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Analysis of the Principle, Applications and Improvements of Foldable Structure for Deep-space Exploration

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Abstract:
As a matter of fact, deployable structures, a technology that has been widely used in deep-space exploration since the 1960s, are receiving more attention due to its applications in various conditions. With this in mind, this article aims to illustrate several space deployable structures available in recent years that have been adopted in the deep-space exploration. To be specific, the main content that have been applied in the deep-space exploration includes deployable antenna, deployable solar arrays and deployable surfaces. In this study, after introduction of the structures, some explanations about the operation of these unique equipment are made. According to the analysis, the current limitations for the state-of-art designs are also clarified. At the same time, the future prospects are demonstrated based on the evaluations. In conclusion, the article tries to give a brief review of the already existing technology and makes an effort to further explore the future potential of these structures.

Keywords: Deployable structures; deep-space exploration; deployable antenna.

1. Introduction

In recent years, with the development of deep space exploration technology and the continued depletion of Earth‘s natural resources, the need to explore another home for mankind in the universe has become urgent. As human beings continue to push to the boundaries of the universe, the deployable structures that could transform from a folded configuration to a deployed structure, have been a vital technology in deep-space exploration. So, this structure allows for more compact storage during launch and deployment in space, as well as the potential for greater flexibility in mission design [1]. Due to its adaptability to multiple environments, deployable structures are used in a wide range of applications. Seen from Fig. 1, the functions of deployable structures make it possible to be useful in varieties of industries such as agriculture, civil engineering and aerospace engineering. Furthermore, the deployable structures are inspired by some natural phenomenon. For example, a sunflower inspired deployable structure is mentioned, which made a analyze of the disk of sunflower and made an origami pattern similar to the natural features.

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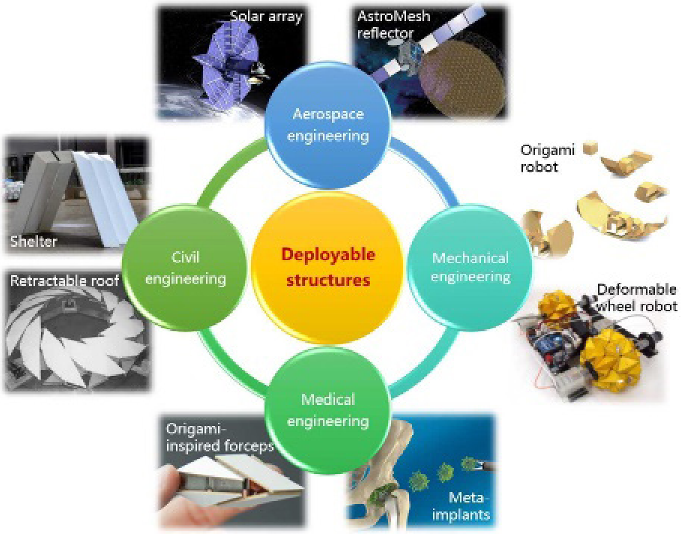

Fig. 1 The functions of deployable structures [1]

The development of expandable structures can be traced back to the early days of space exploration, with the first deployable satellite being launched in the 1960s by NASA (National Aeronautics and space administration) [2]. Since then, research and development in this area have grown significantly, with a focus on improving the materials, design, and deployment mechanisms of deployable structures. A H-style deployable structure is designed to meet the requirements of a borne mash antenna [3]. An articulated deployable structure used to build a flexible solar panel has been put into production and launched successfully by ISS (International Space Station) [4]. The future deployable structure research is also focused on materials and high temperature endured structures. A space deployable bistable composite structures with a shape of letter "C" are introduced. This structure could be able to transform from a shape of drain to a roll. In the case that no actuation force is applied, this structure made from carbon-fiber composite is stable [5]. Moreover, a circular hollow member made from shape memory polymer composite which could recover its original shape is also introduced [6], even under a relatively high temperature of 60 cent degrees (compared to the normal temperature in most part of the Earth), it remains a good ductility with only a little difference compared to its shape before.

Overall, the purpose behind this research is to make a review of existing deployable structures in deep-space exploration and further explore the potential applications of these structures in deep space exploration. Next, the whole structure of this study will firstly include a detailed analysis of the current research on deployable structures, each chapter will focus on a specific aspect of deployable structures, including materials, design considerations, deployment mechanisms, and mission applications. Then it comes to an exploration of the potential applications of these structures in deep space exploration, and finally a discussion of the key challenges and opportunities for future development.

2. Concepts for deployable structures

Before the application of the deployable structures, it is essential to get familiar with the concepts of them. It is illustrated that deployable structures are flexible structures that could fold itself and when needed, deploy to a larger size [7]. For example, while the deployable antenna is still stored in the transport rocket, it is in a folded state, and after launching into space, the entire structure is deployed by means of a power module. One of the key features in this structure is how to make it deployable. The deploy process is usually achieved by initiating a deployment mechanism or system, while this may involve mechanical devices, pneumatic devices, electric motors or other automated devices to drive the deployment of the structure. For instance, in the deployable antenna used in small satellites [8], in order to deploy the antenna, the electrical modules are supposed to transmit electricity to power the whole structure. Once the deployment mechanism is activated, the structure begins to deploy. Finally, after the structure has been fully deployed into its designed form, its stability needs to be further checked which means specific parts of the structure may need to be locked to ensure that it remains stable during use.

Another critical part involved is to determine whether this structure is deployable, and a parameter called DOF (degree of freedom) could be used in judgement. A study has extracted the cell that make up the entire structure and performed a 2D DOF calculation, the structure is shown in Fig. 2 [3]. The formula is shown below:

$$F = 3n - 2PL - Ph \quad (1)$$

where F is the degree of freedom; n is the number of movable members; PL is the number of low side constraints; Ph is the number of high constraints. So, after calculation, F = 3 x 7 – 2 x (8+2) = 1, means that this unit could deploy.

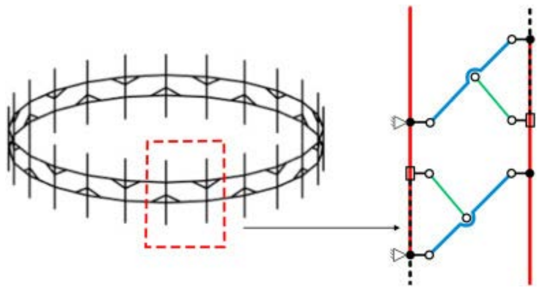

Fig. 2 A structure of DOF [3].

3. Principle and Applications in Deep Space Exploration

3.1 The Deployable Antenna

As mankind's need for the ability to transmit information in space continues to grow, so do the requirements for space antennas. While the carrying capacity of rockets is restricted, so the antenna must be both small and portable for transport and large in space. Fortunately, it is experimentally verified that the deployable antenna structure can achieve a certain percentage of stretch ratio, thus realizing its portable function, which has important applications in modern communication systems. The entire antenna structure is consisted of several single units between each other. So, the main design is on modifying or trying to make another deployable structure units which could endure the environment in space. Some scholars introduced a 2-direction based deployable module to compose the whole antenna [9]. Seen from Fig. 3, 2 kinds of bars are presented, one for the vertical direction another is horizontal direction. At the same time, 3 kinds of connectors are applied depending on the bars it connects. When folded, the whole structure appears to be like a column. Then after deployment, it becomes a structure with 3 rectangles. This satisfies the space antenna's requirements of being both small in volume when folded and large contact area with the signal when deployed. This figure shows the structure's ability of being deployable in 2D conditions, then further explanation in 3D cases should be considered since the height of the module needs to be identified.

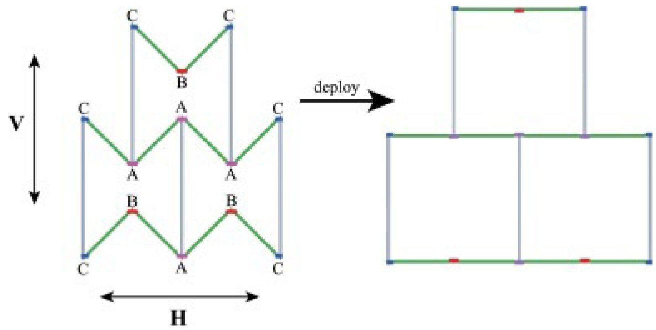

Fig. 3 A sketch of the deploying structure [9].

Then, one considers the condition to be 3D. Fig. 4 shows that in thickness-axis, another connector should be added to the bars. This connector in this axis is to provide the module with an acceptable stiffness, which means that they are responsible for supporting the structure. After constructing the module, the parameter called folding ratio could help determining whether the structure has a good ability of deployment. First, record the statistics when folded, the bar in horizontal direction is 103 mm in length. After deployed, the length appears to be 911 mm. After calculating, the folding ratio is 8.84. Then, the vertical length of the bar when folded is 697 mm, after deployed, the vertical length of the structure changes to 878 mm indicates a folding ratio of 1.26. At last, for 3D cases, the bar in thickness-direction changed from 377 mm to 93 mm, resulting a folding ratio of 4.04. These 3 numbers contribute together to the deployable function.

Finally, it is of great importance to lock the bars when fully deployed. That is because in the space environment, satellites may be subject to various external disturbances, e.g., minor collisions, cosmic dust, which may cause antenna components to move or oscillate. So, locking the deployable antenna with a locking system ensures that the antenna remains in a stable position and avoids unwanted vibration and movement, thus ensuring performance and signal stability. Seen from Fig. 5, 3 kinds of locking systems are designed [9]. The complete locking system consists of a torsion spring, a rotating connector, a member bar connector, a rack, a guide rod, a spring-loaded down-locking system, a pin roller, a stop dog and a node housing. If force is applied to the torsion spring, the rotating link starts to rotate around the pin roller from its initial folded state until the stopping dog reaches the node housing. As the rotating connecting member rotates around the pin roller, the contact between the stop dog and the gear will be locked. The detailed design shows in Fig.7 [9], type B and type C are both simplified versions of type A. Type B lack the rack connector in the middle while the type C only needs one side of the locking system so one side is removed compared to type A.

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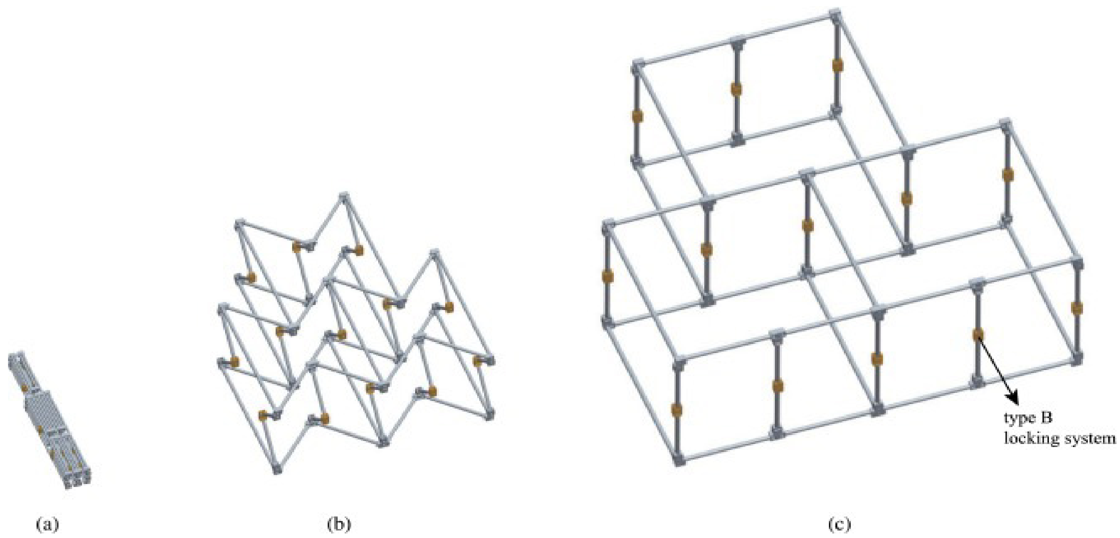

Fig. 4 The structure of 4 thickness-axis [9].

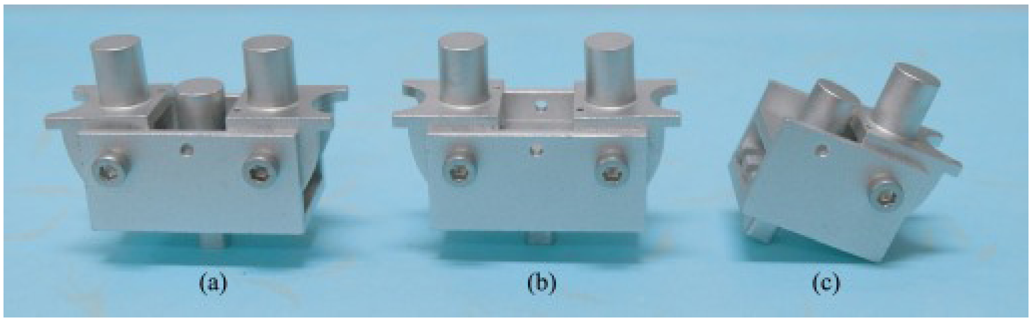

Fig. 5 3 kinds of locking systems [9].

3.2 The Deployable Solar Array

As China's national strength continues to grow, its space technology is steadily rising. One of the main advanced technologies is the solar array. As early as the 1980s, deployable solar arrays were used on the DFH-4 satellite. The solar array on DFH-4 is illustrated in Fig. 6 as a typical rigid type [10], where the deploy process of the solar panels of the DFH-4 satellite involves several key steps. First, the solar panels begin to deploy from their folded state after the satellite enters a predefined orbit, this process is achieved by HDRM (Hold-down and Release Mechanism) whose main function is to stabilize the components of the satellite. Then, HDRM holds the panels in place during launch and releases them once in orbit, allowing the panels to unfold and lock into place to ensure maximum capture of the sun's rays for power generation. Compared to the same type of rigid solar array in Europe whose solar panel's quantity is 6, DFH's designed in China only composed of 4 solar panels. However, its output power reaches to 13.5 kW with only 10.5 kW for PaceBus4000 satellite platform solar array in Europe. The main reason for this is that DFH-4 uses triple-junction gallium arsenide batteries, which allows it to achieve higher energy efficiency. However, as a rigid type of solar array, DFH-4's solar arrays also remain the fallback of high weight due to material used.

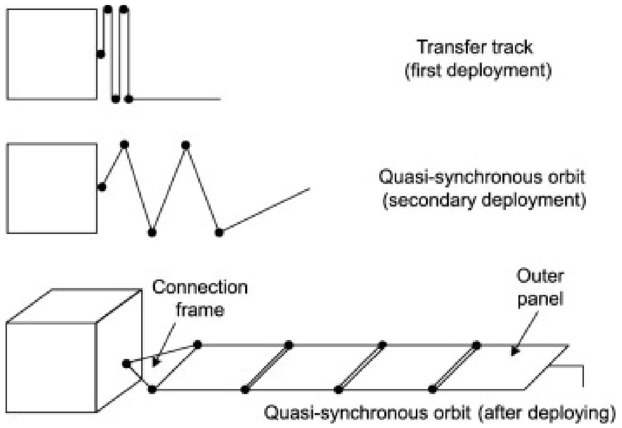

Fig. 6 A typical rigid type [10].

Since the power requirement is increasing for space satellites, some solutions should be considered. Due to the limited energy collecting area of a single solar panel and the influence of the launch volume, the only way to increase the amount of energy collected at present is to increase the number of solar panels. A 2D multiple deployable semi-rigid solar arrays is introduced. So far, this technology has been applied to DFH-5 shown in Fig. 7 [10]. The deploy process contains 2 parts. First, considering 2 sides of the satellite, to meet the energy supply requirements of the base, one solar panel is deployed on each side, called a primary deployment. Second, the rest of the solar panels in vertical direction will deploy. Third, 2 solar panels in horizontal direction will deploy in a “cross” pattern. These last 2 steps together are called quadratic two-dimensional deployment. Temporarily, this satellite is the heaviest one in China with 6 solar panels. The take-off weight of the DHF-5 can reach 8,000-9,000 kilograms, the load carrying capacity can reach 1,500-1,800 kilograms, the power of the whole star is more than 28 kilowatts, the power of the payload is provided up to 18 kilowatts, the heat dissipation capacity of the payload compartment is up to 9 kilowatts, and it has the layout capacity of more than 120 transponders and 14 antennae, and the design service life is as long as 16 years.

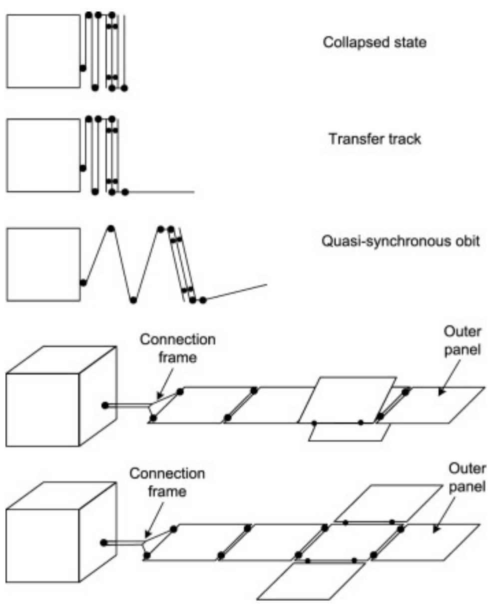

Fig. 7 A 2D multiple deployable semi-rigid solar arrays [10].

Considering the development of aeronautical engineering, the energy demand of large spacecrafts is increasing. So, 2D multiple deployable solar arrays which has an incredible energy collecting ability is being used. As far as 2021, China’s Space Station had possessed the technology of 2D multiple deployable solar arrays. Seen from Fig. 8, the structure is mounted on both sides and parallel to the sides. When launched into the space, the whole structure is firstly moved to be perpendicular to the side. Then, 2 solar panel layers moved to be prepared to deploy. Finally, 2 layers deploy, and the solar panels begin to collect solar energy. Additionally, their lightweight and durable design make them ideal for long-duration space missions. On the one hand, each single array can produce 9kW of power. On the other hand, the whole thickness of the solar panel layer is only about 16.8mm, while for every single panel the thickness is just 0.3mm in thickness. These features help the solar panel array has an ability to achieve optimal energy efficiency, at the same time, relieving pressure on rocket transport.

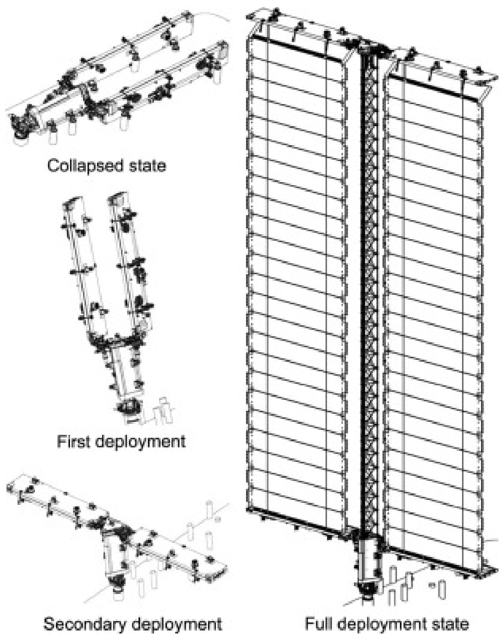

Fig. 8 2D multiple deployable solar arrays [10].

3.3 The Origami-inspired Curved Surfaces

Another novel deployable structure in space is an origami-inspired surface. While it is always wise to get familiar with the original concept, origami structure is a three-dimensional structure formed by folding a two-dimensional material such as paper, sheet metal or polymer, though the technique has its roots in the traditional Japanese art of origami, it is widely used in modern engineering and science.

First, the entire curved surface is made up of many identical small modules. Since the surface is an origami-inspired one, it uses a single plane-symmetric origami pattern to compose the thick surface. Seen from Fig. 9, the six-creases diamond origami pattern is the main idea [11]. Considering that the thickness of the paper is almost negligible, when deployed, the four pieces of paper on the side shrink inwards. Then, the geometric constraints are the same due to the symmetric features, for example the geometric angle for zero-thickness prototype is the same,

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while some other parameters such as angle between fold axes, distance between fold axes for both sides are also identical. However, since that spacecraft components need to be able to withstand high temperatures and high-pressure environments, their surfaces can't be like origami with a small thickness. So, some changes are made considering real conditions. To avoid overlapping surfaces in the middle of the structure, the space in the center needs to be hollowed out.

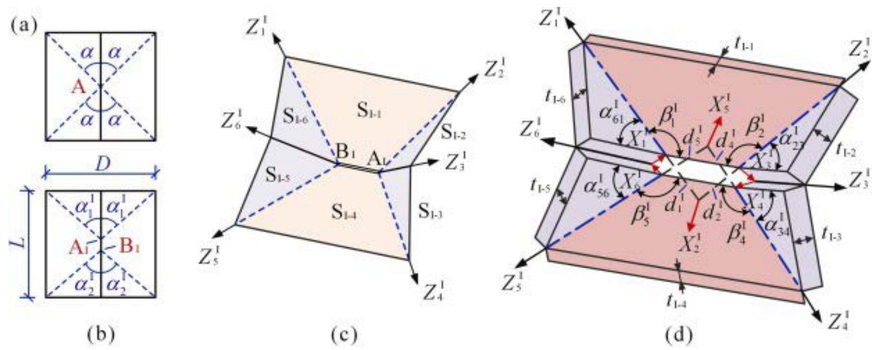

Fig. 9 Six-creases diamond origami pattern [11].

After the concept of module, a waterbomb tessellation is introduced to compose the network. As shown in Fig. 10, 9 modules are used to construct the network, while the dotted line shows the crease [11]. Another kind of module which possess a better kinematic compatibility is also applied in [10]. Similar to the design in Fig. 9 [10], the module is also symmetrical. If seen from the case AIIBII in Fig. 11 [11], it is a linkage with only one degree of freedom, the parameter for determining the deploy process is the angel between fold angles. When deploying, the 2 separated components first moving closer and closer towards each other along the crease. Then, the other components begin to fold along the dash lines. Compared to the previous module, this one ensures continuity and consistency of deformed objects, which means coherence condition ensures that objects do not crack or overlap during deformation.

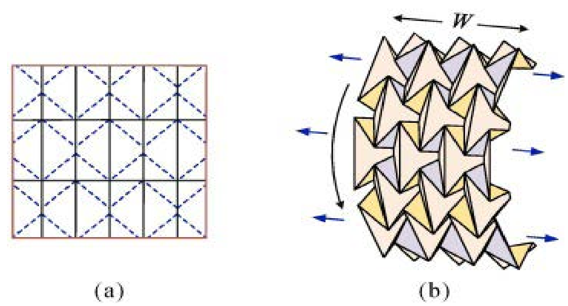

Fig. 10 The construction of the network [11].

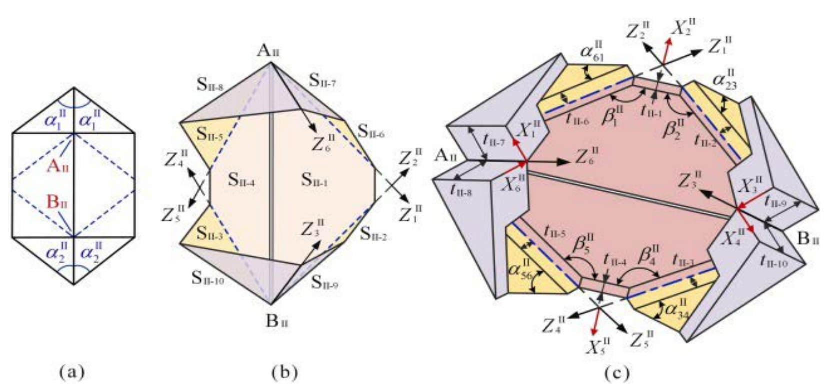

Fig. 11 The case AIIBII [11]

Subsequently, in order to incorporate the advantages of these two models, another model was devised, it contains both the features of being able to fold into a relatively small volume and kinematic compatibility. Seen from Fig. 12, the upper part of the type 2 in Fig. 11 is removed, replaced by type 1 and a combination of these 2 types of modules is presented. Normal to the designs mentioned above, with one degree of freedom, it could be able to deploy along the central line [11].

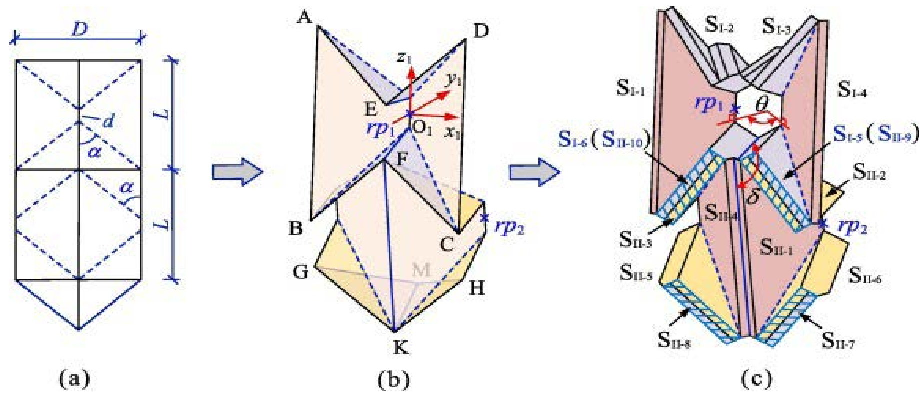

Fig. 12 Hybrid designs [11].

4. The Future Expectations and Current Limitations

Deployable structures not only show great potential in deep-space exploration, but also face many limitations and challenges. First, material limitations are a major issue. Many deployable structures rely on flexible materials, which are often deficient in terms of strength and durability. For example, as illustrated previously [12], although inorganic semiconductor materials in flexible electronics have excellent performances, their brittleness and low strain-at-break limit their use in deployable structures. Then, envelop issues also limit the practical application of deployable structures, as they need to be enveloped in order to protect the internal components, which results in a possible increase in the weight of the entire structure. Moreover, it always appears that the envelop design will reduce the deployable ability of these structures. Next, during launch and in the extremely harsh vacuum environment of space, unfavorable factors (e.g., high pressure) led to the need for excellent material resistance, fatigue and damage may occur in ductile structures during repeated deformation, affecting their long-term reliability and lifetime. Finally, thermal management and heat dissipation issues are particularly essential in the deep space environment since temperatures in deep-space environments vary dramatically, and malleable structures require effective thermal management systems to maintain their performance and stability. So, conventional heat dissipation methods may not be suitable for deep space environments, and new thermal management techniques need to be developed.

However, as a high-technology integrated structure, there are still some amazing future expectations about deployable structures. It is recommended that a modular design should be focused [4]. The feature of modular design is illustrated. Each module can be designed and manufactured independently of the others. Modules are connected to each other through standardized interfaces, ensuring compatibility and interchangeability. The modular design allows parts or all the system to be customized, upgraded or maintained without extensive changes to the entire system. Though still unmature, the design explains these features well. The final surface constructed involves 2 types of modules, if type 1 just failed, type 2 could still function well, which reduce the overall danger and increase safety in operation, and the repairment could be conducted just according to certain area of failure [12]. Another point should be put attention on is the material applied. A kind of shape memory polymer is proposed. Depend on its concept, shape memory polymers are smart materials capable of recovering from a deformed state (temporary shape) to an original state (permanent shape) in response to external stimuli such as temperature, electricity, light. In the work, the experimenters test this material when curved and stretched [13]. When this material is stretched uniformly, the recovery stress of 1.26 MPa under a temperature of 180 cent degrees, while at constant stress of 0.5 MPa and 1 MPa, the item presents its ability to recover. With the increasing temperature, the yield strength and elastic modulus will decrease, and why 180 cent degrees becomes a critical point is that when temperature reaches to this statistic, the material begins to undergo thermal degradation. At present, this material hasn't been applied to aeronautical devices, and further research are made towards this direction.

5. Conclusion

In conclusion, the deep-space deployable structures as an advanced technology are widely applied in today's space projects due to its ability of being functional during different situations. This essay explains firstly the concept of deployable structures, then discussed 3 frequently applied structures following the sequences of deployable antenna, deployable solar array, then deployable surface. For the

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antenna, a H-style one is presented, further calculations such as degree of freedom are also included. For the solar array, the author mainly focuses on DFH series of satellite and described the process. For the surface, the main idea depends on design of different types of modules which compose the whole structure. At last, considering the current limitations of deployable structures, some future expectations, modular design and novel materials are proposed. The research significance relies on a review of deployable structures, and tries to make some future outlook, which make human beings aware of this technology.

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