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Configuration maintaining control of three-body ring tethered system based on thrust compensation

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ABSTRACT

Space multi-tethered systems have shown broad prospects in remote observation missions. This paper mainly focuses on the dynamics and configuration maintaining control of space spinning three-body ring tethered system for such mission. Firstly, we establish the spinning dynamic model of the three-body ring tethered system considering the elasticity of the tether using Newton–Euler method, and then validate the suitability of this model by numerical simulation. Subsequently, LP (Likins-Pringle) initial equilibrium conditions for the tethered system are derived based on rigid body's equilibrium theory. Simulation results show that tether slack, snapping and interaction between the tethers exist in the three-body ring system, and its' configuration can not be maintained without control. Finally, a control strategy based on thrust compensation, namely thrust to simulate tether compression under LP initial equilibrium conditions is designed to solve the configuration maintaining control problem. Control effects are verified by numerical simulation compared with uncontrolled situation. Simulation results show that the configuration of the three-body ring tethered system could maintain under this active control strategy.

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1. Introduction

With the development of aerospace, computer and information technology, mankind has achieved the dreams of earth-observing and earth-perception from space, and the information got have also been applied to the space science research, global disasters and environment monitoring, weather forecast, resources investigation, target detection, etc., playing an important role in the progress of human society [1–4].

In current mature remote sensing technologies, a single spacecraft with multiple sensors is mostly used. However, some researchers indicate that the observation aperture is so small that it can not meet the large-scale and high-precision observation mission requirements. Zhuko et al. [5] proposed a technique for unmixing the data of a lower resolution 'measuring instrument' by its combined processing with the data of a higher-resolution 'classifying instrument'. Gairola et al. [6] reviewed the state of the use of high-resolution remote sensing for ecological studies in the Indian Himalayan Region (IHR) and suggested further potential avenues of research in the region using this technology.

To our knowledge, it is difficult to install remote sensing equipments with larger aperture on a single spacecraft. Thus, researchers found the way of using satellite formation to form a larger virtual observatory aperture. In 2005, Krieger et al. [7] discussed the capabilities of multistatic SAR satellite configurations for different applications like high resolution DEM generation using multibaseline single-pass crosstrack interferometry, 3-D vegetation mapping and layover solution with spaceborne SAR tomography, high resolution wide swath SAR imaging with sparse satellite arrays, multibaseline velocity estimation of moving objects and scatterer fields, spatial and radiometric resolution enhancement in SAR images, and multistatic imaging for improved detection and classification. Furthermore, some major challenges like phase and time synchronisation, multistatic SAR processing, satellite orbit selection, and relative position sensing are also addressed. A year later, they [8] introduced various spaceborne bi- and multistatic SAR configurations, and their potential for different applications such as frequent monitoring, wide-swath imaging, scene classification, single pass cross-track interferometry and resolution enhancement is compared. Furthermore, some major challenges such as phase and time synchronisation, bi- and multistatic SAR processing, satellite orbit selection and relative position sensing were addressed again. In 2007, Krieger et al. [9] gave a detailed overview of the TanDEM-X mission concept which is an innovative spaceborne radar interferometer that is based on two

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TerraSAR-X radar satellites flying in close formation. In 2010, they [10] presented an overview of single-pass interferometric Synthetic Aperture Radar (SAR) missions employing two or more satellites flying in a close formation. Xue et al. [11] also presented an overview of the small satellite literature on earth observation and future developments were put forward in 2008. However, we could find that when the satellites fly in formation, each satellite's orbit is different and there exists natural relative motion between satellites. On the other hand, there is no connection of any kind between them, so nothing could provide effective support for the formation, which brings great difficulties to the formation configuration control [12,13].

Space tether is booming rapidly in both theory and techniques. Therefore, many researchers figured out a solution for space remote observation mission using tethers, which is to maintain the formation configuration by adding connected tethers into the satellite formation. Tragesser et al. [14] investigated the dynamics of tethering several subsatellites together in a three dimensional configuration. To keep the system oriented toward Earth, the Likins-Pringle rigid body equilibria were used as a baseline design. A flexible lumped-mass model was used to assess the stability for the tethered system. Three parameters related to the formation size, masses and spin rate were varied in order to find designs that were stable. Kumar et al. [15] explored the feasibility of rotating formation flying of satellites using flexible tethers. The system they used was composed of three satellites connected through tethers and located at the vertices of a triangle-like configuration. Huang et al. [16] proposed a coupling dynamics model for the tethered space robot system based on the Hamilton principle and the linear assumption. Wang et al. [17,18] proposed a coordinated control of tethered space robot using mobile tether attachment point during approaching phase and post-capture for capturing a target respectively. They [19,20] also proposed the Maneuvering-Net Space Robot System (MNSRS), which can capture and remove the space debris dexterously and mainly focused on coupled dynamics modeling and configuration control problems. In 2008, Vogel [21] assessed the utility of tethered satellite formations for the space-based remote sensing mission. Williams [22] considered a three-spacecraft tethered formation spinning nominally in a plane inclined to the orbital plane and obtained periodic solutions for the system via direct transcription that uses tether reeling to augment the system dynamics to ensure periodicity is maintained. Mori [23] proposed a tethered satellite cluster system, which consisted of a cluster of satellites connected by tethers and which can maintain and change formation via active control of tether tension and length to save thruster fuel and improve control accuracy. By now, most of the papers about multi-tethered system focus on the dynamics modeling and analysis. Hussein [24] studied the stability and control of relative equilibria for the spinning three-craft Coulomb tether problem. This paper mainly focuses on symmetric Coulomb-tether systems, where all three craft have the same mass and nominal charge values.

We find that the basic idea of the spinning tethered system is to use the centrifugal force generated by themselves to produce positive tension in the tether to impede relative movement of the spacecrafts, so that the relative position between them are easier to maintain. Therefore, the existing of connected tethers in the system reduce system configuration maintaining control's dependency on thrusters and prolong the life of the tethered system. However, most of the related papers mainly focus on the dynamic analysis and design criteria of such complex space rigidity–flexibility mixed system, but the most critical configuration maintaining control problem in remote observation missions is rarely involved.

In order to make up for the loopholes above, this paper studies the spin dynamics and configuration maintaining control problem of the three-body ring tethered system under space remote observation background. Firstly, dynamic model of the spinning three-body ring tethered system is established using Newton–Euler method in Section 2 and LP equilibrium conditions are then derived in Section 3. Afterwards, we analyze the influence of the flexible tether and the stability of the equilibrium. In Section 4, the configuration maintaining control strategy based on thrust compensation is proposed. At last, the contributions of this paper are briefly summarized in the Section 5.

2. Dynamic modeling

2.1. System description

Space multi-tethered system can be divided into three basic configuration, which are ring, hub-and-spoke and pyramid configuration, depending on the geometry configuration, and the other complex ones could all be deduced from the above three basic configuration. In this paper, we mainly focus on the typical three-body ring tethered system. The earth-observing mission concept is illustrated in Fig. 1.

The three-body ring tethered system in Fig. 1 consists of three spacecrafts and three tethers, which are connected end-to-end. It is an ideal configuration is an equilateral triangle as shown in Fig. 2.

In Fig. 2, m_1, m_2 and m_3 denote the mass of the three spacecrafts. ρ_{12} is the length of the connected tether between m_1 and m_2; ρ_{23} is the length of the connected tether between m_2 and m_3; ρ_{31} is the length of the connected tether between m_3 and m_1.

2.2. Dynamic modeling

We first make some assumptions for dynamic modeling convenience.

1. The three spacecrafts are assumed as mass points with the same mass. Hence, point i means the ith spacecraft.
2. The connected tethers are all flexible but massless.
3. The tethered system has been completely deployed and the initial length of the three tethers are same and the tethers are in tension and straight.
4. The mass center of the tethered system is in a Kepler circular orbit.

The reference coordinate systems used during the modeling are given in Fig. 3.

As shown in Fig. 3, $\hat{i}$ is the inertial frame with its origin O_e located at the mass center of the earth; $\hat{i}_1 - \hat{i}_2$ plane is the orbital plane. $\hat{e}$ is the orbital reference frame with the origin O_s located at

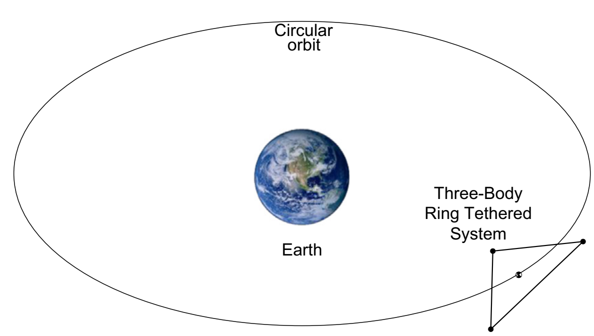

Fig. 1. The earth-observing mission concept.

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