynamic behavior of the system are studied in detail. Simulation results indicate that the proposed model is effective to describe the deployment dynamics of the large-scale flexible solar arrays and the proposed controller is practical to eliminate the drift of spacecraft mainbody.

Keywords: Solar array system; Dynamic modeling; Topology changes; PD control

1. Introduction

Solar array system is one of the important components of spacecraft. It provides power for the spacecraft in on-orbit flight. The solar array system is in folded state during spacecraft launch and ascent. After the spacecraft and launch vehicle are separated and the spacecraft is turned into the free flying orbit, the solar array system will be freed from its fixation position and deployed by driving mechanism. The deployment will disturb the spacecraft flight or even may destroy the structure, so it is important to build precise dynamic model of the deployment process so as to provide support for attitude controller design on the spacecraft. On the other hand, as more advanced missions are posed to spacecrafts and as higher performances are required of mission instruments, more electric power is required for spacecrafts to generate. Despite a trend toward greater diversity in the spacecraft class, an upper limit of electric power demand has increased steadily. To accommodate this requirement, larger solar array paddles have been developed (Markelov et al., 2001; Riel and Morata, 1992). With the advent of large and light-weight solar arrays in spacecrafts, the flexibility of these arrays has become a concern since undesirable vibrations of these components could disrupt the mission of the spacecraft (Smith and Mei, 1997).

Deployable masts are frequently used in various space programs as basic structure members (Yang, 2013; Shan et al., 2013; Natori et al., 1996; Kitamura et al., 1990), and they are classified into two categories due to the ways of stowage (Natori et al., 1996). One is a coilable longeron extendible mast, which is stowed through the coilable deformation of continuous elastic longerons, and the other

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is an articulated one. Generally speaking, the latter shows stiffer mechanical properties for heavy duties, but it consists of a larger number of mechanism parts, which sometimes decrease deployment reliability. In the design and numerical simulation of articulated extendible mast systems for present and future space applications, reliability of deployment mechanisms and applicable dynamic modeling methods are strongly requested.

In recent years, the researches of solar arrays and deployable mast have attracted more and more attention, and considerable theoretical researches and engineering experiments have been done. For example, Loh (1996) built a finite element model of prestressed solar arrays in structural dynamics and analyzed the effects of geometric stiffness on natural frequencies. Iwata et al. (2012) described a design optimization for a large solar array paddle deployment with various practical constraints and presented ground verification results. Yang (2013) established a dynamic model of coilable mast and rigid solar arrays based on the multibody dynamic solver Thudynamics and revealed the parameter sensitivity that influences the reliability of coilable mast deployment. Laible, Fitzpatrick et al. (Michael et al., 2013) performed a detailed nonlinear analysis on the 2A array model to assess possible solutions to modal differences, and their study revealed that the array attachment structure is nonlinear and thus was the source of error in the model prediction of mast modes. Shan et al. (2013) designed a triangular prism modular deployable mast and analyzed kinematics behavior of the mast. From the researches above it can be seen that solar arrays and deployable mast have gained many attentions and many research results have been achieved. However, most of the researches focused on the deployed state of the solar arrays and researches about the deployable mast just studied the kinematics of the deployment and the force analysis of the mast on the deployed state; little attention has been paid to the deployment process of the mast with flexible solar arrays. Even in the very small amount of studies about deployment dynamics of solar arrays, the flexibility of sub-panels was not considered (Yang, 2013, Iwata et al., 2012).

The deployment of the solar array system is a complex process which is completed by the combined effects of the deployable mast, guy-wire and tension control mechanism. In addition, the deployment will affect the position and attitude of the spacecraft (Bai and Zhao, 2012). Therefore, it is necessary to establish a dynamic model to analyze the deployment dynamics and control of the solar array system.

In this paper, deployment dynamics and control of a large-scale flexible solar arrays is investigated. Dynamics modeling for the solar array system is given and numerical simulations are done to reveal the system characteristics. This paper is organized as follows. Section 2 introduces the structure of the solar array system, including spacecraft mainbody, deployable mast, latch mechanisms, drive mechanism, solar arrays, tension control mechanism, guy-wire and joint damper between sub-panels. In Section 3, dynamic equation of the solar array system is established by the Jourdain velocity variation principle and the controller design for the spacecraft mainbody is presented. Section 4 presents numerical simulations to validate the theoretical studies in this paper. Finally, a concluding remark is given in Section 5.

2. Solar array system with deployable mast

In this section, the structure of the solar array system adopted in this paper is firstly introduced (Fig. 1), then the latch mechanism and the limit spring of the deployable mast are studied, and finally the tension control mechanism, the guy-wires and the joint damper are discussed.

2.1. Deployable mast

Deployable mast emerged with the development of aerospace exploring technology (Natori et al., 1996). It is mainly used for extending flexible solar array and supporting deployable antenna, synthetic aperture radar and space telescope. Tubular boom, telescopic mast, coilable mast and some articulated masts have been developed and applied in outer space. In this paper, a triangular prism modular mast (Shan et al., 2013; Shan, 2013) as shown in Fig. 2 is adopted.

Fig. 2 shows the triangular prism modular deployable mast. Three screws are installed outside each node of triangular frames. Each frame can be held in turn by the screw driving the rollers on three corners of the frame. The rollers contain one rotational degree of freedom which is beneficial for decreasing frictions between screws and rollers. There are limiting springs (Shan, 2013) (Fig. 3) so that the latter unit will not be held until the former unit is fully deployed. This sequence repeats until the whole mast is deployed.

2.2. Solar arrays

As shown in Fig. 1. The solar arrays consist of rigid and flexible sub-panels, two containers, four guy-wires and the tension control mechanism. The lower container is fixed on the spacecraft mainbody. The deployable mast drives the upper container, and the upper container pulls the sub-panels by ropes of the tension control mechanism to complete the deployment.

The tension control mechanism (TCM) is designed to provide tensional force to the sub-panels. The purpose of this force is to keep the sub-panel stiff (Kojima et al., 2004). In this paper, the tension control mechanism is simplified as a spring and a damper when the rope is stretched (Fig. 4), and there is no tensional force when the rope is not stretched. The tensional force can be written as

$$F_{\mathrm{tcm}} = \begin{cases} -k_{\mathrm{tcm}} \times \delta l_{\mathrm{tcm}} - c_{\mathrm{tcm}} \times \delta v_{\mathrm{tcm}}, & \delta l_{\mathrm{tcm}} > 0 \\ 0, & \delta l_{\mathrm{tcm}} \leqslant 0 \end{cases} \tag{1}$$