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On-line estimation of inertia parameters of space debris for its tether-assisted removal

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ABSTRACT

This paper presents a new methodology for on-line inertia parameters estimation for a rigid space debris captured by a tethered system, based on a new dynamics model of the system where the base satellite (chaser) and the space debris (target) are modeled as rigid bodies and the attachment points of the tether are offset from the centers of mass of the two bodies. Parameters estimation of unknown debris is critical for subsequent tasks in the space debris remediation mission, in particular, for debris retrieval and de-orbiting. In the proposed algorithm, the chaser and target are modeled as rigid bodies, the latter with unknown inertia parameters. Then, the parameters identification problem is formulated and solved in three phases. First, a coarse estimate of the target mass is obtained during the post-capture phase, while the length of tether is much longer than the offsets of base and target satellite, and the rigid body model is degenerated to a mass point model. Then, with a proper tension control scheme and the coarse estimate used as an initial guess, the debris is retrieved smoothly and a precise mass estimate is achieved during the first half of the retrieval. Finally, when the tether is retrieved relatively short and the rigid body model is used, moments of inertia and the offsets of the space debris will be estimated with a proper tension control scheme for rigid body model.

1. Introduction

The idea of tethers in space is over a century old. Tsiolkovsky (1895) proposed to connect large bodies in space by a long thin cable to provide gravity gradient stabilization [1]. A survey of early works on tethered satellite systems has been conducted by Misra and Modi [2]. Beletsky and Levin [3] gave a detailed exposition on various aspects, for example, the dynamic analysis, problems associated with tethered atmospheric probe, and applications of the space tether systems. The motivation for research in the design, dynamics and control of space tether systems stems from the number and variety of potential applications [4]. Of more relevance to the present paper, a lot work has been carried out on the space capture mission via tether, for example, in the context of space debris removal. A wide range of problems arise in the different phases of the capture mission, the main phases being the approach, capture, post-capture, and retrieval/de-orbit. The deployment/retrieval of satellites via tethers in space continues to be an intensive research area, as new applications of Tethered-Satellites Systems (TSS) emerge in engineering practice [5–8].

Our motivation for studying the dynamics of TSS is in the context of on-orbit servicing and space debris removal.

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Owing to the rapid growth of the number of defunct objects in orbit around the Earth, development of solutions and technologies for debris remediation is considered a high priority strategic goal for the international efforts. Active Debris Removal (ADR) has been shown to be an effective way to reduce the debris population [9]. Some proposed methods [10,11] utilize mechanical grapples, nets, or harpoons as the terminal device connected to the base via tether to grab the debris object which are named as Tethered Space Robot (TSR), and appear to be a promising solution to catch and remove the space debris [12,13]. For different kinds of TSR, each of them has both merit and demerit. Space tethered net/web has a simple structure and is more feasible for capture of space debris who may have various configuration. However, it launches by ejection which indicates only short distance capture is applicable, and the format keeping of net is not easy to achieve due to the complex space environment. An active operational robot which is able to maneuver autonomously is proposed to be a promising terminal device, and a general concept of TSR is shown in Fig. 1 [14]. The autonomous maneuver makes the operational robot more flexible, whereas the structure is much more complex and not economic for debris removal. Furthermore, the way it uses for capture has limitations, such as spinning satellites and those debris who have irregular shape.

Since a number of investigations have been carried out on the concept of using a tethered space terminal device (grapple or net) deployed from the base satellite to capture space debris[4,], orbit and attitude motions of the space debris and the base satellite before and after capture have been studied [15,16]. Aslanov and Yudintsev, analyzed the dynamics of removal when space debris is captured by a tethered space tug, and the inertia parameters are assumed to be known[15]. Huang et al. proposed a post-capture attitude control for a combination system when the target is captured by a TSR [17], where all the information about target (mass, moments of inertia and offsets) is known. The existing papers, however, are based on the assumption that mass of the debris is known[15]. To our knowledge, there are no studies dedicated to parameters estimation of the *unknown* target after the capture with TSS. For tasks following capture in the debris remediation mission, it is critical to identify the inertia parameters of the unknown target, in particular its mass, moments of inertia, and center of mass offsets.

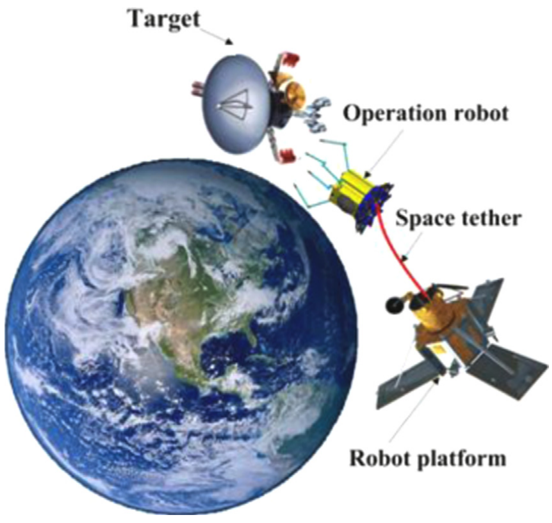

Fig. 1. Concept of the space tethered robot.

Our interest in this problem is motivated by applications of on-orbit servicing and space debris remediation. The particular scenario considered is where a tethered device is deployed from the chaser spacecraft to capture the debris object, referred to as target. The need for inertial parameter estimation arises when the target is unknown with respect to its inertial properties, while their knowledge is required for the subsequent tasks of retrieval and de-orbiting in the space debris remediation mission. Furthermore, the solution proposed in this paper also assumes that the target is uncooperative, and thus, its attitude is not communicated to the chaser spacecraft.

To identify the inertia parameters of the unknown space debris, we present different identification methodologies for three different space debris removal phases. The first phase is post-capture phase and the corresponding dynamics model is mass point model, by treating the base and debris as point masses. Equations of motion based on mass point model is used to formulate the motion during post-capture phase, by reason that the length of tether is much longer than the size of base and target satellites and the libratory motion of two satellites can be considered relatively small in this situation. A coarse estimate of the target mass is obtained in this phase. The second phase is the first half retrieval phase and length of tether, compared to the offsets of satellites, in this phase is still relatively long; accordingly, the mass point model is used and a precise mass estimate is achieved. The last phase is the second half retrieval phase and the offsets of base and target satellites cannot be ignored any more. The estimation of moments of inertia and the offsets for the space debris will be accomplished in this final phase, based on the mass estimate acquired during the first half of the retrieval.

2. Dynamics model

2.1. Rigid body model

A planar dynamics model for the base-tether-target system is derived in this section, which describes the motions of target satellite and tether after the capture and during the retrieval. The base and target are treated as rigid bodies with the offsets from attachment points to each center of mass.

2.1.1. Description of the system

A schematic of the model, as well as the generalized coordinates used to describe the motion, are shown in Fig. 2, where m_1, m_2, m_t are masses of the base satellite, space debris and tether respectively. The position of the center of mass of the system C in its orbit around the Earth is defined by the true anomaly γ and the radial coordinate R_c. Rotating coordinate systems $(C-x_0y_0z_0)$ is used with their origin at the center of mass of the system. The