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Constrained tension control of a tethered space-tug system with only length measurement

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ABSTRACT

The paper presents a tension control law to stabilize the motions of a Tethered Space-Tug system during its deorbiting process by regulating the tension in the tether. The tension control law is designed on a basis of two straightforward ideas, i.e., the potential energy shaping and the damping injection. The law is expressed in an analytical feedback form in terms of only the tether length without the need of the feedback of full state information. Meanwhile, the requirements of measuring velocities are removed with the aid of a dynamic extension technique based on the feedback interconnection of Euler-Lagrange systems. The positive and bounded tension constraint is taken into consideration explicitly by including a pair of special saturation terms in the feedback control law. The relative motions of the space-tug and the debris are described with respect to a local non-inertial orbital frame of reference, whereas the orbital motion equations of the system are formulated in terms of the modified equinoctial elements of the orbit. Finally, the effectiveness of the proposed scheme is demonstrated via numerical case studies.

1. Introduction

Space tethers are long and thin cables used to connect two or more end-bodies in the space environment. Numerous important applications have been identified for the potential use of space tether on a basis of the principles of gravity gradient stabilization, momentum exchange and electro-dynamic interaction, just to name a few [1]. As summarized in review articles [2–6], the past decades have seen substantial theoretical and technical developments in this exciting research field, and many missions have been successful in orbit to demonstrate various key aspects of the space tether technology [1,5].

One of the most appealing applications of the space tether is in the active mitigation of space debris [7,8]. The problem of space debris has been a great concern in the international community of space science and technology [9–11]. At present, there are more than 22,000 large orbital objects (satellites and other traceable objects larger than 10 cm) and many thousands of smaller debris in orbit around the Earth [11]. The problem is becoming even worse due to the fact that colliding large space objects will dramatically increase the number of small debris, as evident by the first ever satellite collision between Iridium 33 and Cosmos 2251 in 2009 [12]. Expectedly, the chain reaction of space debris collisions possibly leads to the disastrous cascade effects of debris, that is so-called "Kessler Syndrome" [11], if no effective measure is taken to control the rapid growth of space debris population. Active Debris Removal (ADR) from overpopulated orbital regions has been widely recognized as a technology of high-priority to keep sustainable space exploration [10]. It has been shown that the Low Earth Orbit (LEO) debris environment can be stabilized by removing five or more

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large debris per year [9]. Tethered Space-Tug (TST) concept has recently been proposed as one of promising ADR solutions. A typical TST system consists of a spacecraft (space-tug) equipped with active thrusters, a large passive debris (e.g. dead spacecraft and spent upper stage of rocket) to tow, and a connecting tether between them. The thrusting action on the space-tug, coupled through the tether to the debris, will deorbit both of the space-tug and the debris.

In recent years, many attempts have been made to gain an insight into the complex dynamics of TST system by using a variety of models. For example, Jasper et al. proposed an interesting ADR design in which an active upstage of rocket (space-tug), after completing its primary mission, uses its remaining fuel reserve to rendezvous and then attach a tether to another rocket debris object [7]. After that, a thruster burn is applied to deorbit both objects with the aid of momentum exchange through the tether. Liu et al. modeled the dynamics of tether-tugging reorbiting system after net capture, and numerically analyzed the influence of the initial conditions and the magnitudes of thrusts on the system dynamic characteristics [13]. In a series of researches on the tethered ADR system, Aslanov and Yudintsev investigated the influence of various parameters of a tethered space-tug system on its motion [8,14], and demonstrated by means of numerical simulations that the high amplitude of the oscillation of a passive body may lead to entanglement of the tether [8]. The research was further extended to account for the flexible properties of large space debris and assess the mutual influence of the tether vibrations and the vibrations of flexible appendages [15,16]. It was indicated that the parameters of tether should be chosen by taking into account the properties of the flexible appendages, and a critical tether stiffness existing for the given space-tug mass should be avoided [15,16]. Recent efforts have also been made on the TST research from a viewpoint of controller design, especially with a focus on the thrust control of space-tug. For example, Jasper et al. proposed open-loop thrusting control schemes based on the idea of input-shaping to reduce the likelihood of post-burn collision between the debris and the tug by considering both continuous and discrete/impulsive thrusting profiles [17,18]. Aslanov and Ledkov devised a thrust control scheme, assuming that the engine of the space-tug can switch between two modes, to provide tension in the tether during the large debris deorbiting [19].

This paper focuses on the dynamics and control of a TST system during its deorbiting process under the assumption that the space-tug has been successfully engaged with the debris via a tether with positive tension. The thrusting force acting on the space-tug is considered constant in magnitude and opposite to the flight direction, so that a maximum deorbiting efficiency can be achieved. Alternative to the previously proposed schemes of thrust control, a tension control law is pursued in the paper to stabilize the motions of the TST system by regulating the tension in the tether. The “tension control” is commonly referred to controlling the tension by actively reeling in/off tether via a mechanical device in the literature [20]. The development of the tension control law is motivated by the practical need to damp out the relative radial motions of the space-tug and debris such that the potential risk of tether slackness and collision between the end-bodies can be reduced. It is also of concern to eliminate the undesired libration motions made by the TST system with respect to the direction of local horizontal.

The tension control law is designed on a basis of two straightforward ideas, i.e., the potential energy shaping and the damping injection. In addition, the physical constraint that the tether tension should be positive and bounded is also taken into consideration explicitly by including a pair of special saturation terms in the proposed feedback control law. Moreover, particular attention from a practical perspective is paid to the fact that the length of a tether can be measured easily, for example, by using optical encoders but the rate of the length is not directly available for measurement. Thus, it is of practical importance to design a feedback control law in terms of only the tether length without the full state information, although velocity-dependent tension controllers have successively been applied to control space tethered systems for other mission scenarios [3,21–23]. To this end, a dynamic extension technique based on the feedback interconnection of Euler-Lagrange (EL) systems is exploited to remove the requirement of velocity measurement (length rate of the tether) [24]. Additionally, to facilitate the analysis, the relative motions of the space-tug and the debris are described with respect to a local non-inertial orbital frame of reference, whereas the orbital motion equations of the system are formulated in terms of the Modified Equinoctial (ME) elements of the orbit, which are singularity-free for all trajectories with inclination less than 180° [25]. To focus on the fundamental of the tension control law, the presented concept is currently verified using a simplified model where no attitude dynamics is considered for either the debris or the tug. The effectiveness of the proposed scheme is demonstrated via numerical case studies.

2. Dynamic model

The TST system of concern consists of a spacecraft S_1 (space-tug) equipped with active thrusters, a passive debris S_2 to tow, and a connecting tether, as shown in Fig. 1. The motions of the space-tug and the debris are described by using two reference frames, that is, the Earth-Centered Inertial (ECI) frame O_1-XYZ and the orbital frame $O_2-x\,y\,z$ as shown in Fig. 1. Here O_1 and O_2 refer to the center of the Earth and the Center of Mass (CM) of the TST system, respectively. The O_1X axis of the ECI frame points to the vernal equinox, the O_1Z axis is parallel to the rotation axis (North Pole axis) of the Earth, and the O_1Y axis completes the right-handed coordinate system. The O_2x axis of the orbital frame points along the local vertical to zenith, the O_2y axis lies in the orbital plane and points in the flight direction, and the O_2z axis is normal to the orbital plane. The unit vectors along each axis of the orbital frame $O_2-x\,y\,z$ are $\boldsymbol{e}_x$, $\boldsymbol{e}_y$ and $\boldsymbol{e}_z$, respectively.

The thrusting force $\boldsymbol{F}$ acting on the space-tug is of a constant magnitude F, and points opposite to the flight direction of the system, such that $\boldsymbol{F} = -F\,\boldsymbol{e}_y$ holds. The dimensions of