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A space tethered towing method using tension and platform thrusts

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Abstract

Orbit maneuver via tether is a promising countermeasure for space debris removal and satellite orbit transfer. A space tethered towing method is explored that utilizes thrust to fulfill transfer and bounded tension to stabilize tether heading. For this purpose, a time-energy optimal orbit is designed by Gauss pseudospectral method. The theoretical attitude commands are obtained by equilibria analysis. An effective attitude control strategy is presented where the commands are optimized first and then feedback controller is designed. To deal with the underactuated problem with tension constraint, hierarchical sliding mode theory is employed and an adaptive anti-windup module is added to mitigate the actuator saturation. Simulation results show that the target is towed effectively by the thrusts, and a smooth tracking for the commands of tether length and in-plane tether heading is guaranteed by the bounded tension. In addition, the designed controller also presents appreciable robustness to model error and determination error.

Keywords: Space tether; Tethered towing method; Underactuated control; Actuator saturation; Anti-windup

1. Introduction

The increasing space debris have attracted great attention as they pose a collision risk to spacecraft (Liou et al., 2010; Huang et al., 2016). As a booming Active Debris Removal (ADR) technology, the use of Tethered Space Robot (TSR) has aroused expanding interest (Huang et al., 2015; Moss, 1990; Kurt and Peter, 1994) due to its advantages of large work space and small impact on platform (Meng and Huang, 2014; Huang et al., 2016a, 2016b, 2016c, 2016d). As a result, it has highlighted a novel use of tether for capture and transport of non-cooperative targets.

Currently, there are three methods to remove the debris using tether, tether momentum exchange (Johnson et al., 1999; Sorensen, 2003; Lennert and Cartmell, 2006; Chen and Cartmell, 2007), retrieval de-orbit scheme (Shin et al., 2009) and tethered towing (Huang et al., 2015; Mashayekhi and Misra, 2014; Cho and McClamroch, 2003; Wang et al., 2015). Compared with the first two approaches, tethered towing is able to lower the collision potential and shorten the tether length. It therefore promises to be effective for debris removal and tether-assisted maneuver. The towing mission can be divided into several stages. Prior to the capture, there are rendezvous and mechanical interfacing (Aslanov and Yudintsev, 2014). After capture, the target and the platform form a dumbbell-like combination, as shown in Fig. 1, which will transfer using the platform thrust. The dynamics of the combination is complicated by the space tether due to its elasticity and flexibility. As a result, during thruster-burn and post-burn phase, the main technical challenges are collision, twist with tether, whiplash effects and tether libration. To illustrate the dynamics behavior of two-body

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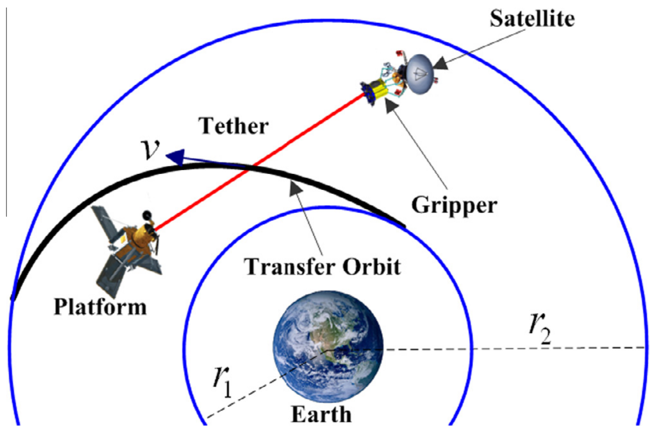

Fig. 1. Structure of tethered towing system (TTS).

tethered system, considerable studies are conducted by Aslanov (2015), Aslanov and Aslanov (2015), and Aslanov and Yudintsev (2015a, 2015b) in terms of chaos behavior and flexible appendages. For post-burn phase, input shaping techniques are proposed by Jasper and Schaub (2014a, 2014b) to avoid collision. For thruster-burn phase, the particular attention of this paper is given to the tether libration suppression.

Orbit design should be first taken into account for towing mission. Hohmann transfer is an effective method from the fuel-saving point of view, and it can also be applied to the long tethered system. Zhong and Xu (2010) study a means of Hohmann transfer for TSS using direct collocation method. Liu et al. (2012) investigate a Hohmann tether-tugging de-orbit in detail, including acceleration, equilibrium, rotation and return. By contrast, the impulsive transfer is unattractive for the short tether, because the effect of the sudden change of orbit elements on tether libration is extremely large. As a result, the optimal tethered orbit transfer is first presented in Aslanov and Aslanov (2015) and low-thrust transfer is proposed in Sun et al. (2010). To transfer more efficiently, it is better to minimize both the time and fuel consumption. A time-energy optimal orbit would be more suitable for the short tether system.

During the maneuver, the platform thrust is not always aligned with the tether, which will cause the self-rotation of TTS called tether libration. In that case, the platform trajectory is disturbed and the system becomes unstable. Thus tether stabilization including command generation and controller design is indispensable. Given that the command is closely related to the equilibria, researches on librational characteristic are of crucial importance. Zhao et al. (2012) study how the system parameters affect the tether librational characteristic and find that the frequency of libration is intensively influenced by the tether length. Furthermore, the study concerning the effect of thrust acceleration on libration is conducted in Sun et al. (2012). Based on these studies, Sun et al. (2013) analyze the effect of thrust acceleration on the equilibria and derive the approximate analytical solution of command. This inaccurate command, however, inevitably leads to more control energy consumption, while little attention has been directed towards the means of obtaining the accurate command.

Limited by the physical structure, the gripper is unexpected to provide thrust, thereby the stabilizing tether orientation is essentially a underactuated problem. Several control strategies using thruster (Cho and McClamroch, 2003; Wang et al., 2015) or tension control (Sun et al., 2013; Zhu et al., 2011) have been suggested in the literatures. Cho and McClamroch (2003) employ only platform thrust to control both orbit maneuver and tether attitude. As a result the attainable range of thrust is constrained extremely. Wang et al. (2015) propose another thruster control strategy where gripper thrust was adopted to suppress the libration. However, that is fuel-consuming. To free the thrust from the attitude control, utilizing tension to suppress the tether libration is fuel-saving and efficient. Sun et al. (2013) employ hierarchical sliding mode theory to develop the underactuated tension law. Liu et al. (2014) present a tension control law depending upon an expected rate of tether. Note that the tether can only provide pulling force rather than 'pushing' force and should be bounded by maximum force to avoid collision. However, this property is not considered in the present tension controller design, which weakens the robustness. Once the tension saturations take place, the serious discrepancies between command and actual effort will lead to degradation and instability of system. Thus, the anti-windup technology should be introduced in the controller design. Adaptive control is known to be an efficient anti-windup technique applicable to systems with actuator constraint, and it has been addressed in some previous studies for spacecraft attitude control (Zhu et al., 2011; Xiao et al., 2011; Ferrara and Rubagotti, 2008; Yin and Du, 2013). One of interests of this paper is investigating how to stabilize the tether heading smoothly using only the bounded tension.

Motivated by those problems, this paper is concerned with proposing a tethered towing method using tension and platform thrusts. The Gauss pseudospectral method based transfer orbit is designed and the bounded tension is developed to control system attitude. During maneuver, to ensure an appreciable control performance, the command obtained by equilibria analysis is optimized first then the underactuated controller is designed depending upon hierarchical sliding mode theory. An adaptive anti-windup module is introduced to deal with the tension saturation.

The paper is organized as follows: the dynamic model of TTS is established in Section 2. This is followed by the control strategy in Section 3, including the design of transfer orbit, attitude command and anti-windup underactuated controller. In Section 4, an example of satellite tether-assisted orbit transfer is studied to validate the control scheme. Finally, conclusions and future work are discussed in Section 5.

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