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Space tether deployment with explicit maximum libration angle constraint and tension disturbance

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Abstract

This paper investigates the deployment control problem of tethered space systems subject to an explicit constraint of maximum libration angle and disturbance of tether tension. A two-stage control procedure is developed to design a simple and effective tension control law that is capable of limiting the magnitude of libration angle and suppressing the tension disturbance in the tether deployment process. First, the deployment reference trajectory is designed by a modified barrier Lyapunov function with an explicit constraint on the maximum libration angle. Then, a disturbance observer-based tension control law is developed to track the reference trajectory with the consideration of tension disturbance. Stability analysis of the controller shows that the estimate and tracking errors are bounded to desired ranges. Simulation results demonstrate the proposed simple tension control law is effective and robust in restricting the maximum amplitude of libration angle and suppressing tension disturbance, while guaranteeing a stable deployment without tether slack.

Keywords: Space tether deployment; Barrier Lyapunov function; Explicit libration angle constraint; Disturbance observer; Tension control; Underactuated system

1. Introduction

Stable deployment of a space tether is mission critical for tethered spacecraft missions (Carroll, 1993; Cosmo and Lorenzini, 1997; Gates et al., 2001; Kruijff et al., 2008; Sanmartín et al., 2010; Ohkawa et al., 2017). For many tethered spacecraft systems (TSS), the tether tension is the only control input in the deployment process because no thrust is available on the tethered spacecraft or used for tether deployment to save fuel. For such an underactuated system, significant efforts have been devoted to achieve a stable and fast tether deployment with various tether tension control laws. For instance, Misra and Modi (1982) developed a tether length rate control law to damp out the in-plane libration in deployment and retrieval. Similarly, a TSS deployment controller by following an optimal path was studied by Fujii and Anazawa (1994). An asymptotically stable tension control law was developed by Vadali (1991) to deploy and retrieve tethers by the Lyapunov approach. Lorenzini et al. (1996) applied a deployment strategy for a real space tether mission, small expendable deployment system **II**, by tracking an optimal reference trajectory designed in advance by solving a two-point boundary value problem. A simple feedback tension control law was derived by Pradeep (1997) to deploy a tether based on equilibrium state linearization and Kelvin-Talt-Chetayev theorem. However, the linear simplification and simple feedback control result in unwanted overshooting of tether length in the deployment. Williams (2008) developed an optimal control for the TSS

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deployment and retrieval to address the issue. Although effective, computational loads for online optimization may restrict its implementation in a real mission due to the limited onboard computing power. Sun and Zhu (2014) extended Pradeep's work into fractional-order tension control law. The integration-derivation characteristics of fractional-order calculus have effectively attenuated the overshoot of tether length deployment while achieving a faster and more stable tether deployment. However, these model-based control laws assume an ideal TSS without consideration of tension disturbance that may be experienced in reality due to model simplification and/or environment perturbations. To address this challenge, Kang et al. (2017) expanded the work by Sun and Zhu (2014) to a fractional-order sliding mode (FOSM) controller to suppress the disturbance. Ma et al. (2017)proposed an adaptive saturated sliding mode control for TSS deployment with consideration of thrust limitation on the sub-satellite. However, few TSS missions are equipped with thrusters on sub-satellites.

The fast deployment inevitably results in an increase of libration angle due to the Coriolis effect. In real TSS missions, it is desirable to limit the libration angle within certain range, such as 65°, to prevent the tether from slack (Corsi and Iess, 2001; Hong and Varatharajoo, 2012). Hoyt (2002) even gave a more critical threshold value 45°. In addition, the deployment stability should also be guaranteed simultaneously in the presence of disturbance (Kang et al., 2017). The existing control laws limit the maximum libration angle by tuning control parameters, which are case specific. This limit is relaxed in the current work by a two-stage control scheme. In the first stage, the ratio of tether deployment velocity over length is defined as a new control input for internal dynamics. A deployment trajectory with the explicit maximum angle constraint is derived by the Barrier Lyapunov Function (BLF) method (Tee et al., 2009; Tee and Ge, 2011) using the ratio and TSS initial values. In the second stage, the disturbance is estimated and suppressed by a disturbance observer-based (DOB) tracking control law (Chen, 2004; Do, 2010; Zhu and Zhao, 2013) based on the Lyapunov stability theorem. Finally, the effectiveness and robustness of the newly proposed tension control law are demonstrated by numerical simulations.

2. Dynamics of space tether deployment

To focus on the control law development, only the in-plane libration motion in a TSS deployment is considered in the current work. Although it is known that the out-of-plane libration is coupled with in-plane angle via higher order term, the influence is very weak in the short deployment duration. Thus, the out-of-plane angle is omitted in this work. The TSS consists of a main-satellite and a sub-satellite. The two satellites are connected by an inelastic and massless tether with a length L. The tether is deployed downwards by a winch type device and remained taut during the deployment. Moreover, the mass of the sub-satellite is assumed much smaller than that of the main-satellite, so that the center of mass (c.m.) of the TSS will coincide with the c.m. of the main-satellite approximately (Vadali, 1991; Pradeep, 1997; Sun and Zhu, 2014; Wen et al., 2015; Kang et al., 2017). This assumption is reasonable in reality when considering massive spacecraft, such as International Space Station, Chinese space station Tiangong-2 and upper stages of rockets. Besides, in the analysis of electrodynamic tether (EDT) system that is one of the promising applications of TSS, Wang et al (2016) found the mass of the sub-satellite and tether can be theoretically zero without losing the libration stability in the deorbit process.

Based on above assumptions, the dynamics of the tether deployment in the orbital plane can be expressed in a dimensionless form:

$$\begin{aligned} &\ddot{l} - l[(1+\dot{\theta})^2 - 1 + 3\cos^2\theta] = -\hat{T} \\ &\ddot{\theta} + 2(\dot{l}/l)(1+\dot{\theta}) + 3\cos\theta\sin\theta = 0 \end{aligned} \tag{1}$$

where $l \in (0, 1]$ is the dimensionless instantaneous tether length and cannot be zero to avoid the singularity, θ is the in-plane libration angle,$\hat{T} = T/(m\Omega^2 L)$ is the dimensionless tether tension, T is the tether tension, m is the sub-satellite's mass. Here it is worth noting that even if the mass of the sub-satellite is in the similar order to that of the main satellite, m in Eq. (1) should be replaced by the equivalent mass (Kang and Zhu, 2017). Ω is the orbital rate of TSS, and $(\dot{\ }) = \partial(\ )/\partial\tau$ denotes the derivative with respect to the dimensionless time $\tau = \Omega t$. The objective of our work is to deploy the tether from its initial state vector $[l \quad \dot{l} \quad \theta \quad \dot{\theta}]^T = [0.01 \quad v_0 \quad 0 \quad 0]^T$ to the desired or equilibrium state vector $[1 \quad 0 \quad 0 \quad 0]^T$ quickly in the presence of the tension disturbance and the constraint of maximum in-plane angle $\theta_{\max}$. Since $l(0) = 0$ will lead to singularity in Eq. (1), it is a common approach in the literature to set $l(0) = 0.01$.

For the sake of analysis convenience, one can introduces a set of new state variables $[x_1 \quad x_2 \quad x_3 \quad x_4]^T = [l-1 \quad \dot{l} \quad \theta \quad \dot{\theta}]^T$ to transform the equilibrium state to a zero state $[0 \quad 0 \quad 0 \quad 0]^T$ if and only if the tether is fully deployed and the tension at equilibrium is $\hat{T} \equiv 3$. Then, the new initial state becomes $[x_1 \quad x_2 \quad x_3 \quad x_4]^T = [-0.99 \quad v_0 \quad 0 \quad 0]^T$. Accordingly, Eq. (1) is reduced to a system of first-order differential equations with a zero equilibrium state, such that,

$$\begin{aligned} &\dot{x}_1 = x_2 \\ &\dot{x}_2 = (1+x_1)[(1+x_4)^2 - 1 + 3\cos^2 x_3] - \hat{T} \\ &\dot{x}_3 = x_4 \\ &\dot{x}_4 = -2\frac{x_2}{1+x_1}(1+x_4) - 3\cos x_3 \sin x_3 \end{aligned} \tag{2}$$