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Dynamics and offset control of tethered space-tug system

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A R T I C L E I N F O

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A B S T R A C T

Tethered space-tug system is regarded as one of the most promising active debris removal technologies to effectively decrease the steep increasing population of space debris. In order to suppress the spin of space debris, single-tethered space-tug system is employed by regulating the tether. Unfortunately, this system is underactuated as tether length is the only input, and there are two control objectives: the spinning debris and the vibration of tether. Thus, it may suffer great oscillations and result in failure in space debris removal. This paper presents the study of attitude stabilization of the single-tethered space-tug system using not only tether length but also the offset of tether attachment point to suppress the spin of debris, so as to accomplish the space debris removal mission. Firstly, a precise 3D mathematical model in which the debris and tug are both treated as rigid bodies is developed to study the dynamical evolution of the tethered space-tug system. The relative motion equation of the system is described using Lagrange method. Secondly, the dynamic characteristic of the system is analyzed and an offset control law is designed to stabilize the spin of debris by exploiting the variation of tether offset and the regulation of tether length. Besides, an estimation formula is proposed to evaluate the capability of tether for suppressing spinning debris. Finally, the effectiveness of attitude stabilization by the utilization of the proposed scheme is demonstrated via numerical case studies.

1. Introduction

Since the Soviet Union's first launch of the artificial satellite, Sputnik-1, in 1957, the space environment has entered a new stage where more and more human-built spacecraft is occupying the precious outer-space around the Earth. The increasing number of satellites, on the one hand, provides human beings a better way of life, but on the other hand, leads to great probabilities of collisions between satellites. Operational Iridium 33 and the inactive Kosmos 2251 satellite collided with each other on 10 February 2009, creating a debris cloud in the vicinity of the collision with 1740 debris catalogued as of March 2010 [1]. Such incidents occurred more than once when recalling the history of human spaceflight. According to the statistics by August 2017, space around the Earth is crowded with 14145 rocket bodies & debris and 4495 payloads, mainly in the low Earth orbit [2]. Now, the collisions between space debris, between satellites, and between debris and satellites are unprecedented frequent, which are recognized to be the leading causes of the increase of small fragments at an accelerating speed [3]. The large quantity of space debris pose a great potential hazard to well working satellites as the debris may hit the crucial structure and result in irreparable damage to the spacecraft [4–6]. Such damages promote the development of active debris removal using laser [7], balloon [8], foam-based method [9], mechanic arm [10–13], space net [14–16], electrodynamic tether [17–19], and tethered space-tug (TST) [20,21].

Among all these techniques, the TST system has the advantages of simple structure, no restriction for the environment, and unlimited usage for large objects, which make it one of the most appealing techniques to efficiently reduce the population of large space debris around the Earth. The removal mission can be divided into three phases: approaching phase, stabilization phase, and post-capture phase. There are lots of published literatures discussing various approaching ways, tether deployment methods, orbit control schemes and the reuse of the TST system [22–25]. For the stabilization phase, which is the main focus of this paper, lots of researches have gained fruitful results. In most of their works, the tug is considered as mass point, and the debris is regarded as rigid body or even mass point for simplification. Aslanov and Yudintsev derived two dynamic models of the TST systems with the consideration of tug being a mass point and debris being a rigid body with fuel residual [26] and with flexible appendages [27]. Wen et al. [28] even treated both the tug and debris as mass points, and then developed a tension control law with only length measurement feedback to stabilize the motion of the TST system. There is no denying that with the consideration of tug and

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debris being a mass point and a rigid body, respectively, or both mass points contribute to the simplification of derivation and the acquisition of system analytical solutions. But it ignores that the force imposed by the tether does not only have effects on the space debris but also influence the attitude of the tug. Besides, the potential hazard of post-burn collision between the debris and tug may also bring failures to space debris removal. Therefore, it is necessary to take both of the tug and debris as rigid bodies in the study of the behavior of the TST system. With this in mind, Zhang and Huang [29] derived the TST system dynamic model within the orbital plane by Lagrange method, and investigated the control scheme in equilibrium and non-equilibrium state. Aslanov [30] studied the chaotic behavior of the TST system in a plane. However, this system is scarcely possible to be planar as lots of disturbances and perturbations may drive the debris to go out of the orbital plane. Thus, it is necessary to build the dynamic model in three dimensions. Zhang et al. [31] developed a 3D double-rigid model of the TST system using Newton-Euler method and proposed an estimation algorithm to evaluate the inertia parameters of the space debris on board. Jasper and Schaub [32] utilized a six degree-of-freedom rigid body model of the tug and debris and a discrete model of the tether, and then proposed an open-loop discrete thrust input shaping control scheme to avoid post-burn collision between the space debris and tug. Linskens and Mooij [33] took advantages of the double-rigid-body model of the debris and tug in three dimensions, and designed a sliding-mode controller for closed-loop relative motion, an attitude control method for the tug and an open-loop throttle-control system for the main engine of the whole TST system in the deorbiting mission. The 3D double-rigid-body model is the foundation of a comprehensive analysis of the TST system as the probability of collision between the debris and tug, the attitude evolution of the tug and debris, the risk of post-burn can be fully depicted. Moreover, when modeling the system in Lagrange method, the physical meanings of every term in the formula are more explicit, and it is much convenient to analyze the dynamic characteristics of the system compared with the Newton-Euler method. Therefore, in this study, a 3D precise model of the TST system derived by the Lagrange's equation is explored in which both the debris and tug are considered as rigid bodies.

The TST system may suffer remarkable oscillations during the deorbit mission. Aslanov and Yudintsev [34] studied the deorbit process of large spinning debris around the Earth in a perturbed space environment using tethered space-tug system, and evaluated the influence of system parameters on the oscillation of debris attitude and the tether. They advised that the oscillation during the deorbiting of the space debris must be avoided as it may result in tether break or tether tangles. Aslanov [30] also researched the chaotic behavior of the tethered space-tug system subject to the gravitational moment and thrust force in a planar motion. The existence of the saddle and the periodic perturbations facilitate the occurrence of chaos which may exist during a tethered tow of space debris according to the numerical simulation result. Thus, oscillation suppression of the TST system is prior to the descent process, so as to guarantee a stable debris removal. In the previous study, there were lots of ways proposed to avoid considerable oscillations of the TST system, such as regulating the deployment velocity of the tether [35] [36], designing PID control laws [37] or nonlinear control schemes [35] to govern the tether tension, using electrodynamic tether [38], modulating the direction and magnitude of the thrust [39], introducing spring-damper in the attachment point of the tether [40], and splitting the tether into four when connecting the debris [41]. Following these methods, the TST system would not give rise to dramatic oscillations or chaotic state provided that the debris stays still at the very start. While for an initially rotating debris, which is the main focus of this paper, one of the effective ways to suppress the spin is by regulating the tether length in a double-tethered space-tug system. When the two tethers are in turn in being slack and stretched, the oscillation of the debris can be efficiently suppressed. However, this method has only been validated in a planar motion scenario in Qi's publication [42]. Moreover, when rupture occurs in one of the two tethers, this method would be invalid. Therefore, to deal with the stabilization by using single tether, Godard et al. [43] brought forward with the idea of exploiting tether offset variations, and investigated the optimal techniques to control the attitude of a satellite in planar motion. Some shortages occurred in Ref. [43], which are stated in Section 3.2, do impede its application. Under such circumstances, new methods and improved algorithms in three dimensions need to be proposed to carry out the concept of offset control by using single tether, so as to imitate the effects of double tethers in stabilizing the oscillation of the TST system both in and out of the orbital plane.

The primary goal of this work is to analyze the dynamical behavior of the TST system and to develop a control law which would suppress the initially spinning debris and tug, as well as the oscillation of the tether, by regulating the tether length and the tether offset in a single-tethered space-tug system. Section 2 presents the precise 3D dynamic model of the TST system using Lagrange's equation in which both the debris and tug are regarded as rigid bodies and the tether is considered massless and elastic with material damping. Furthermore, three simplified models are derived, so as to conduct the study of the system dynamics. In Section 3, stable configurations with respect to the TST system are explored, and an offset control law is proposed aiming to suppress the system oscillations. Besides, a prerequisite is formulated to estimate the maximum debris angular acceleration that the tether can handle, which is utilized before starting the debris removal. Section 4 presents the attitude stabilization of the TST system with initially spinning debris via numerical simulations. It is proved that this designed stabilization strategy can achieve a steady debris removal process. Finally, Section 5 concludes the work.

2. System dynamics

2.1. Dynamic model

The tethered space-tug (TST) system consists of an active space tug, a passive debris, and a tether connecting the two bodies, as shown in Fig. 1. A large debris is taken as the chief object of study of which the dimension is comparable with the tug. Therefore, both the debris and tug are modeled as rigid bodies. The tether is considered massless and elastic with material damping. Note that longitudinal and transverse wave propagations of the tether are ignored because the system can be regarded as quasi-static when performing attitude stabilization. Under such a circumstance, the deployment of tether has already been completed, so the variation of tether length is small when conducting the stabilization. According to Ref. [44], this state of dynamical system is recognized as quasi-static in which the longitudinal and transverse waves play insignificant roles in the system dynamics and therefore ignored in the current research. Besides, the mass of the tether is far less than the heavy defunct satellite. Thus, it is reasonable to omit the tether mass.

The mass center of i-th rigid body is denoted by C_i, in which $i = 0, 1$, and 2 represent the TST system, tug, and debris, respectively. The mass of the tug and debris are m_1 and m_2, respectively, and their principle moments of inertial are denoted by $[J_{x1}, J_{y1}, J_{z1}]$ and $[J_{x2}, J_{y2}, J_{z2}]$. The

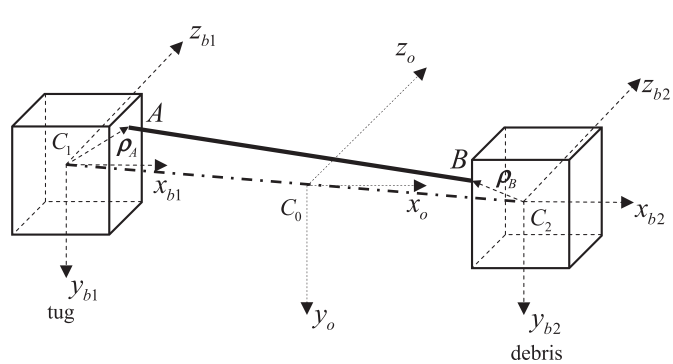

Fig. 1. Geometry of the tethered space-tug system.