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Fractional order sliding mode control for tethered satellite deployment with disturbances

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Abstract

This paper proposes a fractional order sliding mode control for the deployment of tethered space systems with the consideration of uncertainty of external disturbances and unmodeled system dynamics. The proposed fractional order sliding mode control consists of two sub-sliding manifolds that are defined separately for the actuated and unactuated states. This, in turn, generates a control scheme to make all states move toward to the desired states. The stability analysis of the proposed control law indicates not only all states converge to the desired states at equilibrium but also disturbances caused by the uncertainty can be suppressed satisfactorily. Parametric studies are conducted to investigate the influences of fractional order and sub-sliding manifold of unactuated states on the performance of the proposed control law. The performance is compared with the sliding mode, PD and fractional order PD control laws for a baseline scenario of tether deployment. The proposed control law performs better than others in the settling time and the maximum pitch angle control in the presence of unwanted disturbances. Effectiveness and robustness of the proposed control law are demonstrated by computer simulations.
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Keywords: Tethered space system; Tether deployment; Fractional order; Sliding mode control; Uncertainty

1. Introduction

A fundamental challenge in missions of tethered space systems is the successful deployment of tether in a quick and stable way. It is well known that the space tether is prone to the undesirable libration in the deployment process, which may lead to tether slackness or winding around the main spacecraft during the deployment (Carroll, 1985). Many efforts have been devoted to the control of tether deployment in the past (Kumar, 2006). For instance, a tension control law was firstly introduced by Rupp (1975) based on the feedback of tether deployment length and velocity. Pradeep (1997) proposed a simple linear tension control law for tether deployment based on the linearized equation of motion in the neighborhood of equilibrium state and the Kelvin-Talt-Chetayev stability theorem. To further improve the performance of control laws, Modi et al. (1982) proposed a nonlinear feedback control to limit the libration angles. Vadali and Kim (1991) developed a feedback nonlinear controller for 3D deployment and retrieval by the combination of tension control and out of plane thrusting using the Lyapunov stability theory. Fujii and Ishijima (1989) designed a controller for both deployment and retrieval based on a mission function. However, the asymptotical stability of the tension controller may not deliver a fast convergence without overshoot. To address the challenge, Sun and Zhu (2014a,b) developed a fractional order tension control law to achieve

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the fast, stable and accurate deployment and retrieval of tether.

Although effective, the performance of these model-based controllers will be affected adversely by nonlinear tension disturbances caused by the unmodeled system dynamics as well as the uncertainty of external disturbances. For example, one of the main nonlinear disturbances, friction in deployment/retrieval mechanisms, is difficult to model precisely. This is because its mathematic models are either too complicated for implementation in control design or hard to be validated experimentally in space environment to sufficient accuracy. The other unmodeled dynamics and environmental/orbital disturbances are the variation of gravitational field, atmospheric drag, temperature oscillation, lunisolar perturbations and other minor forces. Therefore, it is necessary to develop advanced, nonlinear and robust control schemes that are capable of tolerating the inaccuracy of system model to ensure better system performance. Among nonlinear robust control techniques in the literature (Abdallah et al., 1991), Sliding Mode Control (SMC) is one of the prominent robust control methods with proven properties in addressing uncertainties and disturbances of nonlinear systems (Xu and Özgüner, 2008; Young et al., 1999). However, the asymptotic stability of conventional sliding manifold cannot guarantee a fast convergence without imposing strong control force. Terminal sliding mode control (TSMC) and nonsingular terminal sliding mode control (NTSMC) were developed to provide finite-time stability and high accuracy under strong disturbances (Yang and Yang, 2011). Moreover, the SMC and NTSMC are further enhanced in recent years with the fractional order calculus (Bandyopadhyay and Kamal, 2015) by taking its favorable characteristics, such as, the differintegral with unique historical memory effect and better dynamic response to control input (Delavari et al., 2010; Efe, 2010; Tang et al., 2013; Wang et al., 2014).

Although the fractional order control has been extensively studied, its application in space is very limited. The first application of fractional order control in space dealt with the attitude control problem of flexible spacecraft (Manabe, 2002). Then, several fractional order controllers were proposed and applied to control the attitude of satellites to achieve a good compromise between stability and performance (Kailil et al., 2004). To the best knowledge of authors, the previous works (Sun and Zhu, 2014a,b) are the first application of fractional order control in the deployment and retrieval of tethered space systems. In the current work, a fractional order sliding model control (FOSMC) is developed for the control of tether deployment by considering uncertainties. It is an extension of the previous works (Sun and Zhu, 2014a,b) by integrating the fractional order with the sliding model control to establish an efficient control law that deploys the space tether in a fast, stable and precise manner under the effects of environmental perturbations and model uncertainties.

2. Problem formulation

Consider a tethered space system (TSS) with a long tether connecting two satellites at its ends. The system is orbiting in a circular Keplerian orbit in a central gravitation field of earth. The tether is assumed straight, inextensible and massless and the tethered satellites are considered as lumped masses due to the large ratio of tether length over satellites' dimensions. Accordingly, the TSS can be simplified as a dumbbell model. Based upon the assumptions, the TSS motion can be decomposed into the orbital motion of the system's center of mass (CM) and the local libration motion of tether about the CM in the orbital plane, as shown in Fig. 1. It is well-known that the out-of-plane libration is coupled with the in-plane libration through the higher order term, which is very weak. The influence of the out-of-plane libration angle changes has very little effect on the pitch angle in the short period of time, such as in the tether deployment process. Thus, the out-of-plane libration is ignored. The libration motion of the system is described in a local orbital reference frame with its origin at the CM. The y-axis points toward the Earth center. The x-axis lies in the orbital plane perpendicular to the y-axis and pointing toward the moving direction of main satellite. The z-axis completes a right-hand coordinate system. By ignoring the effect of aerodynamic drag due to the short deployment time, the dynamics of tether deployment can be described by a second order nonlinear system (Pradeep, 1997),

$$\begin{aligned} &\ddot{L} - L[\dot{\theta}^2 + 2\dot{\theta}\Omega + 3\Omega^2\cos^2\theta] = -\frac{T}{m_e} \\ &\ddot{\theta} + 2\left(\frac{\dot{L}}{L}\right)(\Omega + \dot{\theta}) + \frac{3}{2}\Omega^2\sin 2\theta = 0 \end{aligned} \tag{1}$$

where L is the instantaneous tether length, θ is the libration (pitch) angle, T is the tether tension, Ω is the orbital angular velocity of TSS and m_e is the effective mass $m_e = Mm/(M+m)$ where M and m are the masses of the main and subsatellites respectively. If the mass of main satellite

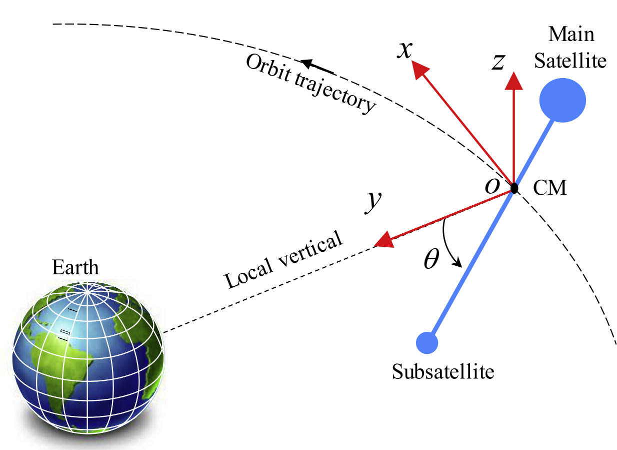

Fig. 1. Orbital coordinate system of the space tether system.

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