Contents lists available at ScienceDirect
Aerospace Science and Technology
www.elsevier.com/locate/aescte

Deployment/retraction of the rotating Hub-Spoke Tethered Formation System

Panfeng Huang [a,b,*], Yakun Zhao [a,b], Fan Zhang [a,b], Jun Ma [c], Zhongjie Meng [a,b], Zhengxiong Liu [a,b], Yizhai Zhang [a,b]

[a] National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, Xi'an 710072, China
[b] Research Center for Intelligent Robotics, School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China
[c] No. 203 Research Institute, China Ordance Industries, Xi'an 710065, China

ARTICLE INFO

Article history:
Received 14 September 2016
Received in revised form 21 April 2017
Accepted 10 July 2017
Available online xxxx

Keywords:
Hub-Spoke
Tethered Formation System
Deployment and retraction
Dynamics modeling
Optimal control

ABSTRACT

The Hub-Spoke Tethered Formation System (HS-TFS) is now a hot issue in many space applications, such as multi-point measurements, providing flexible frame for solar sail and other membrane or net structures. To achieve the valuable advantages, such as reduction of fuel consumption, promotion of the formation stability, the HS-TFS is usually in the rotating state. In addition, it is necessary to change the length of the tethers to obtain a variable coverage of the entire plane of the rotating HS-TFS in some applications, that is, the deployment and retraction problems of the rotating HS-TFS. However, the rotating motion will increase the complexity of the deployment and retraction of the rotating HS-TFS. In this paper, the deployment and retraction of a rotating HS-TFS is investigated. Firstly, a mathematical model is derived to describe the dynamics of the rotating HS-TFS. Then, the Gauss pseudospectral method is employed to solve the optimal deployment and retraction problems of the rotating HS-TFS. Finally, numerical simulations for deployment and retraction of the rotating HS-TFS are performed. Numerical simulation results reveal that it is necessary to apply active control on the deployment and retraction phases of the rotating HS-TFS, and after employing the optimal control (Gauss pseudospectral method), the HS-TFS can reach the desired configuration.

1. Introduction

Research on space robotics [1,2] has drawn much attention in recent years and tethered space system [3–5] is one of current hot spots in the field of space robotics. Tethered Formation System is kind of tethered space system which presents many attractive and potential advantages in space applications. These advantages can be summarized as follows: A variable configuration baseline for interferometric observations achieved by deploying or retracting the tethers [6,7]; Coverage of the entire plane carried out continuously by rotating the whole formation system; Reduction of propellant consumption in control system of each spacecraft [8]. The Tethered Formation System can have various configurations, but all of the configurations can be separated into three basic configurations according to the shape they look like, which are Opened-String configuration, Closed-String configuration and Hub-Spoke configuration (demonstrated in Fig. 1). The Opened-String configuration (Fig. 1(a)) consists of several spacecraft, and each of them is connected to another by tether, forming as an Opened-String configuration. The Closed-String configuration (Fig. 1(b)) is similar to the Opened-String configuration except that all spacecraft are connected to each other end to end, forming as a Closed-String configuration. The Hub-Spoke configuration (Fig. 1(c)) is a radial configuration with a master-spacecraft in the center of the formation system. The radial tethers are released from the master-spacecraft, and a sub-spacecraft is connected at the end of each radial tether. The Hub-Spoke configuration is provided with a particular trait: many formation control operations can be achieved by the master-spacecraft independently, including deployment, retraction and rotation of the whole formation system. This trait contributes two significant advantages compared with other configurations: simplification of the formation control, and reduction of fuel consumption of the sub-spacecraft. Therefore, the Hub-Spoke configuration has been widely used in Tethered Formation Systems.

The Hub-Spoke Tethered Formation System (HS-TFS) requires keeping rotating to provide a centrifugal stiffening force. Thus, a uniform rotating configuration is the frequently-used configura-

* Corresponding author at: National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, Xi'an 710072, China.
E-mail address: pfhuang@nwpu.edu.cn (P. Huang).

http://dx.doi.org/10.1016/j.ast.2017.07.013

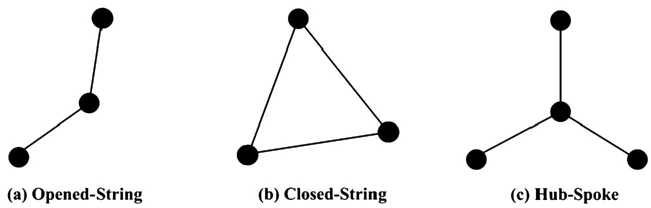

Fig. 1. Basic configurations of the Tethered Formation.

tion in space applications. However, deployment and retraction operations will lead to the inevitable variable coverage of the rotating HS-TFS and destroy the uniform rotating. So the deployment and retraction make the dynamics of rotating HS-TFS more complex. Therefore, the control of the deployment and retraction operations is necessary, but seems to be a difficult problem.

Many studies have been studied on the dynamics and deployment/retraction of the Tethered Satellite System, Tethered Space Robot System and the Tethered Formation System, which can provide valuable methods for the deployment/retraction of the rotating HS-TFS. Sun develops a new control strategy to deploy and retrieve the tethered satellite system stably and quickly using the fractional order control theory [9,10]. Huang proposes a new tethered space system [11,12] and studies the impact dynamics and control scheme of this new tethered system [13–15]. In reference [16], Huang and his team also study the rotating motion of the Hub-Spoke Space Robot Formation System. Misra et al. studies the dynamics of a three-mass tethered formation system based on Opened-String configuration for both constant and variable length tethers [17]. The equilibrium and stability of these systems are studied with more detail in [18]. In reference [19], the control problems of two different configurations of Tethered Satellite Systems (TSS) for NASA's Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) mission are studied. Su and Zhai [20] focus on the control during spinning deployment for Hub-Spoke configured multi-tethered satellite formation. The dynamics of N-body Tethered Formation System based on Opened-String configuration are studied in references [21] and [22]. In reference [22], the equations of motion of N-body Tethered Formation System are derived using the Lagrangian Formulation. The elasticity and mass of the tethers are taken into account in the discussions. Nakaya et al. considers the deployment of a Tethered Formation System based on Closed-String configuration in a circular low Earth orbit using virtual structure architecture [6,23]. The tethered formation system is modeled as three rigid bodies connected via tethers represented by lumped masses. Deployment profiles are determined either as functions of the system angular momentum or tether tension. Control of the system angular momentum is achieved by thrusters on the satellites. Paul Williams studies the deployment/retrieval of the similar Tethered Formation System based on Closed-String configuration [7]. The Tethered Formation System is modeled by point masses connected via inelastic tethers. Optimal deployment/retrieval trajectories using tension control are determined for different rotating conditions. Deployment and retrieval trajectories are planned to maintain the tether spinning at a desired rate and keep the system in a desired physical arrangement at the end of deployment/retrieval. Ary Pizarro-Chong and Misra examine the dynamics of Tethered Formation System based on Hub-Spoke configuration [8]. Some simplifications are made during the research of the dynamics: The spacecraft in the formation system are point-masses, the tethers are massless and straight, and the motion of the master-spacecraft is prescribed. Two formation configurations are investigated, including typical Hub-Spoke configuration and a Closed Hub-Spoke configuration (integration of Closed-String configuration and Hub-Spoke configuration).

The Lagrangian formulation is often used to derive the motion equations of the Tethered Formation System in most studies, and many valuable conclusions of the Tethered Formation System have been drawn. However, the rotating motion of the whole formation system is not considered in most research. Some inspirations of the Hub-Spoke Tethered Formation System dynamics can be found in the existing studies of the deployment of large space web [24–28]. The huge space web is simplified as several straight tethers during the centrifugal deployment, and a hub in the center of the space web can provide spinning torque to control the deployment process. An analytical model based on these simplifications is used to describe the deployment of the large space web. The large space web has the similar configuration as the Hub-Spoke Tethered Formation System in the simplified analytical model, since both of them can be described as a main-spacecraft connected with several radial tethers and sub-spacecraft at the other end of tethers. Furthermore, in the releasing phase, a centrifugal controlled rotation is necessary for both of them. Therefore, the dynamics of the Hub-Spoke Tethered Formation System can be described by the same analytical model. The disparity is that the length of the tethers of the Hub-Spoke Tethered Formation System is variable and controllable. The aim of this paper is to investigate the optimal deployment and retraction of the rotating HS-TFS based on a planar dynamics model derived from the specialty of the rotating motion.

This paper is divided into four major sections as follows: In section two, the dynamics of the Hub-Spoke Tethered Formation System is investigated. In section three, the optimal control theories and optimal deployment and retraction of the rotating HS-TFS are described in detail. In section four, numerical simulations are implemented to validate the optimal deployment and retraction of the Hub-Spoke Tethered Formation System. The contribution of this paper is briefly summarized in conclusion section.

2. Dynamics model

It is very common to employ suitable low-order models of a dynamic system for control system design. Because of the flexibility of the tether, dynamics of tethered space system is governed by complicated nonlinear equations. Therefore it is acceptable to derive the single-tethered system dynamic model as a rigid, inextensible model [3,9]. And in some cases, based on this simplified model, the simulation results are good enough for analysis and controller design [10]. Thus, in order to study the deployment and retraction dynamics of the rotating Hub-Spoke Tethered Formation System, a relatively simple analytical model is derived. For simplification, only two-body Hub-Spoke Tethered Formation System is considered and the analytical results can be enlarged to the multi-body situation.

The following assumptions are made for the analytical model of the two-body Hub-Spoke Tethered Formation System.

(1) The master-spacecraft is a rigid hub, which can provide rotating torque. The sub-spacecraft are regarded as mass points.
(2) The radial tethers are assumed to be symmetrically straight relative to the center of the master-spacecraft, and the centrifugal force acting on the sub-spacecraft results in the tether tension.
(3) The masses of the radial tethers are ignored.
(4) The gravity gradient and the elasticity in the radial tethers are neglected.
(5) The rotating motion is in a planar plane, and the out-of-plane motion of the system is ignored.
(6) Energy dissipation caused by deformation, friction and environmental effects are neglected.

Please cite this article in press as: P. Huang et al., Deployment/retraction of the rotating Hub-Spoke Tethered Formation System, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.07.013