Observer enhanced control for spin-stabilized tethered formation in earth orbit☆

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ABSTRACT

This paper addresses the issues relevant to control of spin-stabilized tethered formation in circular orbit. Due to the dynamic complexities and nonlinear perturbations, it is challenging to promote the control precision for the formation deployment and maintenance. In this work, the formation dynamics are derived with considering the spinning rate of the central body, then major attention is dedicated to develop the nonlinear disturbance observer. To achieve better control performance, the observer-enhanced controller is designed by incorporating the disturbance observer into the control loop, benefits from the disturbance compensation are demonstrated, and also, the dependences of the disturbance observer performance on some important parameters are theoretically and numerically analyzed.

1. Introduction

Tethered satellite formation, which consists of several members that connected by means of flexible tether, has attracted significant attentions in recent years [1–3]. In general, the tethered satellite formations are commonly divided into two different categories: static and dynamic. Dynamic formations always spin with respect to orbital frame, while the static ones remain static during the operation. When dynamic space tether spins along a given reference axis, the formation could be stabilized by the generated centrifugal force, which makes it possible to maintain the formation with less fuel consumption to achieve longer lifetime. Moreover, by regulating the length of connecting tether, the spin-stabilized formation can provide long and variable baselines for distributed space observations. Due to the above mentioned advantages, spin-stabilized tethered formations are widely proposed for future distributed space observations. One example is NASA initiated mission SPECS [4,5] (*Submillimeter Probe of the Evolution of Cosmic Structures*), which it contains a tethered satellite formation, rotating about its primary optical axis for photon collection. By combining the collected results from each member, an angular resolution comparable to the ones that produced by large aperture can be obtained. Other distributed space observation systems [6,7], such as synthetic aperture radar and telescope, are also proposed based on the implications of spin-stabilized tethered formation.

However, there are many challenges concerned to this system implementation in practice, such as the operation on the spin-stabilized system, including the deployment, retrieval and maintenance, in which all of them should be controlled with high precision. In general, the difficulties concerned with control primarily come from complexities of spin-stabilized dynamics. Since, the effective control scheme significantly depends on the deep insight of the dynamic behaviors; many researchers have investigated the dynamic of spin-stabilized system before. For simplicity, some initial studies established the dynamic models under rigid-body assumption [8], so the corresponding results are very limited for indicating the variation of tether tension. Motivated by the potential applications of this system in Earth sensing and surveillance, Tragesser [9,10] studied the motion of a spinning tethered ring formation, but found no stable Earth-oriented configuration due to the dynamic coupling caused by tether flexibility. Without considering the perturb effects from the central body libration, Pizarro-Chong and Misra [11] studied the three-body spinning interferometer and they extended their work to the formation with hub-and-spoke configuration. The behaviors of such formations were discussed for different dynamics environments and the passive stability of both open and closed configurations are also investigated theoretically and numerically. The stability of spin-stabilized system is also interrelated with eccentricity of its operating orbit, G.Aanzini and Fedi [12,13] discussed the effects of orbit eccentricity on the dynamics of a tethered satellite formation, the
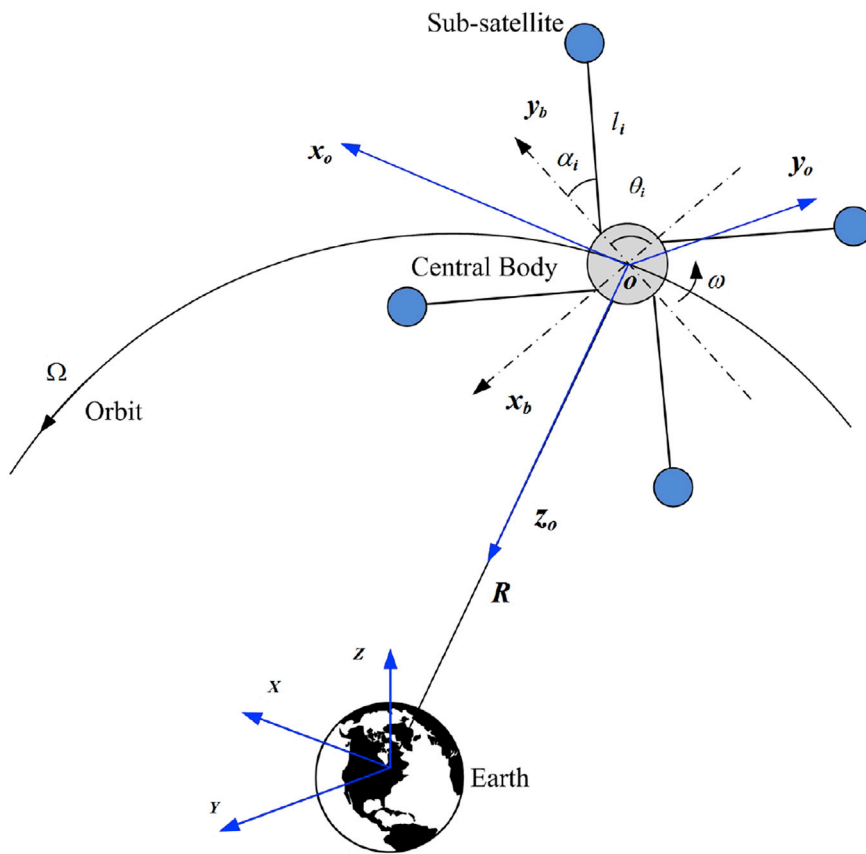
oscillations caused by time-varying gravitational gradient are analyzed based on series of numerical simulations. Aiming at applying the tethered formation for deep space observations, Brin [14] and J.Zhao [15,16] dedicated their work to investigate the tethered formation dynamics in halo orbit near collinear Lagrangian points, to cope with the serious dynamic coupling and time-variations, the full nonlinear and time-varying motion equations are used to conduct numerical simulations for the station-keeping and reconfiguration stages. Additional achievements associated with spin-stabilized tethered formation dynamics can be referred from the cited works [17–19]. Based on above mentioned works, it is clear that the spin-stabilized formation is characterized with nonlinearities, couplings and time variations, furthermore, if the external disturbances are considered, the dynamic complexity becomes even more challenging and difficult and also sometimes impossible to find an analytical solution without any model approximations.

The dynamic complexity also remarkably increases the difficulty on system control. With the purpose of facilitating the controller design, approximations are commonly performed to relax the dynamic complexities. To maintain the configuration of triangular tethered formation, Decou [20] derived a control strategy with rigid body assumption in the presence of gravity gradient disturbances, he also introduced a method of damping tether vibrations using linear offset control scheme. Misra and Modi [21] investigated the N-body formation dynamics, based on the dynamic linearization, this work also developed the linear control laws for in and out-of-plan libration. Williams's work [22,23] studied the deployment and retrieval of spin-stabilized tethered formation and the formation members are treated as point masses connected via inelastic straight tether, the results indicated that the tether deployment rate should be appropriately planned to guarantee stable and successful deployment. Also, he extended his research to the closed-loop control for

the three-body tethered formation by using optimal control methodology. Tragesser [24] developed a minimum-time control law in presence of input limitations. He could demonstrate that although, significant out-of-plane oscillations occur during the formation deployment, the configuration errors are finally bounded within a certain level. Based on input-state feedback linearization, Kim and D.Hall [25,26] developed the asymptotic tracking laws for triangular tethered formation deployment, their research shows that the smooth reference trajectories are essential to guarantee satisfactory control performance. Although lots of work has addressed basic control problems of the spin-stabilized tethered formation, little attention has been paid to promote the control performance. In fact, the errors introduced by dynamic approximation inevitably degrade the control performance, especially for the steady-state accuracy. Consequently, further efforts are still worth well to improve the formation control performance.

With the purpose of developing a robust controller with high performance, a spin-stabilized tethered formation in hub-and-spoke configuration is studied in this paper. Based on the previous works, the nonlinear formation dynamics is extend to the case of considering the spinning motion of central body, thus the dynamic couplings between central body spinning and tether deployment are involved in motion equations. To promote the control performance, a nonlinear disturbance observer is developed to estimate the lumped disturbance caused by dynamic approximation, and then by incorporating the disturbance observer into the control loop, the robust controller that capable of rejecting the disturbance by feedforward compensation is formulated. Finally, series of numerical simulations are carried out to demonstrate the benefits from the disturbance compensation, and also, the dependences of the disturbance estimation accuracy on some critical parameters are theoretically and numerically analyzed.