A Review of Bionic Design in Satellite Solar Wing Structures

Junwei He¹, a, Yasheng Zhang², b, Zeyin Shangguan³, c and Lu Yang⁴, *

¹Department of Graduate Management, Space Engineering University, Beijing, China
²Department of Space Command, Space Engineering University, Beijing, China
³EMC Test Station, Shunyi District, Beijing, China
⁴Department of Space Science and Technology, Space Engineering University, Beijing, China

*Corresponding author e-mail: yanglu_mailbox@aliyun.com, a1170396271@qq.com, b2628846201@qq.com, c191984065@qq.com

Abstract. This article summarizes the development process and trend of satellite solar wings from the perspective of structural design. At the same time, it summarizes the research on the deployment mechanism based on the principle of bionics. The results show that the expansion mechanism exhibited by natural organisms has natural advantages in terms of folding optimization and smoothness of the unfolding process. It has important reference significance for the structural design of space folding mechanism such as satellite solar wings.

1. Introduction

The satellite solar wing, as the core power supply equipment of the satellite, is a typical space deployable structure. With the development of aerospace, the structure of the satellite solar wing has also changed greatly.

In the late 1950s, solar cells were mostly body-mounted, that is, the cells were directly arranged on the surface of the satellite. The spherical body-mounted was mainly used in early smaller satellites, such as the US Pioneer I satellite, as shown in Fig. 1(a) and China's Dongfanghong-I satellite, as shown in Fig. 1(b), the cylindrical body-mounted is mainly used for large barrel satellites, as shown in Fig. 1(c). Limited by the surface area of the satellites, the utilization rate of body-mounted solar cells is low. For example, the utilization rate of spherical-type solar cells is only about 10%, and the maximum output power is less than 1 W [1].

Figure 1. Body-mounted satellite.

With the increase of satellite energy demand, a paddle-structured solar wing with a larger lighting area has emerged, which can be folded during launch and unfolded into a working state after the satellite enters orbit, as shown in Fig. 2(a). In the 1970s, the development of sun-oriented technology
resulted in a single-plate solar wing with higher lighting efficiency, as shown in Fig. 2(b). Until the 1980s, on the basis of the single-plate deployment structure, the most widely used multi-plate deployment solar wing appeared, as shown in Fig. 2(c), such as the GPS satellites and communication satellites in Germany and France. And almost all of the satellites in China are multi-plate, with a deployment size of up to 70 meters and can provide up to about 15kW of power. It can be seen that the enlargement of the solar wing is an inevitable result of the growing demand for satellite energy, but the limitation of the space carrying capacity has also increased the difficulty in designing the solar wing structure.

![Figure 2](image.png)

**Figure 2.** (a) Paddle-structured satellite, (b) Single-plate satellite, (c) Multi-plate satellite.

In the 1960s, bionics was officially born as a new independent discipline. The emergence of bionics provided a new way for the study of traditional space deployment structures. The folding mechanism contained in natural organisms shows natural advantages, providing new ideas for the structural design of satellite solar wings, and has attracted the attention of many scholars. This article focuses on the current research results on biological deployment mechanisms and the application of solar wing structure design.

### 2. Research on Bionic Deployment mechanisms

Since the 1950s, people have realized the importance of biological systems for structural design, and have begun to study biological systems. From the perspective of biological prototypes, they are mainly divided into four aspects: wings spread, leaf growth, insect emergence, and flower blooming. In terms of research methods, most of them use origami to equivalent biological deployment mechanism, and carry out geometric constraint analysis based on origami models, or use high-speed cameras for detailed observation.

J. H. Brackenbury from the University of Cambridge simulated the unfolding and folding modes of various Coleoptera insects in the form of origami, as shown in Fig. 3(b). The result shows the deployment mechanism can reduce the wingspan length by 40%, and the angle of inward rotation of the wing tip is determined by the angle between the concave and convex creases [2].

![Figure 3](image.png)

**Figure 3.** The folding mechanism of cantharis.

Fabian Haas from Karlsruhe Institute of Technology divides the folding mechanism of insect wings into two types, and each type can be equivalent to a panel rotating around four polylines that intersect at one point, which is in fact a leverage system with one degree of freedom. As shown in Fig. 4(a) and 4(b), the first type of folding mechanism is shown, and Fig. 4(c) and 4(d) are the second type of folding mechanism, where $\alpha$, $\beta$, $\delta$, and $\gamma$ are the top corners of the four plates, the concave and convex...
fold lines A, B, C, and D can be equivalent to hinges, ε is a deployment angle, and the relative positional relationship of each plate at any time is determined by α, β, δ, γ and the deployment angle [3].

![Figure 4. Geometric models of four folding methods.](image)

Fabian Haas aimed at the mechanical problems of the hind wings of Coleoptera insects. Through the high-speed camera, the unfolding process of the hind wings was recorded and analyzed in detail. The research found that the unfolded area of the hind wings was at most 4 times that of the folded state [4].

Biruta Kresling, through the study of four natural deployment structures, points out that the deployment mechanism exhibited by biological structures can help to solve the deformation problem caused by the mass of the unfolded structure, and can effectively avoid the risk of seizure caused by obvious friction in the hinge [5].

H. Kobayashi of Osaka University took maple leaves as an example to carry out a detailed study of the process of folding and unfolding. The position changes of leaf elements, the position of creases, and the area changes after unfolding were calculated during the process. As shown in Fig. 5, the study pointed out that the folding mechanism of leaves can provide us with new ideas for designing foldable structures, such as solar wings and antennas of satellite. H. Kobayashi carried out a detailed geometric analysis of the beech leaf unfolding process, as shown in Fig. 6, the results show that the single-leaf folded structure can be unfolded simultaneously in two directions perpendicular to each other, and has a higher storage rate perpendicular to the direction of the veins and a lower storage rate along the vein direction [6].

![Figure 5. Geometric Analysis of Maple Leaf Folding Mechanism.](image)

![Figure 6. Folding and unfolding process of beech leaves.](image)
In the book *Deployable Structures in Nature*, Julian F. V. Vincent of the University of Bath pointed out that biology is the natural history of deployed structures. With the evolution of biological organisms in nature, they have shown the existence of deployment states, such as insect emergence, as shown in Fig. 7, the blooming of flowers, as shown in Fig. 8, and the growth of leaves, etc., all show the superiority of the deployment structures, such as the stability of the deployment process, the efficiency of structural layout, and the adaptability to the environment [7].

![Figure 7. The emergence process of dragonflies.](image1)

![Figure 8. The flowering process of morning glory.](image2)

Potato flowers usually consist of five or six petals. Hidetoki Kobayashi uses vector analysis method to analyze the folding and unfolding forms of potato flowers, as shown in Fig. 9. The results show that when the petal number is 5 or 6, the energy required for unfolding is far less than that of other petal models. It can be seen that natural selection makes potato flowers use the best petal number to reduce the energy consumption in the unfolding process [8].

![Figure 9. Folded and unfolded model of potato flower.](image3)

Kazuya Saito [9] of Tokyo University made a detailed analysis on the folding and unfolding process of ladybug’s back wing, as shown in Fig. 10. Based on the research of Fabian Haas, he pointed out that ladybug’s back wing has a stable unfolding mechanism, which has great potential for the design of deployable structure. He also gave the factors to be considered in application from three aspects: shape, structure and material.

1. Membrane wings can absorb the strain during the folding process, and it is difficult to show this deformation through the creases on the paper.
2. Lack of quantitative research on the mechanical properties of hindwing veins, which is very important for the analysis of hindwing structure stability.
3. The special protein of the hind wing gives the elasticity required for vein deployment, which is the inherent elasticity of the material, which will facilitate the self-deployment of the space deployable structure without additional mechanical drive. It is very important to reduce the structural mass and improve the reliability.
Kazuya Saito observed the folding process of the hind wing through artificial transparent coleoptera transplantation, and then established a 3D model of the hind wing by tomography technology. The study found that a hinge mechanism similar to the band spring played a very important role in the folding process of the hind wing, as shown in Fig. 11. Besides the structural reinforcement property, first, the veins can be bent at an arbitrary position by forming localized folds during wing storage, and therefore can serve as compliant hinges where appropriate. The second function of the tape spring vein is to store elastic energy for wing deployment [10].

Based on the above research, Kazuya Saito pointed out that the design of deployable structures must also meet the conditions of rigid folding, because rigid engineering materials cannot absorb strain like wings during the folding process, and rigid folding can be achieved through calculation [11], as shown in Fig. 12.

3. Design of bionic satellite solar wings

Sihang Bai [12] of Northeastern University designed an inflatable bionic space deployable structure based on butterfly emergence experiments and analyzed the structure for stress, modal, response spectrum, vibration and harmonic response by finite element analysis software. The results show that the structure has good mechanical property and can provide a reference for the design of satellite solar wing structure. Fig. 13(a) is the structural stress analysis and Fig. 13(b) is the prototype model.
Figure 13. Stress Analysis and Prototype of Bionic Developable Structure.

Xinge Li [13] designed a new bionic deployable solar wing, who was inspired by the unfolding process of earwig's wings, as shown in Fig. 14(a). The BC cardboard was chosen as the main material of the solar wing's plate, as shown in Fig. 14(b). Three key parameters, driving torque, locking stiffness and lock vibration were tested during the deployment process of the prototype, the result is as follows:

1. The minimum driving torque is 0.44Nm.
2. The locking stiffness of the hinge is about 1203Nm/rad.
3. When the hinge was about to be fully unfold, there was no significant acceleration and only a slight vibration after it was fully unfold.

Figure 14. The earwig's wings and the prototype.

On the basis of the above research, Yaopeng Ma [14] redesigned the solar wing prototype with the aluminum honeycomb plate, which is closer to the engineering application, as shown in Fig. 15, and carried out the dynamic simulation analysis of the solar wing deployment process by ADAMS, the results show that the installation position of the hinge driving device has an effect on the stability of the deployment process.

Figure 15. Simulation of deployment process by suspending prototype.

Rugui Wang [15] designed a deployable structure that can be used for solar wings and large diameter antennas based on the petal expansion mechanism, as shown in Fig. 16. By analyzing the geometric relationship and folding conditions of the unit, the feasibility analysis of the device is performed from each sub-function, and 5 feasible schemes and 36 configurations are given.

Figure 16. Schematic diagram of space deployable structure.
4. Conclusion

Due to the increasing energy demand of satellites, the satellite solar wing structure is constantly changing, and large-scale is an inevitable trend for the development of satellite solar wing. The limitation of space carrying capacity makes the limitations of traditional structure solar wing increasingly prominent. Research on the bionic mechanism and the maturity of new flexible battery technology have provided new ideas for the design of satellite solar wings's structure. However, there are still some issues worth discussing, such as the differences in material properties between engineering materials and biological tissues, and the adaptability of bionic space deployable structures to the space environment.

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