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Tension control of space tether via online quasi-linearization iterations

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Abstract

The paper presents how to stabilize the deployment and retrieval processes of a space tether system via the tension control, where the model predictive control is exploited to optimize the control performance while the nonlinear dynamics and tension constraint are explicitly taken into account. A new scheme of online quasi-linearization iteration is proposed to transfer the nonlinear optimal control problem into a series of linear optimal control problems that can be solved in sequence at a series of sampling instants. Consequently, it avoids the complete solution of the nonlinear optimal control problem at each sampling interval such that the computational load can be greatly alleviated. Furthermore, the scheme extends the conventional quasi-linearization schemes by distributing the iterative process across sampling instants and online updating the initial condition of the linear optimal control problem. The problems of linear optimal control are discretized using a pseudo-spectral algorithm and then solved by a solver of linear quadratic programming. Numerical case studies indicate that successful deployment and retrieval of the system can be achieved using the proposed control scheme without violating the positive tension constraint. The time cost for each online optimization in the proposed scheme is on the order of 10 ms and far below the sampling interval under consideration.

Keywords: Space tether; Deployment; Retrieval; Tension control; Quasi-linearization

1. Introduction

Over the past decades, the concept of space tether system (STS) has gained a great deal of attentions from many researchers due to its potential use for a wealth of important applications in space engineering (Cosmo and Lorenzini, 1997; Wen et al., 2008a). Especially, the technology of space tether has been identified as an appealing strategy for the active mitigation of space debris (Aslanov and Yudintsev, 2015; Zhong and Zhu, 2013). In an STS, two or more end-bodies in space are connected to each other via one or more thin and long tethers. There are usually three main stages involved in a typical STS mission, that is, the deployment, retrieval, and station-keeping phases (Wen et al., 2008a). Among them, the deployment and retrieval processes received special attentions since the change of tether length may lead to significant librations and vibrations of the tether. From a perspective of control, however, it is very challenging to achieve deployment and retrieval of an STS in a simultaneously fast and stable manner. The highly nonlinear dynamics of any STS excludes the application of many analytic techniques well-established for linear systems. The control problem is further complicated by the preference of adopting a simple, low-cost and effective tension control law to deploy and/or retrieve the tether over applying control action, e.g., thrusters, at the main/sub-satellites. As a result, the STS is an under-actuated and single-input-multiple-output system. Another key point to note is the requirement of satisfying the control constraint

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that tether tension should be positive all the time to avoid the slackness of the tether.

As summarized in the review articles (Cartmell and McKenzie, 2008; Chen et al., 2014; Kumar, 2006; Misra, 2008; Wen et al., 2008a), a great deal of research efforts have been made to solve the problem of stable and fast deployment and retrieval of an STS from a viewpoint of controller design. Notably, nonlinear optimal control (NOC) has been recognized as one of the most appealing solutions to the nonlinear control problems of deploying and retrieving space tethers (Fujii and Kojima, 2003; Jin and Hu, 2006; Steindl, 2014; Wen et al., 2008d; Williams, 2008, 2011). The main advantage of NOC is that it enables the optimization of a specified performance index while stratifying the nonlinear dynamics and system constraints. However, it remains an open problem to synthesize an optimal control law in closed-form for such a highly nonlinear system even in an unconstrained case. As an alternative, many numerical techniques have been proposed to find, in an open-loop sense, the optimal deployment and retrieval trajectories of an STS (Fujii and Kojima, 2003; Jin and Hu, 2006; Steindl, 2014; Wen et al., 2008d; Williams, 2008, 2011). Due to the great difficulty of solving the Hamilton–Jacob i–Bellman (HJB) equation (Ross and Fahroo, 2003), it is even more challenging to design a nonlinear optimal closed-loop control law such that the effects of online disturbances can be counteracted. Numerical optimization based Nonlinear Model Predictive Control (NMPC), also known as Nonlinear Receding Horizon Control (NRHC), has been proposed to circumvent the theoretical difficulty of analytically solving optimal feedback control law (Grüne and Pannek, 2011; Hu et al., 2013; Wen et al., 2008c; Williams, 2004). The control law based on NMPC is usually generated online by repeatedly solving an open-loop NOC problem defined over a receding time horizon. For example, Williams (2004) solved an unconstrained NRHC law of retrieving an STS by a combination of quasi-linearization and pseudo-spectral (PS) approximations. Wen et al. (2008c) presented a shrinking horizon and online grid adaptation scheme to address the optimal feedback control problem of deploying an STS. They also extended the investigation, via ground-based experiments based on the principle of dynamic similarity, to demonstrate the application of the real-time NMPC law to the deployment and retrieval of a tethered satellite simulator (Hu et al., 2013). Though effective, these NMPC schemes could still be too computationally demanding to be implemented in a spacecraft with limited on-board computational capacity, due to their requirements of completely solving a complex NOC problem in each sampling interval.

This paper focuses on the tension control of an STS during its deployment and retrieval processes. In this study, NMPC is exploited to optimize the control performance while the inherent nonlinear dynamics and positive tension constraint are explicitly taken into account. To tackle the computational challenge of NMPC, a strategy of online quasi-linearization iteration (OQLI) is proposed to transfer the NOC problem into a series of linear optimal control (LOC) problems that can be iteratively solved in sequence at consecutive sampling instants. The resulting LOC problems are discretized using a PS algorithm and then solved by a solver of quadratic programming (QP). To the best knowledge of authors, it is the first attempt to extend the conventional quasi-linearization schemes (Jin and Hu, 2006; Wen et al., 2008b; Williams, 2004, 2011) by distributing the iterative process across sampling instants and using the latest state feedback to update the initial condition of the LOC problem. Consequently, the proposed scheme reduces the computational load substantially by avoiding the complete solution of the NOC problem at each sampling interval. Different from Lu (1998) and Houska et al. (2011) where only a linear optimization problem needs to be solved in each sampling interval, new strategies are proposed in the current work to formulate and discretize the LOC problems. Finally, numerical case studies demonstrate the performance of the proposed scheme satisfies the requirement of fast and stable deployment and/or retrieval of an STS with significantly reduced computational load.

2. Problem formulation

To focus on the fundamentals of the NMPC scheme, the scope of the current work is limited to the in-plane deployment and retrieval of an STS orbiting the Earth in a circular orbit. In the STS of concern, a main-satellite is connected to a relatively small sub-satellite via a tether with variable length l. The attitude of the tether is described by its pitch angle θ with respect to the local vertical of the system orbit. The dynamics of the STS is modeled on a basis of the following simplifications: (a) the tether is treated as an inextensible and massless wire whereas the satellites are simplified as lumped masses; (b) the orbital motion of the system does not depend on the attitude one; (c) the mass of the sub-satellite is negligible compared with the main-satellite; (d) the main-satellite orbit is predefined and has circular shape.

By applying the Lagrange's equation, the governing equations of the STS is derived in the following dimensionless form (Sun and Zhu, 2014; Williams, 2011), such that,

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

where the dot represents the derivative with respect to the dimensionless time $v = \Omega t$, and the dimensionless tether length ξ and tension u are defined as,

$$\xi = l/l_c, \quad u = T/(m\Omega^2 l_c) \tag{2}$$

In the above formulations, m is the mass of the sub-satellite, Ω denotes the orbital rate of the system, T represents the tension in the tether, and l_c is a reference length.

Taking u as the control input and introducing the state vector $\mathbf{x} = (\theta,\ \xi,\ \dot{\theta},\ \dot{\xi})^{\mathrm{T}}$, one obtains the following state space representation of the system dynamics