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A review of applications of deployable structure

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Abstract. Simple and reliable deployable structures already play a role in every aspect of our daily lives, from shopping bags and baby carriages to large buildings such as balconies and stadium roofs. In recent decades, people have been more interested in the various applications of deployable structures, for example, aerospace engineering. This paper reviews some examples in the field of deployable structures, including from the basic elements to more complex ensembles such as planar double-chain linkages and deployable antennas. Due to its properties including lower cost, smaller volume, and multiple usages, deployable structures have been extensively applied to the design and manufacture of satellites and other devices for space activities. Sizeable space antennas, as a key technology currently developed for space probes, are reviewed in this paper by using formulas to explain their functions and highlight abilities. The system of paraboloid cable net is also reviewed due to some benefits. We have discussed and summarized some challenges in applying deployable structures, along with strategies for potential solutions.

Keywords: Deployable structures, double chain linkages Membrane antenna, retractable roof.

1. Introduction

The deployable structure has affected the lives of humans in many essential ways, which include the structures used in architecture, medical equipment, and space, e.g., the retractable roof of the stadium in architecture, and some medical equipment in medicine.

In the principle of architecture, retractable roofs used in stadiums also demonstrate plenty of benefits. They were taking three of them as examples to be mentioned:

1） Retractable roof stadiums provide comfortable playing and watching conditions for outdoor sports in extreme weather.

2） Retractable roofs enable the growth of natural grass playing fields in regions with harsh weather conditions.

3） A retractable roof allows sunlight control while maintaining the audience's view.

In medicine, a stent made by Boston Scientific has been used to help patients solve their health problems [1]. The primary advantage of this stent is the ability to isolate bacteria and salts containing magnesium and calcium to increase the success rate of surgery.

In aerospace, a Membrane antenna is an example of a deployable structure [2]. Compared with traditional antennae, many advantages can be observed in Membrane antennae, which include the bigger size with a smaller weight, less volume needed in the satellite, and less costs [3]. We have challenges in this field; for instance, only a few countries can use Membrane antennae in space, which means combining the new technology (deployable structure) and conventional techniques is still faced with some problems.

The organization of this review can be separated into the following three sections. Section II reviews how to make a double-chain linkage using some essential elements and approaches. In Section III, we review some applications and kinematics by emphasizing the significance of using the deployable structure and formula of solution, respectively. The conclusion of this review occupies section IV.

2. Core Principles of Designing Double Chain Linkage

Double chain linkage is a classical and widely used deployable structure formed by scissors-like essential elements, as seen in Figures 1, and 2. Two basic elements are scissor-like structures, but various types are used to make planar double-chain linkages. These similar parts have some of the same features—one connection revolute joint and four pivots (link with other elements).

As for how to make a double chain linkage, two methods can form this structure: solving it by using symmetry and drawing a vector polygon. Some double-chain linkages are symmetric; the entire structure will likely be obtained by pairing when one part is finished. The second way shows the double chain linkages are divided into two kinds of vectors (see Fig. 3)(assume blue vectors are pi while yellow vectors are qi). Only if pi and qi form polygons, respectively, the double chain linkages are not fixed structures, so two polygons formed by the same amount of vectors are supposed to be written on paper; the double chain linkages can be made by composing vectors together [4].

Figure 1. Scissors-like basic element

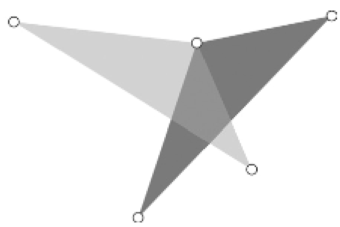

Figure 2. Angulated scissor-like elements

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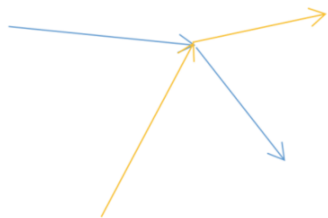

Figure 3. Vector form of basic element.

It can also be found that there are some fixed points in double-chain linkages (see Fig. 4), such as D1, D2, D3, and D4. The structure can still move fluently when these points are fixed in planar [5]. Proves the existence of fixed points [6]. Fixed points can be any point in the same planar with double chain linkage; this means the position of a fixed point is arbitrary if these points can form a polygon, which can also be formed by vector pi or qi [7].

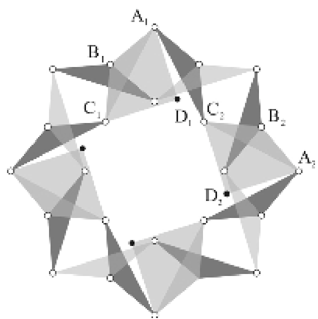

Figure 4. Example of double chain linkage.

Double-chain linkages are widely used nowadays and have developed rapidly. This kind of structure is applied to architecture and spacecraft. For example, a deployable roof can be designed to open on a sunny day or close on another day. Solar panels for satellites can also adopt this structure as it can transport larger areas of solar panels in a smaller volume.

3. Applications and Kinematics

Building spacecraft employs the technology of deployable space structures, mainly when folding and deployment capabilities are needed. The structures are released, deployed, and placed after they are in orbit. Space-used deployable structures are a hot topic for space science and technology research due to the advancement of communication, remote sensing, and navigation satellites. They include massive space mesh antennas, space solar arrays, and methods for deep-space exploration. This review studies the overview of the current research situation and development trend for deployable structures for aerospace engineering. It focuses on the kinematic studies and solutions of large deployable space antennas.

The best answers to engineering issues in the realm of aircraft were viewed as deployable structures, which were a synthesis of mechanisms and structures. Over-constrained membrane, cable, and rod deployable structure systems have a straightforward design and good rigidity. Numerous design theories have been developed to examine deployable systems' configuration, kinematics, and dynamics. For instance, the configurations of mechanisms are greatly enhanced by graph theory, a topological method frequently used in the configuration design of deployable structures. For the over-constrained deployable structures with double or multiple loops, screw theory can quickly analyze the kinematics using the Denavit-Hartenberg (D-H) method, as it can rapidly determine the position of the axis. In addition, based on the screw theory, kinematic chains can be analyzed [10].

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Because of their vast size, high precision, and low cost, sizeable deployable space antennas have been used extensively in many space missions. Typically, the composition of a deployable antenna includes a paraboloid cable net and a deployable structure, as shown in Fig. 5. The cable net system consists of four main parts: surface net, metal surfaces, vertical cables, and support cable net (see Fig. 6). The accuracy of cable net, a crucial part of deployable antennas, is necessary. A tolerance between 1/30 and 1/50 of the operational wavelengths must be attained. Thus, form finding—including determining the required shape that effectively satisfies particular property requirements—plays a crucial role in the design of cable nets [11].

Figure 5. Composition of a deployable antenna.

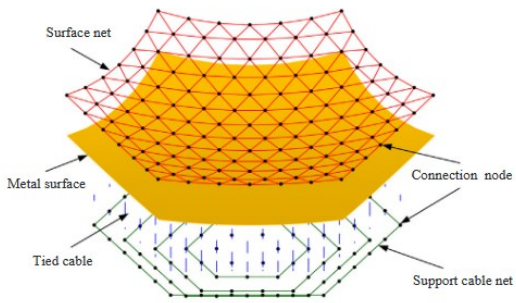

Figure 6. Cable net system in the deployable antenna.

A space paraboloid must often be threaded through numerous space plane components to build a cable net. In this study, a triangle facet is chosen as a commonly advocated idea to serve as the fundamental building block of the cable net. A m-sided polygon is first split into m sectors (see Fig. 7). In this investigation, m is assumed to be six. Then, nn triangles are separated into each sector (see Fig. 8). Finally, the triangular plane cable net is projected onto the chosen paraboloid to generate the shape of the space cable net (see Fig. 9)

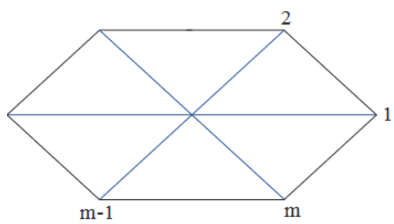

Figure 7. M-sided polygon

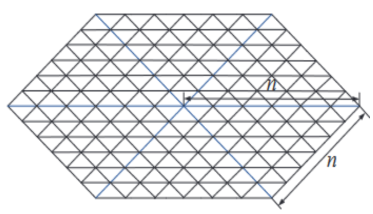

Figure 8. Subdivision of order n

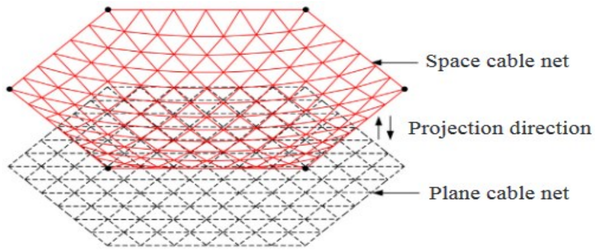

Figure 9. Vertical projection to the paraboloid

The geometric faceting mistake is always present when several triangular planar elements are considered, regardless of size or shape. Considering that is the geometric faceting error, the diameter, and focal length, respectively. According to Agrawal P et al. [12], the triangular element with cable length satisfies the following relationship

The above equations prove that the error of the component is only affected by the number of separated sections. It also helps to analyze the relationship between the number of separated sections and the error in geometric components. According to Fig. 10, a negative relationship between the number of segments and the error is indicated. This graph indicates that the total amount of separating sections should be manageable while designing the structure. Moreover, a notable result from this diagram is that as the number of sections increases to 6, the error in components approaches 2.8mm and tends to be stable. This evidence provides a sufficient number of designers who aim to achieve the proper operation of a deployable antenna.

$$L = \frac{1}{2}\sqrt{\frac{(64F^2+D^2)\times\delta_f\times\sqrt{15}}{F}} \tag{1}$$

Considering that each sector consists of triangles, we can express the length of the cable as

$$L = \frac{D}{2\cdot n} \tag{2}$$

Hence, Eq. (1) can be expressed as

$$\delta_f = \frac{D^2F}{n^2\sqrt{15}(64F^2+D^2)} \tag{3}$$

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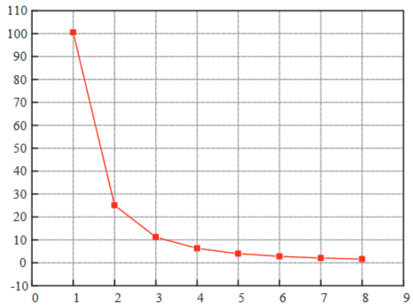

Figure 10. The relationship between several identical sections and the error.

A triangular plane cable net's vertical projection ensures that the nodes connecting the plane and the space cable nets have identical x and y coordinates. Hence, based on the view from the y-axis of the foldable antenna (Fig. 11), a coordinate system can be established, while the origin of the system lies in the center of the entire structure.

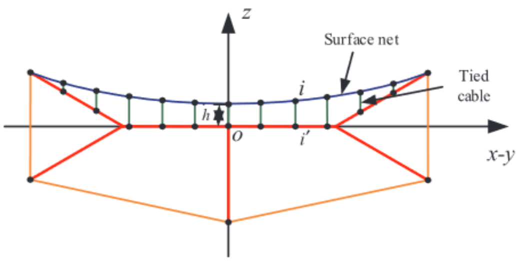

Figure 11. Sideview of the cable net.

The parabolic equation based on the surface net is given as follows:

$$z_i = \frac{x_i^2 + y_i^2}{4F} + h \tag{4}$$

Where h stands for the height from the origin to the middle point of the external net, while x and y are the exact coordinates of the thickening points in the plane. However, outermost wires have relatively high-tension connections to the deployable antenna, which leads to high heterogeneity and poor accuracy in the wire's periphery. The proportion between droop and cross is a notion that is used to address this issue. Consider a triangle (Fig. 12), which makes up 1/6 of the net of wires of the antenna. Due to its symmetry, the triangle is warped by the hang of the wires in the outermost chain.

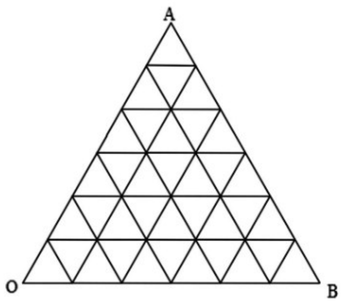

Figure 12. The outmost triangle without the sag effect.

The formula of ratio of droop and cross can be written as:

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$$\rho = \frac{\delta}{s} = \frac{\delta}{2R_0 \tan\left(\frac{\theta}{2}\right)} \tag{5}$$

A key question that needs to be solved is: What is the functional radius of the antenna, is the droop, and is the cross?

The positions of the wire's thickening points are evenly distributed on the arc, with a radius of r and a critical angle of theta, as shown in the geometric arrangement in Fig. 13, which is written as follows:

$$\begin{cases} R' = \dfrac{\delta^2 + R^2 sin^2\left(\frac{\theta}{2}\right)}{2\delta} \\ \gamma = 2 \arccos\left(\dfrac{R' - \delta}{R'}\right) \end{cases} \tag{6}$$

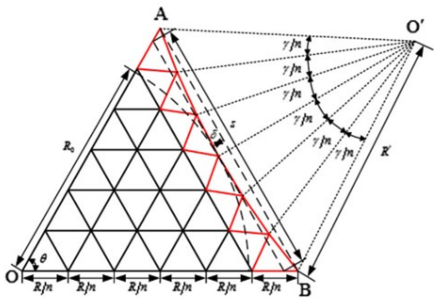

Figure 13. Case when considering the sag effect.

Therefore, an unambiguous identification of the nodes' coordinates on the plane is possible using Eq (6). The desired nodes' spatial coordinates can then be found.

As seen in Fig. 6. An external force f is applied to a thickening point I in the wire network linked to multiple wires in the space. If we use the force density formula, the equilibrium equation is as follows:

To discover the equilibrium configuration of wire network structure, taking into account specific constraints in design and mechanical and geometrical qualities, a form-finding method with enough accuracy is required. The force density approach is introduced in this case to establish and approximate the systematic equilibrium equations of the thickening points on the wire network.

$$f_{ix} = \sum_{k=1}^{c_i} q_k (x_i - x_j) \tag{7}$$

In this equation, f is the component of the external force acting on the thickening point and q is the number of wires connecting the point. The equilibrium equations can also be written in the exact directions similarly. Graph theory can use a connection matrix to describe the topological relationship between all nodes [13]. As evidenced by

$$C^{(k,p)} = \begin{cases} 1, & forp = x \\ -1, & forp = j \\ 0, & otherwise \end{cases} \tag{8}$$

Hence, in terms of the matrix form, all points are given by

$$C^T QCS = F \tag{9}$$

This linear equation should help solve and obtain each cable element's length and corresponding tension in the configuration.

4. Conclusions

In applying deployable structures technology to the development of antennas for the expanding satellite market, there are two areas of significant challenge: the actual physical dimensions of the satellite and the size and weight limitations of the launch vehicle. To address this challenge, a viable solution strategy is to provide a ruggedized antenna that is capable of accomplishing its mission within these size and weight constraints and surviving the harsh space environment. This thus justifies further exploration of the application of deployable structures technology in the antenna field.

In a word, the study of many features of deployable structure has become increasingly mature, which includes exploring the different geometric compositions of the deployable system and the dynamic analysis of its components and connection points. Researchers have also explored the structural features of deployable structures with the help of 3D modeling and drawing techniques [14].

This review introduces the basic principles of the deployable structure but also focuses on the application of the system in the field of aerospace. Before contemplating formation flying or in-orbit assembly, deployable structures must be developed since astrophysical missions are approaching the boundaries of what existing launchers can put into orbit in bulk and size.

However, structures that have made progress and breakthroughs in the current research field, such as coiled boom and telescopic hangers, have yet to successfully cope with the more demanding working environment in the aerospace field. While shape memory composites with a thin coating of reflective material for astrophysical applications have only been shown for tiny apertures (1m diameter) [15], the technology has previously been employed in principle for large deployable antennas since they do not need strict surface accuracies. As a result, a bigger size would present difficult issues.

More research results, such as sizeable deployable space antennas like the U.S. NROL-44 satellite to be launched by ULA in 2020, with a parabolic antenna diameter of more than 100 meters, are still in the theoretical or experimental stage for civil satellites [16]. There is still a certain distance from being put into civil applications. In practice, the mission designs are often restricted by challenges in operation, structure complexity, and development risk. The compensation of this distance requires the further development of aerospace engineering, and more frequent space activities will increase the demand for deployable structures, which brings more room for expansion. Only with the cooperation of multiple disciplines can deployable structures be widely used in the aerospace field and realize their value.

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