Modeling and analysis of deployment dynamics for a novel ring mechanism

Bing Li, Xiaozhi Qi*, Hailin Huang, Wenfu Xu*

Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen 518055, PR China

Abstract

With the development of satellite-communication and earth-observation technologies, the demands for large and light space-deployable antennas have become more and more urgent. In this paper, a deployable ring mechanism capable of supporting a large flexible cable net antenna reflector is presented. The mechanism is driven by torsion springs and controlled by cables. It is composed of multiple deployable modules and has a high deploy/fold ratio, therefore, it has good application prospects. To improve the reliability of the mechanism, a dynamic simulation must be conducted at the design stage to investigate the mechanical characteristics. First, a full kinematic model is established and the position, velocity, and acceleration of the mechanism are analyzed. Next, taking into account the influence of the flexible cable net, frictional damping and the torsion springs, the deployment dynamics of the mechanism are modeled by using a Lagrange's method. Finally, forward dynamics and inverse dynamics simulations are conducted to investigate the rules the governing system-energy variation, and the influence of viscous damping on the motion of the mechanism. A modified deployment motion planning method based on force-control is proposed, and the relationships between control force and motion are ascertained and verified by a prototype of the ring mechanism.

Keywords: Deployable mechanism  Dynamic modeling  Motion planning  Dynamic simulation

1. Introduction

With the development of the aerospace industry, increasingly large and light structures such as solar sails, deployable masts, and space antennas are required to meet the needs of space missions such as earth observation, satellite communication, and scientific research [1]. As the transport rockets used today have limited storage space, large space structures are usually designed as deployable mechanisms that expand from a compact folded state during deployment, and can support some loads as a complete stable structure [2]. Large deployable antennas play a significant role in the development of advanced satellite communication and deep space communication systems. In recent years, many structural designs have been presented, and several engineering models have been successfully launched and used in space by space agencies [3].

Many types of space antenna have been constructed [4–5], such as mesh antennas with knitted lightweight metallic mesh reflectors supported by deployable mechanisms. The Japan Aerospace Exploration Agency developed a large deployable reflector (LDR) consisting of fourteen modules [6], each composed of a cable network, a mesh surface, and a support structure containing six basic radial deployable mechanisms. Two LDRs were launched with the Engineering Test Satellite VIII on December 18, 2006. Each had a 13-m aperture and weighed 170 kg [7]. The Astro-Mesh antenna developed by Astro Aerospace Corporation, which is composed of a mesh reflector, a cable-network system, and a deployable ring structure [8], has experienced no failures in more than 15 years of continuous

*Corresponding authors.

E-mail addresses: libing.sgs@hit.edu.cn (B. Li), xiaozhiq@163.com (X. Qi), dwenhcl@gmail.com (H. Huang), wfxu@hit.edu.cn (W. Xu).

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development, and is currently the most advanced and reliable reflector technology available. You presented a cable-stiffened pantographic deployable structure that can be used to build a deployable mesh antenna [9]. In this structure, two peripheral and concentric pantographic rings of different heights are radially connected by a third set of pantographic pairs. The whole mechanism has a single degree of freedom and good stiffness and accuracy. Chinese researchers [10] have proposed two types of deployable double-ring truss antenna based on parallelogram mechanisms, and verified their structural stiffness in prototype experiments.

The deployment of large deployable antennas from their most compact folded state to their full deployment configuration is a complex process. To improve deployment reliability, many researchers have used simulations to predict the deployment performance of the mechanisms under study. Li [11] established a multi-rigid-body dynamic deployment model of a hoop truss antenna. To ensure smooth deployment, the second derivative of a quintic polynomial was used to model the antenna’s expansion speed. However, flexibility and joint friction must be considered when modeling the dynamics of larger structures. Using a composite of plate and beam elements, Neto et al. [12] built a flexible multi-body dynamic model of the European Remote Sensing (ERS) satellite ERS-1, consisting of flexible solar arrays, a flexible truss, and a rigid body. Modal synthesis was used to reduce solving difficulty, and the dynamic coupling properties of the flexible space structure were analyzed in relation to various aspects of the satellite ontology. Mitsugi [13] set up a flexible-body dynamic model of a deployable hexagon truss antenna with a flexible cable network to examine the antenna’s deployment dynamics. The values obtained for the tension of the cable were close to the measured results. Zhang et al. [14] constructed a flexible multi-body dynamic model to investigate the dynamic characteristics of a flexible deployable antenna, and proposed a decoupling control method to reduce the deployment vibration caused by flex factors.

The authors’ research group has investigated several issues related to large deployable mechanisms, such as synthesis [15], mobility analysis [16], optimization design [17], and cable net form finding [18]. In this paper, we introduce our recent work on the dynamic simulation and analysis of a novel deployable ring mesh antenna with a flexible cable network. We present a deployable ring mechanism for use in space missions such as satellite communication and earth observation. The mechanism, which comprises multiple deployable modules, is driven by torsion springs and controlled by cables. The deployment of the mechanism is modeled to enable the prediction and investigation of its dynamic deployment characteristics.

The remainder of this paper is organized as follows. First, in Section 2, a deployable ring mechanism capable of supporting a large flexible cable net antenna reflector is presented. In Section 3, a full kinematic model is established and the position, velocity, and acceleration of the mechanism are analyzed. In Section 4, the deployment dynamics of the mechanism are modeled, taking into account the influence of the flexible cable net, frictional damping, and torsion springs. In Section 5, forward dynamics and inverse dynamics simulation analysis are used to further investigate the dynamic characteristics of the mechanism. Conclusions are drawn in the last section of the paper.

## 2. Novel deployable ring mechanism

The mesh-reflector antenna consists of a support truss and a flexible cable net that generates an approximately parabolic reflector as the working surface of the antenna. The performance of the antenna is affected by the precision of its surface shape. The primary task of the support truss is to enable the flexible cable net to deploy from a collapsed configuration to a working configuration with sufficiently high profile accuracy to meet the requirements of the antenna. Many factors, such as the effectiveness of the support truss, determine the precision of the mesh reflector. Increasing the size of the antenna’s aperture makes it very difficult to construct the flexible cable net with high profile accuracy. Therefore, it is necessary to design a novel space-deployable truss system with a small folded size and a small mass to better support the mesh reflector and increase the precision of its surface shape. As the mass per unit area of the deployable ring structure decreases as its expansion diameter increases, a variety of deployable ring structures have been used in recent years to build large-scale, lightweight mesh antennas. For example, an AstroMesh antenna built in the U.S. [8] is deployed by shortening a cable and then by changing the diagonal length of a parallelogram mechanism. However, the stowed height of the antenna is greater than its deployment height, which leaves room for improvement. In this paper, a combination module with a six-bar mechanism is proposed as the basic structure of a large ring mechanism that is the same height when stowed and deployed, and can be used to build a ring structure to support a large-scale mesh reflector.

The deployment of the two basic modules of the deployable ring mechanism is shown in Fig. 1. The basic module is a six-bar mechanism, and the deployment of adjacent modules is synchronized using dual slider–crank mechanisms. In each module, the synchronous movement of two sliders on a vertical rod is realized using a closed-loop cable, which is passed through pulleys at both ends of the vertical rod and attached to the two sliders, as shown in Fig. 2. The closed-loop cable ensures that the two chords connected with the vertical supporting rod move synchronously during deployment. Dual slider–crank mechanisms and closed-loop cables enable multiple modules of the deployable ring mechanism to be deployed or folded synchronously, and the whole ring mechanism has one degree of freedom, which is conducive to smooth deployment. Large torque springs are attached to the rotational joint of the mechanism to drive the antenna when deployed, and the deployment speed is controlled by two cables positioned symmetrically around the ring mechanism. The release rate of the cables can be adjusted.