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Research paper

Conceptual configuration synthesis and topology structure analysis of double-layer hoop deployable antenna unit

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ABSTRACT

A method involving conceptual configuration synthesis and topology structure analysis is developed based on graph theory to obtain a series of double-layer hoop deployable antenna units (DHDAUs) that can be folded into straight lines. First, a procedure for synthesizing the conceptual configurations of DHDAUs is obtained by combining graph properties, weighted adjacency matrixes, and several principles. Second, a fundamental topological graph is presented to describe joint connections in a DHDAU on the basis of the adjacency matrix. The fundamental topological graph is reduced to a two-color topological graph by applying various simplified rules and topology properties. Third, a procedure for the identification of kinematic joints is established to fold DHDAUs into lines. Finally, three types of DHDAUs are obtained through this synthesis approach. The models, which were produced via 3D printing, can be deployed flexibly, thus proving the correctness of the theoretical analysis. These methods can provide guidance for the design of large aerospace deployable mechanisms.

1. Introduction

A space antenna is an important functional platform for implementing tasks, such as mobile communication, deep space exploration, and radio astronomy [1,2]. With the development of the aerospace industry, large and light space antennas are required to meet the demands of high earth observation resolution, long-distance space communication, super-large sending and receiving data capabilities, accurate air strike [3–5]. Given the limited storage space of transport rockets used at present, a space antenna with a large diameter must be designed in such a manner that it can be folded into a compact configuration before being launched and deployed into a predetermined shape in orbit [6–8]. According to the composition of the antennas' working surface, deployable antennas can be divided into three categories, namely, solid reflective surface expandable, inflatable deployable, and metal mesh deployable [9]. The metal mesh deployable antenna has become a research hotspot because of its high deployment accuracy, large diameter, and mature technology.

A representative structure of metal mesh deployable antennas is Japan's engineering test satellite ETS-VIII deployable truss antenna. Its support truss consists of 14 six-prism modules, each of which consists of six basic units [10,11]. Another example is the United States' AstroMesh hoop truss deployable antenna. Its entire truss is composed of dozens of modules, each of which consists of a variable (length of the diagonal rod unit), and the diagonal rods of adjacent units are

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arranged in a reverse order [12]. Russia's deployable antenna and Canada's RADARSAT-1/2 satellite, which are constructed with rectangular pyramid units, are also examples [13,14]. Other types include ring column, scissor [15], radial rib, winding rib, and tension rod. The hoop truss deployable antenna is an ideal structural form of a large-aperture antenna due to its high folding ratio and small mass, which enable the device to maintain stable mass and avoid radical mass fluctuation when its diameter is increased [16]. When the diameter is increased, the stiffness of existing single-layer hoop deployable antennas constructed with plane units is no longer able to meet stiffness requirements in a normal working state, whereas the stiffness of double-layer hoop deployable antennas with the same diameter is significantly improved and can meet the demands of large-diameter antennas. Therefore, scholars have proposed double-layer structural forms. Escrig proposed a Pactruss deployable antenna composed of inner, outer, and central deployable trusses [17]. Datashvili presented a double-hoop deployable truss and verified its deployable function [18,19]. You et al. developed a double-layer hoop mechanism with a scissor hinge [20]. Guan et al. proposed a double-layer deployable antenna mechanism based on the United States' AstroMesh hoop truss deployable antenna [21–23]. Qi and Li proposed a large hoop deployable mechanism based on Bricard and six-bar linkages [24,25]. However, when the diameter is increased to 100 m or above, all existing antenna forms cannot meet the required stiffness and deployment ratio. Therefore, a new double-layer hoop deployable antenna with high stiffness, small weight, and high deployment ratio should be developed. A double-layer hoop deployable antenna is usually composed of two parts, namely, deployable support truss and metal reflector network. The support truss is made up of several identical modules or basic units, and all types of antennas involve a topological transformation of modules or basic units. Given that a module is composed of several units, the basic unit is the minimum structural element that supports the truss. Thus, the basic unit is the key factor in building new large deployable structures.

The basic units of a deployable mechanism can be divided into three types, which are scissor, polyhedral deployable, and spatial overconstrained. You and Pellegrino [26,27], Tanaka et al. [28], Zhao et al. [29], and Lu et al. [30] proposed a set of 2D and 3D deployable structures consisting of the scissor mechanism. However, with the increase in the diameter of the deployable mechanism, the mass of the scissor mechanism becomes too large to meet the mass limit of the spacecraft. Hence, scissor units are unsuitable for large deployable structures. Wohlhart [31], Gosselin and Gagnon-Lachance [32], Kiper [33,34], and Ding et al. [35,36] worked on polyhedral deployable units. A series of polyhedral deployable structures have been obtained by inserting planar links into regular polyhedral surfaces and combining various planar polygonal linkages. Nevertheless, a networking method to construct large deployable mechanisms by connecting numerous polyhedral deployable units remains lacking. Moreover, the deployment ratios of existing polyhedral deployable units are small because these units cannot be folded into a line. Analysis indicates that existing polyhedral deployable units are unsuitable for building large deployable mechanisms. Spatial over-constrained units have become a research hotspot due to their high deployment ratios and favorable stiffness. You and Chen proposed improved Bennett, Myard, and Bricard linkages and various spatial closed-loop over-constrained deployable mechanisms by using single-loop over-constrained spatial linkages as base units [37–40]. They cooperated with Liu [41], Song [42], Chai [43], Yoda [44], Lengyel [45], and Baker [46] to investigate the kinematic characteristics and singular configurations of over-constrained deployable mechanisms. Dai and Wei proposed several over-constrained deployable mechanisms recently [47–52]. Over-constrained units are unsuitable for large deployable mechanisms due to their specific geometric requirements. In summary, no suitable deployable units can be used to build a large double-layer, hoop deployable antenna, which requires high stiffness and a large deployment ratio. Therefore, new double-layer hoop deployable antenna units (DHDAUs) should be established.

Existing structural synthesis design methods of deployable units depend mainly on personal experiences, and minimal attention has been devoted to the synthesis of deployable units. The most recent research on space multi-loop structural synthesis focused on parallel manipulators, which belong to five main groups [53], namely, displacement subgroup method [54], motion synthesis method [55,56], Gf synthesis method [57], screw theory method [58,59], and Lie's group theory [60,61]. Deployable units are multi-looped and highly flexible, which are properties that differ from those of parallel mechanisms. Thus, the structural synthesis methods mentioned above are unsuitable for deployable units. The topological features and the configuration of a kinematic pair of deployable units can be expressed well by graph theory. Many novel deployable units have been developed based on graph theory according to Warnaar et al. [62,63]. Nevertheless, existing studies on the synthesis of deployable units by graph theory focused on planar units. Only a few studies concentrated on a synthesis approach for DHDAUs, whose deployed state is a 3D structure and whose folded state is a straight line. New DHDAUs can be obtained using a synthesis method based on graph theory.

To address the requirement of large-diameter, double-layer, hoop deployable antennas, we develop a battery of DHDAUs that can be folded to a line by applying the conceptual configuration synthesis and topology structure analysis method. Initially, graph properties, a weighted adjacency matrix, and several principles are used to describe the characteristics of DHDAUs. A procedure for synthesizing the conceptual configuration of DHDAUs is then obtained. Next, a two-color topological graph is established to describe and analyze the relationship among the components of DHDAUs. A procedure for the identification of kinematic joints is then established to make DHDAUs fold into lines. Three types of DHDAUs are obtained using the abovementioned method.

The rest of this paper is organized as follows. Section 2 briefly introduces the composition of a double-layer hoop deployable antenna and the general process of configuration synthesis. Section 3 presents a procedure for synthesizing the conceptual configuration of DHDAUs by integrating graph properties, a weighted adjacency matrix, and several principles. Section 4 provides a two-color topological graph of DHDAUs, and Section 5 shows a procedure for the identification of kine-