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A large ring deployable mechanism for space satellite antenna

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A B S T R A C T

With the development of space technology, new demands for satellite communications services, space and earth observations drive the requirement for large aperture space antennas. In order to meet the missions, this paper presents a kind of novel single mobility deployable ring mechanism based on a set of planar six-bar linkages. The ring mechanism has very high deploy/fold ratio, which is suitable for building large scale satellite deployable antenna. The mobile assembly of the ring structure and synchronous movement compatibility conditions are investigated, then the synchronization movement of the six-bar linkage modules can be realized by using close-loop cable and dual slider-crank mechanisms, which ensure the single mobility of the whole ring mechanism. Two types of driving mode for the deployable ring mechanism including cable driven and torsion spring driven are studied, and the high rigidity driving joints are designed. Finally, a ground experimental prototype of a 3.9 meter in diameter is fabricated to show the feasibility of the proposed mechanism, the deployment accuracy are also tested and the results show the good repeatability for the ring deployable mechanism.

1. Introduction

Deployable mechanism refers to a kind of mechanism which can be transformed from a compact folded state to an anticipatory deployed form, and can become a complete stable structure with adaptive capacity of supporting loads [1,2]. Due to the good performance at space applications, deployable mechanisms are widely used in building large space structures, such as deployable mast, deployable antenna, and so on, and play a significant role in space missions such as earth observation, telecommunications, scientific researches etc. Because of the high storability and light weight, the deployable antenna with flexible cable net is one of the highly desired antennas in aerospace applications [3,4]. Many efforts, including innovative design concepts, analysis methods and experiments, were contributed to enhance the deployable antennas technology.

Large deployable antennas have been built for space missions with different structural schemes, however, most of them can be classified as radial structures (e.g. Lockheed's Wrap-Rib antenna, Harris' Rigid-Rib and ESA's MBB antenna Hinged-Rib), modular structures (e.g. JAXA's ETSVIII, Tashkent's KRT10, OKB-MEI's TKSA-6) and peripheral truss (e.g. Northrop-Grumman's AstroMesh, Harris' hoop-truss and hoop-column, GTU's MIR reflector experiment, ESA's LDA) [5,6]. Among these, the peripheral ring antennas with the advantage of self-synchronization, high thermo-elastic stability and deployment reliability is investigated for the past few years. Ever since early 1980s for the Soviet space programs originated at GTU, researches into several pantograph ring concepts and associated technologies have been made [7,8]. In 1999 a 5.5-m peripheral pantograph structure with radial tensed membrane ribs was flown and deployed on the MIR station. Pantographs and derived linkages have been extensively investigated at GTU, TUM and other research groups [9]. On the other hand, double rings structure, such as Cambridge's Deployable Mesh Reflector, it consists of two peripheral and concentric pantograph rings with different heights radially connected by a third set of pantograph pairs, in spite of the apparent complexity, the overall mechanism has single mobility and good stiffness and accuracy [10]. Chinese researchers have proposed two types of double-ring deployable truss concepts which are based on parallelogram mechanism, structural stiffness are verified by prototype experiments [11]. Astro Aerospace Corporation developed one kind of AstroMesh deployable antenna, which consists of two symmetrical parabolic cable nets, one metal mesh reflector surface and one deployable ring mechanism, they have over 15 years of continuous development history [12,13]. JAXA has also developed two truss antennas with the diameter of 19 meters, which works for the satellite communication service with engineering test satellite

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ETS-VIII launched in December 2006. The antenna was supported by 14 hexagonal truss modules with a diameter of 4.9 meters, and each module contains of mesh surface, cable network and deployable structures composed of six basic deployable units [14]. Research team led by L. Datashvili developed the concept of double pantograph based peripheral ring [15], which satisfies the demand of significantly less mass and smaller folded volume while maintaining stability and deployment reliability.

Apart from the above mentioned design concern, our research group in HIT has done some efforts about large deployable mechanism, such as synthesis of deployable mechanism [16], mobility analysis [17], optimization design [18], cable net form-finding [19] and so on. This paper introduces our recent work on the novel design concept of large mesh deployable antennas. In order to meet the demands of satellite communications services and earth observation missions, one kind of the ring mechanism is presented, which is composed of multiple deployable modules of six-bar linkage. The ring mechanism has the very good deploy/fold ratio, which can be used to build large scale satellite deployable antenna. The degree of freedom of the mechanism is one, and the deployment process can be controlled by the cables. Since there is no use of gears and other big joints, the mass of the overall mechanism is very light.

The rest part of this paper consists of the following five sections. Section 2 presents the design concept of the basic deployable unit, and the geometric modeling of the ring deployable mechanism is studied. The synchronous movement compatibility conditions are presented and the kinematics analysis of ring deployable mechanism is investigated in Section 3. The detailed designs consisted of deployment driving modes and driving joints are developed in Section 4. One ground experimental prototype of a 3.9 meter in diameter is fabricated and the deployment accuracies are tested in Section 5. Finally, Section 6 summarizes the work of this paper and puts forward the suggestions for future work.

2. Proposal of ring deployable mechanism

For mesh reflector antenna, it is mainly made up of flexible cable net and support truss. The front net of flexible cable net system which is an approximate parabolic is the working surface of antenna, and the precision of the surface shape directly determines the performance of the antenna. The support truss system is to drive the cable net system smoothly to the working configuration, which could ensure the cable mesh reflector meet high profile accuracy requirements. The precision of cable net reflector is affected by multiple factors, with the rising of the antenna size, the building of flexible cable network to meet high profile accuracy is very difficult, it is desired to design the space truss system which has high rate of collapse, high reliability and the light mass, in order to better support the cable mesh reflector and increase the precision of its surface shape. In this paper, a module with planar six-bar mechanism as the basic of large ring expansion mechanism is proposed; it can be used to build the support structure of large-scale network reflectors.

2.1. Basic deployable unit

As shown in Fig. 1, a six-bar linkage consists of two vertical rods and four short rods, all the rods are connected by rotational joints and a single closed loop of the linkage can be formed. The lengths a, b, c, d, e, f of six rods within the mechanism satisfy the following geometrical relationship,

$$\begin{cases} a = d \\ b = c = e = f \\ b \le a/2 \end{cases} \quad (1)$$

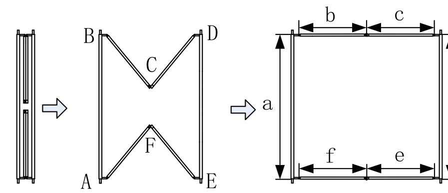

Fig. 1. Schematic diagram of six-bar linkage.

From Fig. 1, when the unit is folded, the four short rods BC, CD and AF, EF are parallel with each other. Then, two vertical rods AB, DE on both sides move towards left and right respectively, the joints C, F of short connecting rod move up and down respectively. When short connecting rods rotate to horizontal position and are locked, the unit could achieve maximum deployable configuration, similar to a rectangle.

The two adjacent elements can be connected by sharing vertical rod together, in order to achieve kinematic synchronicity, two double-crank slider mechanisms are installed in both ends of the vertical supporting rods as shown in Fig. 2. Due to sharing the vertical supporting rod, the slider and the prismatic pair, the short rods of the adjacent units can realize the synchronous deployment or folding. Multiple basic units can be assembled through the same method and a ring expansion mechanism can be built.

2.2. Geometric modeling of ring deployable mechanism

Due to the fact that the paraboloid can focus a lot of parallel signals on one point, so the parabolic form or part of approximate paraboloid fitted with spherical surface is used as the working surface of the satellite antenna, and the satellite signal receiver is located at the focus of the paraboloid. According to the different positions of the rotary axis of the paraboloid and the antenna working surface, the satellite antenna can be divided into two types, prime focus antenna and offset antenna, as shown in Fig. 3. The prime focus antenna has circular contour, and the offset antenna has elliptic contour.

Generally, the multiple units are designed with the same geometric parameters to construct the ring deployable mechanism, the supporting truss of prime focus antenna's is round, and the basic assembly principle adopts regular polygon to approximate a circle. The design parameters are simple, and the angles between the adjacent units are equal. As shown in Fig. 4, a regular polygon is inscribed in a circle, the number of edges is n, α is the angle between the adjacent edges, β is the exterior angle of polygon, R is the radius of antenna, b is the length of the short connecting rod on the surrounding truss antenna. Then, the angle between the adjacent units can be gained as follow,

$$\alpha = 180 - \beta = 180^\circ - 360^\circ/n \quad (2)$$

As the antenna reflector cable network is compos of approximate triangles, the number n of the units in the circular truss is the integer times of 6. By Eq. (2), we can get the angles between the adjacent units in the circular truss corresponding to different number n of edges. When the number n of edges is determined, the angles of the connection joints between the adjacent units can be gained.

According to Fig. 4, the diameter D of antenna can be obtained,

$$D = 2R = \frac{2b}{\sin(\beta/2)} = \frac{2b}{\sin(180^\circ/n)} \quad (3)$$

From Eq. (3), it can be seen that the deployment diameter of the ring mechanism is directly proportional to the length b of the short connecting rod, and the deployment diameter will increase with the increase of the number n of units.