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Dynamics of multi-tethered pyramidal satellite formation

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ABSTRACT

This paper is devoted to the dynamics of a multi-tethered pyramidal satellite formation rotating about its axis of symmetry in the nominal mode. Whereas the combination of rotation and gravity-gradient forces is insufficient to maintain the mutual positions of satellites, they are assumed to be equipped with low-thrust rocket engines. We propose a control strategy that allows the stabilization of the nominal spin state and demonstrate the system's proper operation by numerically simulating its controlled motion. The discussed multi-tethered formations could be employed, for example, to provide co-location of several satellites at a slot in geostationary orbit.

1. Introduction

This paper presents a study of the multi-tethered satellite formation's dynamics. This formation consists of a main body connected by means of cables with several deputy satellites. Let us note that the deputy satellites are only connected with the main body and not with each other. In nominal regime it has a shape of a pyramid with its top directed towards the Earth (Fig. 1). To keep the tethers taut the formation is spinning, but the combination of rotation with gravity-gradient is insufficient for it and therefore the deputy satellites are equipped with low-thrust engines to stabilize the desired dynamics of the system.

If tethers are long enough such a formation can be used to maintain the main body in geosynchronous motion (i.e., in the motion with an orbital period of one sidereal day) below the geostationary orbit (assuming that the mass center O of formation moves in GEO). If tethers are passing not too close to the formation's mass center O, an "ordinary" geostationary satellite can be placed inside the discussed pyramidal structure. And, of course, any other applications mentioned typically in papers on the dynamics of multi-tethered formations remain relevant (space interferometry, multi-point measurements, etc).

I. Bekey was probably the first to discuss three-dimensional multi-tethered formations, he proposed a double-pyramid configuration [4]. Then the dynamical properties of multi-tethered formations were intensively studied.

To specify formations comprised of a main body and deputy satellites attached to the main body by tethers (as in our case) Pizarro-Chong and Misra introduced the term "hub-and-spoke" [13]. The behavior of such formations was studied in different dynamical environments: in circular orbit [2], in elliptic orbit [3], in halo-orbit [25,5] and near collinear Lagrangian points [22].

Interesting examples of 3D equilibrium configurations of a chain of four satellites connected by three weightless

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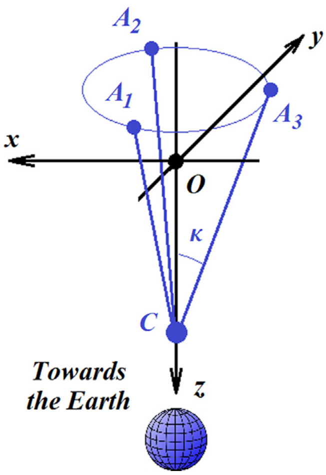

Fig. 1. Earth-facing multi-tethered satellite formation: C – main satellite, A_1, A_2, A_3 – deputy satellites.

rods were presented in [7], although at least one rod in these configurations is compressed and thus cannot be replaced with a tether.

Worthy of special mention is a recent series of papers by Schaub, Seubert et al. [15,16,12], etc., where the concept of the Tethered Coulomb Structure (TCS) is introduced. In general TCS is a 3D structure consisting of discrete spacecraft components (nodes) connected by tethers. The discrete components are electrostatically charged to produce repulsive forces between them and to prevent the slack of any cable. The convincing justification of the TCS technical feasibility is provided, several control algorithms are developed to maintain the desirable attitude motion of such a structure. Nevertheless, it appears that the Coulomb repulsive forces are the effective countermeasure against slacks only in the case of relatively close nodes: the discussed length of the tethers in [15,16,12] has an order of magnitude of 10 m.

The SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellite) system, developed by MIT Space Systems Laboratory, NASA, DAPRA and Aurora Flight Sciences, was proposed as a testbed for dynamical experiments with tethered formations [6]. There are three SPHERES satellites currently onboard the International Space Station. Being equipped with twelve carbon dioxide thrusters these satellites can maneuver with great precision in the ISS interior safety for its crew. Videos of on-ground tests of tethered formations consisting of SPHERES satellites are available on the site of MIT Space Systems Laboratory (http://ssl.mit.edu/spheres/videos.html).

As the novel trend one can distinguish the studies on dynamics of the space webs composed by the large number of spacecrafts connected by tethers (e.g., [11,24]). Evidently, a sophisticated control strategy is needed to maintain the desirable shape of the space web and to provide the required orbital and attitude dynamics. In particular, this strategy should take into account the gravity-gradient effects and centrifugal forces applied to such a very flexible structure. Below we will be dealing with similar requirements.

More references can be found in reviews [8,20], where special sections are devoted to multi-tethered formations.

Since multi-tethered satellite formation is a mechanical system with a very large number of degrees of freedom, in general its dynamics is rather complicated. Taking into account that the satellites' dimensions are much smaller than length of the tethers the former are usually approximated as point masses. Another commonly used simplification is an assumption that the tethers are weightless. Some authors employ the so-called lumped mass discretization to analyze the dynamics of the system in a more realistic way (e.g., [1,2,21]).

In Section 2 we start with the consideration of a simplified dynamical model of multi-tethered formation (point masses + massless tethers). We derive a control strategy allowing to maintain the formation in the uniform rotation around the local vertical and provide the stability conditions of controlled motion. The modification of the control strategy that allows the formation to stay in steady rotation around the axis making a specified angle with the local vertical is proposed in Section 3. In Section 4 we present the results obtained by numerical simulation of the system's dynamics.

2. Control strategy to maintain the system's rotation about the local vertical

2.1. Basic assumptions and equations of motion

As stated in the Introduction, we will consider a space system composed of the $N+1$ bodies: the main satellite $C$of mass m_1 and N deputy satellites $A_1, \ldots, A_N$ of mass m_2 each. The deputy satellites are linked to the main satellite by tethers; all the tethers are assumed to be identical; unless otherwise stated the tethers' masses are ignored.

The desired nominal mode of motion is a uniform rotation of the system about the local vertical (i.e., a straight line running from the Earth center of mass (CoM) to the system CoM O). In the nominal motion the main satellite is located on the local vertical at a distance d_* from the CoM O and the deputy satellites move around in a circle in the plane normal to the local vertical; the neighboring satellites are located the same distance apart (Fig. 1). To maintain a system in such a rotation the deputy satellites are equipped with low-trust engines.

Developing a control strategy we will use the central field approximation for the Earth gravity field (in Section 5 we present the results of numerical simulations demonstrating the efficiency of the proposed strategy for a more realistic model of the space environment including, in particular, high-degree Earth Gravitational model, Moon and Sun perturbations). The system CoM O moves nominally in circular orbit with the mean motion ω_0.

To write down the motion equations, we introduce a Local Vertical Local Horizontal (LVLH) reference frame, centered on the nominal position of the system CoM in its orbital motion: the Ozaxis is aligned with the local vertical, the Ox is running tangentially to the orbit in the direction of the CoM O motion and the Oy axis is directed along the normal line to the orbit plane.

We start with the equations describing the deputy satellite motions:

$$m_2\ddot{\mathbf{r}}_i = \mathbf{F}_i^e + \mathbf{F}_i^{cor} + \mathbf{T}_i + \mathbf{U}_i, \quad i = 1, \ldots, N. \tag{1}$$