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A Review of Origami-Based Deployable Structures in Aerospace Engineering

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A Review of Origami-Based Deployable Structures in Aerospace Engineering

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Abstract: Origami is a traditional art form of paper folding that originated in east Asia. In recent decades, the concept of origami has been extensively used to design deployable structures. Due to the strict space and load capacity limitations of the aircraft and spacecraft, the equipment they carried must be deployable and light in weight. The origami-based deployable structures provide the possibility for carrying more aerospace equipment. This paper is an overview of current research on origami-based deployable structures and applications in aerospace engineering, which mainly demonstrates the geometric properties, engineering implementations, advantages, and applications of origami-based deployable structures in aerospace engineering. Some of the latest origami-based space instruments are reviewed to have an insight into their basics and applications.

1. Introduction

1.1 The Requirements for Aerospace Machinery

Constrained by the development of rocket and aero engines, spacecraft and aircraft are strictly limited in volume and load capacity. Nowadays, spacecraft need to carry loads of scientific research instruments and many scientists. Under this circumstance, modern aerospace machinery should satisfy the following requirements:

- Smallest possible storage volume
- Good strength and stiffness
- As light as possible
- High reliability
- Good performance and operability
- Short production cycle and low cost
- Non-susceptible to buckling and vibration

To meet the above demands, many researchers have put forward their own views in the field of advanced composites, motion structures, and manufacturing processing to deal with these problems.

Three main composite materials including carbon fiber, fiber-matrix interface, and resin materials, are of widespread use in aerospace structures (tails, wings, and fuselages) and wind turbine blades [1]. These improved materials could be used to substitute conventional materials (aluminum and titanium alloys) to build primary structures because of their advantages in lightweight and stiffness.

The motion structures, especially the foldable structures mainly help us reduce the size of large machines and enhance reliability. To provide enough power for spacecraft, the size of the solar panel should be large enough. Considering the space inside CubeSats is limited, the solar panel must be foldable so that it can be carried. Recently, researchers have designed and realized a modular solar panel system for CubeSats [2]. This modular system impulses the miniaturization of CubeSats and improves the standardization of components for multiple astronautic missions.

Apart from advanced materials and motion structures, manufacturing processing is crucial to realizing foldability and a high strength-to-mass ratio of materials. Because of the complexity of aerospace structures, researchers and engineers tend to use additive manufacturing to produce aeronautic and astronautic components. It has been suggested that one of addictive manufacturing's advantages is to manufacture lightweight parts [3]. In this case, it is extremely possible to achieve deployable structures with a high strength-to-mass ratio.

1.2 The Applications of Deployable Structures in Aerospace Engineering

The deployable structure is defined as a configuration that can be folded and unfolded multiple times into a target shape. The main advantages of deployable structure in aerospace engineering lie in its following properties which include:

- The miniaturization of large configurations
- The improvements in accuracy
- The reduction of drive machinery
- Standardized components

Due to the advantage of miniaturization of large configurations, many scientific instruments can be carried with small artificial satellites. Also, most of the deployable structures have a lower degree of freedom (DOF). This means that fewer servo motors are needed to drive these structures. In addition, quite a few deployable structures have a DOF of 1, which indicates that only one motor is needed. In this way, the movements of all individual parts are highly synchronized, which makes the whole configuration more precise. Finally, standardized components also reduce design and production costs. Here, we discuss some types of deployable structures in aerospace engineering.

Large Deployable Antennas (LDA). The development of the aerospace industry contributes to higher requirements for space antennas. It has been indicated that modern antennas should have a large aperture, high accuracy, lightweight, and high rigidity [4]. Considering these antennas are huge, and are up to tens of meters in diameter, they cannot be manufactured and transported as a whole. Therefore, they should be deployable so that current transport vehicles can carry them with limited space.

Some scientists mentioned three new concepts in LDA: segmented-panel LDA reflectors, furlable reflector strips, and membrane reflectors [5]. They conceptualized and evaluated several LDA design approaches and stated that it is possible to build an antenna with a designated size and accuracy.

Self-deployable Structures in Structural Sheet and Solar Sail. It has been found that a kind of shape-memory material can change its shape upon external stimulus [6]. One of the shape-memory materials can change its shape according to temperature fluctuations, named thermally induced shape-memory material. It has been indicated that current methods of deploying large structures (including solar arrays, solar sails, sun shields, and radar antennas) are independent of extra electromechanical mechanisms and mechanically expandable booms [7]. However, based on thermally induced shape-memory materials, the self-deployable structures can change in shape under the cold environment in space instead of external driving mechanisms.

Biomimicry Deployable Structures. There exist a lot of deployable structures in nature. Species gradually form their own biological structures to adapt to the evolution of the environment. It has been mentioned a foldable structure from the unfolding of flower petals [8]. This type of deployable structure involving many basic mechanisms is named as Miura-ori folding pattern. Later Miura-ori was also used for designing a solar steam generator. Based on the Miura-ori folding pattern, some researchers designed a three-dimensional solar system generator that achieved nearly full utilization of solar energy [9].

1.3 Origami-based Deployable Structures

Origami means “paper folding” in Japanese. It is an ancient art form originating from east Asia. In recent decades, researchers and engineers are inspired by this traditional art form and conceptualized some motion structures which can be used in aerospace engineering.

The reason why origami can be used in motion structures is that the creases that the folding process creates can be regarded as revolute joints which can be implemented easily through hinges, studs, and bolts in mechanical design. Also, since origami can transform large planar structures into small stereoscopic ones, origami-based deployable structures gain their popularity in folding plate structures such as panels and sails more than other types of deployable structures. Furthermore, there exist many shapes in origami (flowers, leaves, cranes, stars, etc.), which enables us to employ multiple configurations in engineering.

Three researchers from Brigham Young University indicated that engineers and scientists focused their interests on the following properties of origami which contain:

- Stowability
- Portability
- Deployability
- Fewer components
- Manufacturability
- Lower volume and mass
- Ease of miniaturization and assembly [10]

Through these properties, we discover that they are exceedingly significant to aircraft and spacecraft machinery designs. Currently, an increasing number of origami folding patterns are applied to designing different varieties of deployable structures. These structures have different kinematic properties which suit different equipment designs. The summary of origami folding patterns, and their applications are of great importance for researchers to learn about different configurations and their characteristics. Therefore, in this review paper, we summarize the mathematical principle and design methods among origami-based deployable mechanisms and explore their existing or potential applications in aerospace engineering.

2. Engineering Implementation of Rigid Origami

Rigid origami is defined as a branch of origami without deformation. This type of origami has no deformation during the folding process, which is similar to some motion structures in mechanical engineering. Therefore, rigid origami can be implemented with mechanical linkages. Viewed from large planar structures, the folding patterns of rigid origami can be categorized into two types: mountain creases and valley creases. They are demonstrated in Figure 1.

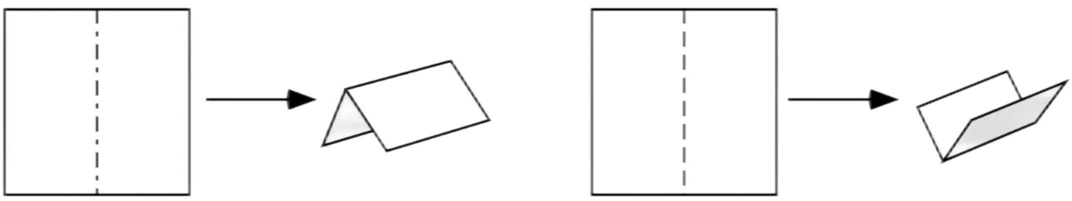

Figure 1. Mountain crease (left) and valley crease (right), figure reprinted from [11]

The mountain crease forms convex after folding while the valley crease forms a concave. The conditions of flat foldability for the crease pattern with a single vertex can be demonstrated as follows:

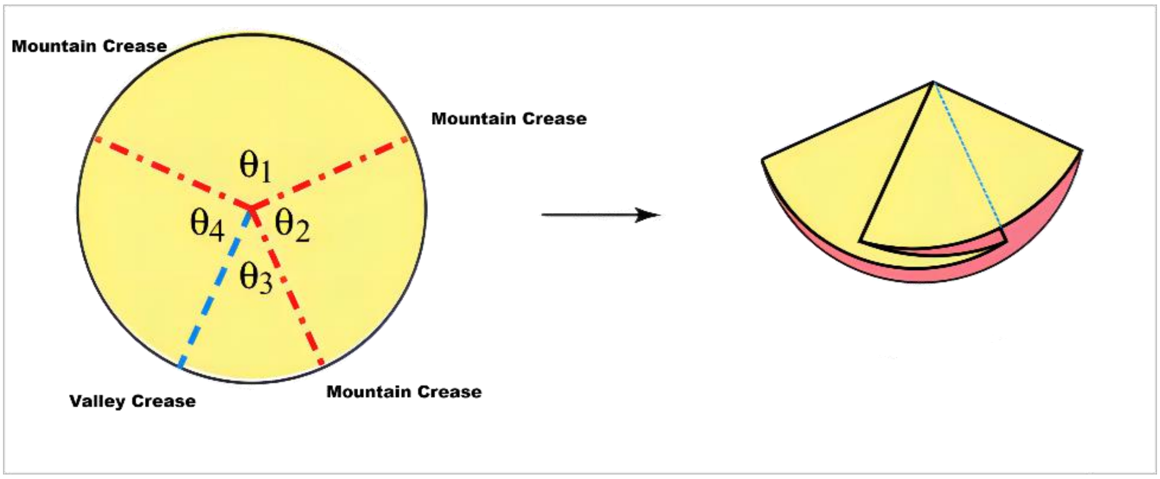

Figure 2. Single Vertex Crease Pattern, figure reprinted from [12].

For a flat sheet of paper with zero thickness in Figure 2, a single vertex crease pattern defined by angles $\theta_1 + \theta_2 + \cdots + \theta_n = 360\,°$ are flat foldable if and only if:

- The total number of creases is always an even number.
- 2 is the minimum number of creases.
- The number of mountains and the number of valleys differs by ± 2.
- The relationship of angles should meet the requirements of Kawasaki's theorem:

$\theta_1 + \theta_3 + \cdots + \theta_{n-1} = \theta_2 + \theta_4 + \cdots + \theta_n = 180\,°$ [12]

Since each rigid part of origami can rotate around the creases, the creases can be regarded as revolute joints in mechanical design. Similarly, the whole crease pattern with a single vertex can be treated as a spherical linkage. That is because the intersections of creases and the edge have the same distance from the vertex when the paper is folded into a 3-D structure. Normally, as we can see in Figure 3, common components such as bearings, hinges, pins, etc. are widely used to realize revolute joints in mechanical design.

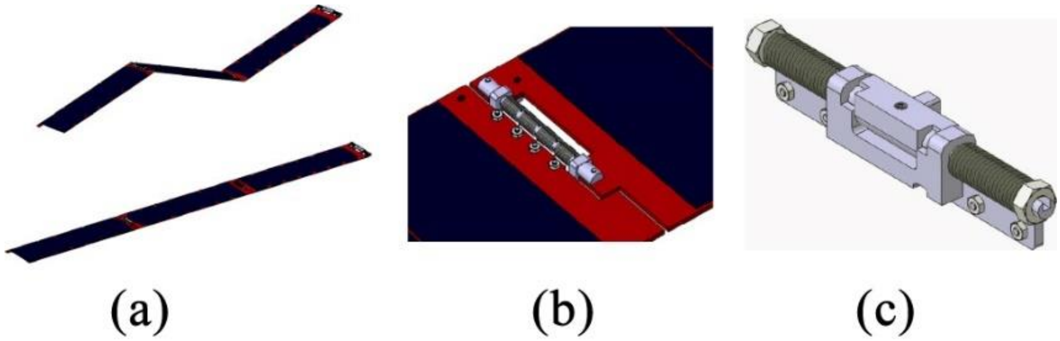

Figure 3. Revolute Joint in Deployable Solar Panel, figure reprinted from [2]. (a). Solar panel assembly; (b). Main hinge assembly; (c). Main hinge assembly

The above flat foldable crease pattern is only applicable for zero-thickness sheets. Yet, for most practical mechanical engineering applications, planar structures cannot simply be treated as zero-thickness sheets. Recently, Yan Chen and co-workers presented a solution to achieve origami with thick panels [13]. For single vertex folding patterns, they created kinematic equivalent models by applying spatial 4R, 5R, and 6R linkages to 4-crease, 5-crease, and 6-crease patterns (shown in Figure 4). Through this approach, origami-based deployable structures can still be designed based on zero-thickness prototypes. With corresponding spatial linkages, the zero-thickness folding patterns can be synchronized to thick panel origami-based deployable structures.

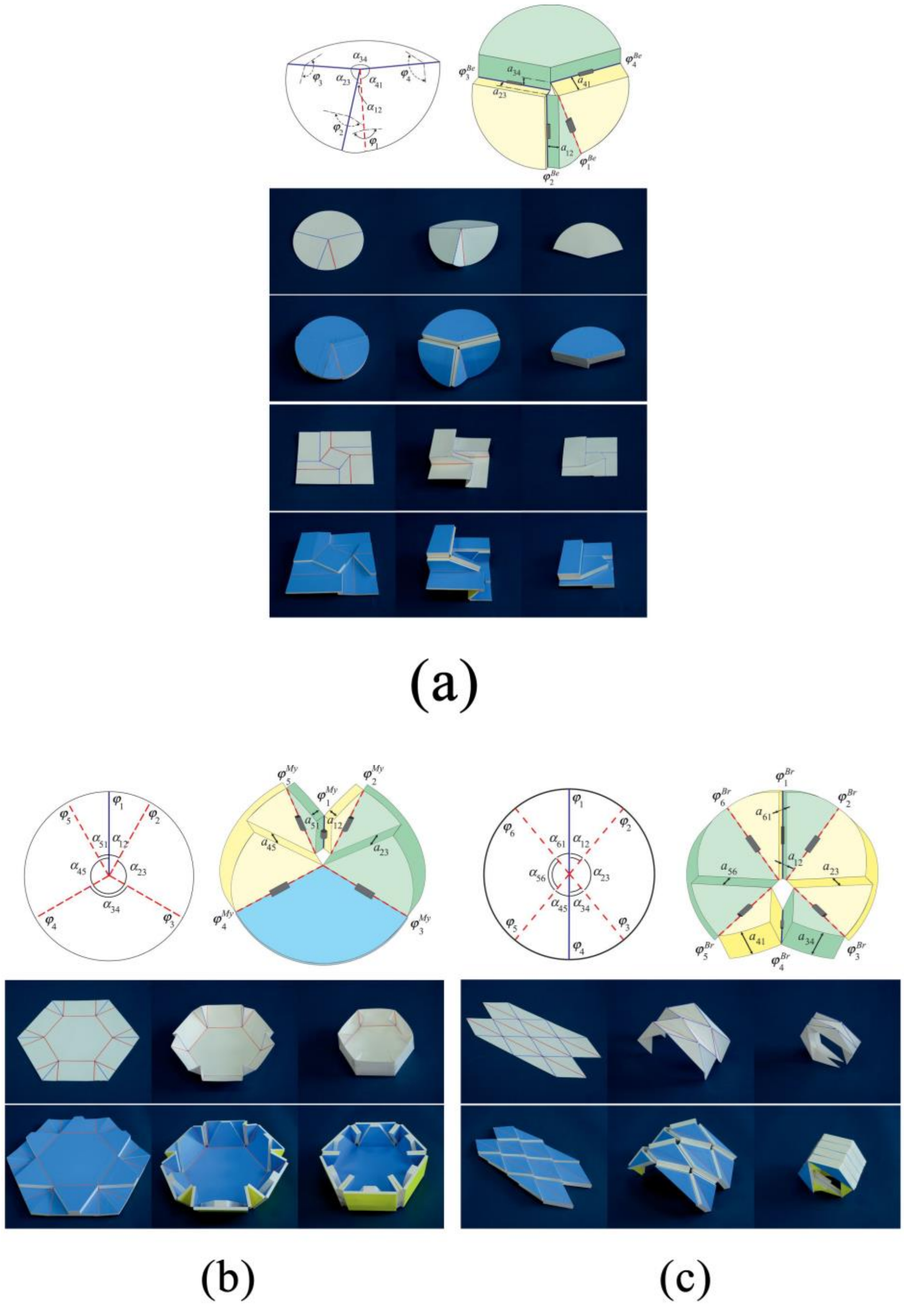

Figure 4. 4-crease, 5-crease, 6-crease Folding Pattern, and Corresponding Spatial Linkage, figure reprinted from [14]. (a). 4-crease thick panel; (b). 5-crease thick panel; (c). 6-crease thick panel

3. Main Folding Patterns and Applications in Aerospace Engineering

3.1 Miura-ori Folding Pattern and Solar Sail

The Miura-ori folding pattern (shown in Figure 5) has been in widespread use in many fields of mechanical engineering, especially in aerospace engineering. In the early 1980s, this very fundamental and revolutionary folding pattern for deploying large planar structures was proposed [15]. It was first successfully applied to the design of the solar sail [16].

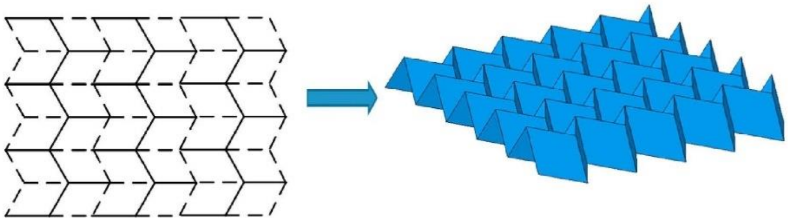

Figure 5. Miura-ori Folding Pattern, figure reprinted from [17]

The solar sail is required to be large, thin, and have a highly reflective area that can be folded into a small volume for launch [18]. The development of Miura-ori provides new approaches to the design of the solar sail.

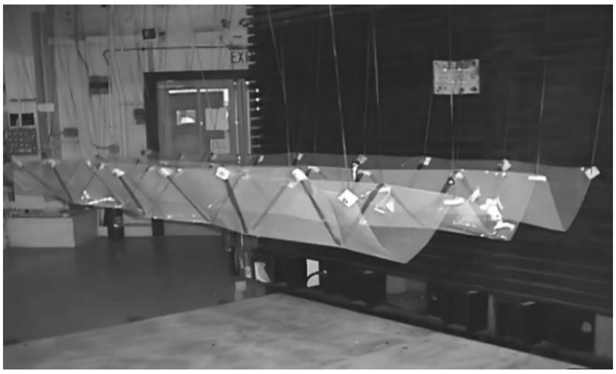

Figure 6. Miura-ori Inspired Solar Sail, figure reprinted from [18]

It has been stated that the strip should be folded the way of the Miura-ori pattern at an angle between 75 to 85 degrees [18]. The large area membrane (shown in Figure 6) fabricated this way can expand as struts inflate. Then this membrane can carry along the whole sail until fully deployed. Compared to the normal deployable structures, this membrane has a unique ability. Since it has a DOF of 1, it is exceedingly convenient to deploy it by applying forces along the diagonals. Also, the whole deployment process is synchronized [18].

3.2 Origami-based Solar Panel

"Flasher" (shown in Figure 7) is another folding pattern of origami. It is a rotational symmetric folding pattern that enables a large planar area to be folded into a small three-dimensional structure. It has been stated that researchers started to use this pattern to design solar panels in the 1960s [19].

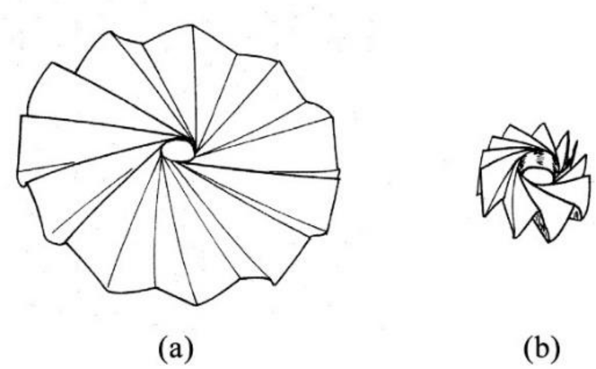

Figure 7. Flasher Folding Pattern, figure reprinted from [19]. (a). Flasher before deployment; (b). Flasher after deployment3.3 3.

In the early 1990s, Guest and co-workers first presented a complete prototype (shown in Figure 8) for the design of solar panels based on the "flasher" and zero thickness assumption [19]. To accommodate the problem of thickness, another approach was developed, and it achieved a ratio of the deployed-to-stowed diameter of 9 [20]. With shape-memory polymers, Chen et al. design a solar panel that is self-deployable and achieves a high expansion ratio based on the flasher [21].

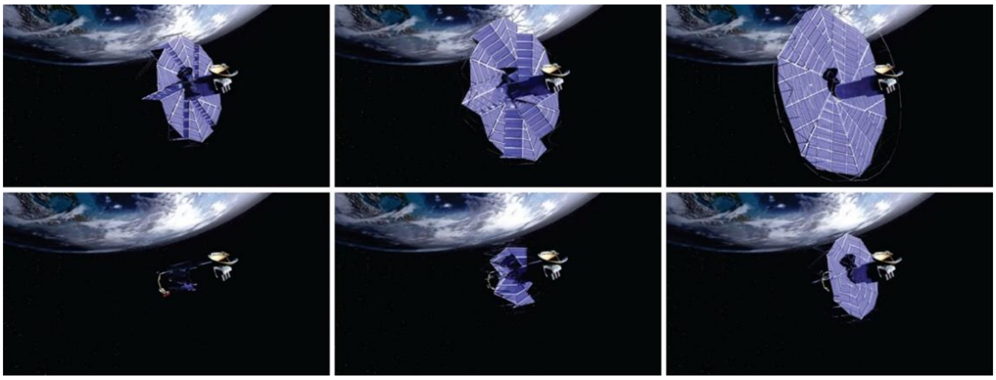

Figure 8. A Computer-generated Model of Flasher Solar Panel, figure reprinted from [20]

3.3 Helix Folding Pattern and Large Antenna

The helix folding pattern (shown in Figure 9) is another form of origami that has wide applications in large space instruments. In 2006, it was first proposed in the field of DNA origami design [22]. Then, it was applied to designing large antennas. This folding pattern allows the long cylindrical structure to be miniaturized into the substrate.

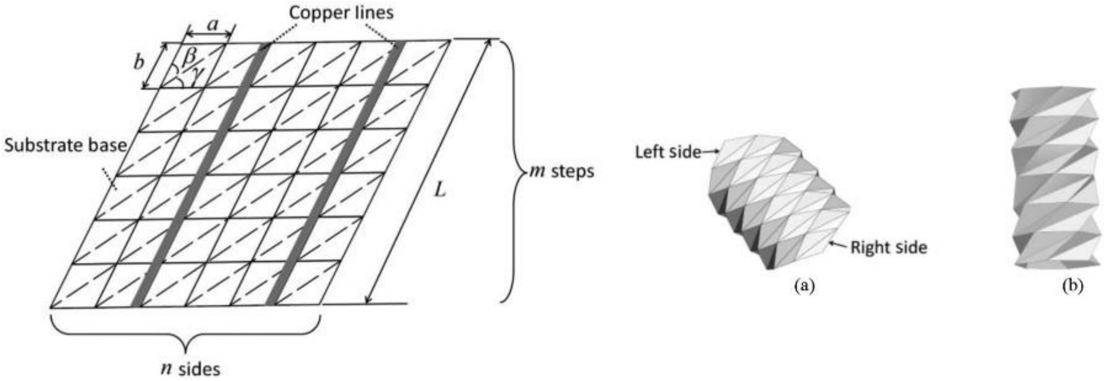

Figure 9. Helix Folding Pattern, figure reprinted from [23]. (a). Helix folding pattern; (b). Helix the origami cylinder by connecting the left side to the right side.

Because of the axial miniaturization property, researchers started to optimize this pattern and apply it to the space industry [24]. A new reconfigurable origami bifilar helical antenna (shown in Figure 10) has been designed to adjust working frequencies by changing the height (Liu et al. 2015). One of the potential applications is that this antenna can sense multi-signals in different bands.

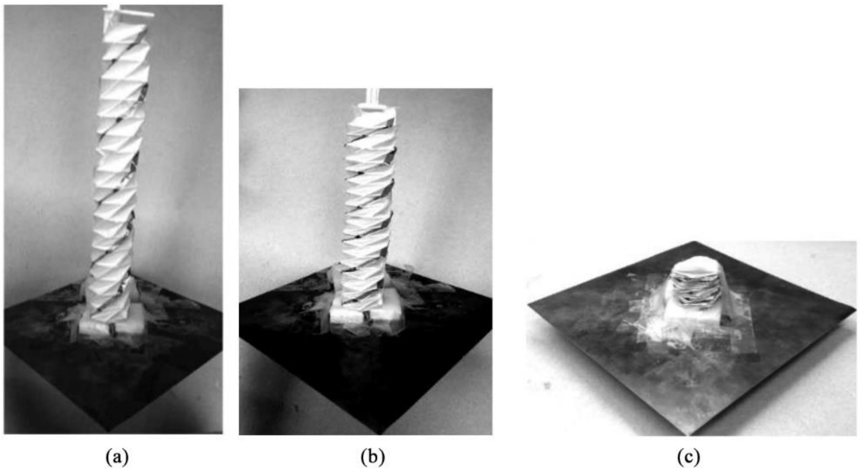

Figure 10. Prototype of Reconfigurable Origami Bifilar Helical Antenna, figure reprinted from [23]. (a). Before deployment; (b). During deployment; (c). After deployment

3.4 Waterbomb Folding Pattern and Robotic Gripper

As a traditional origami, waterbomb folding pattern (shown in Figure 11) has already been applied to designing small-size robots for years [25,26]. It consists of two parts: the waterbomb base and the waterbomb tessellation [13].

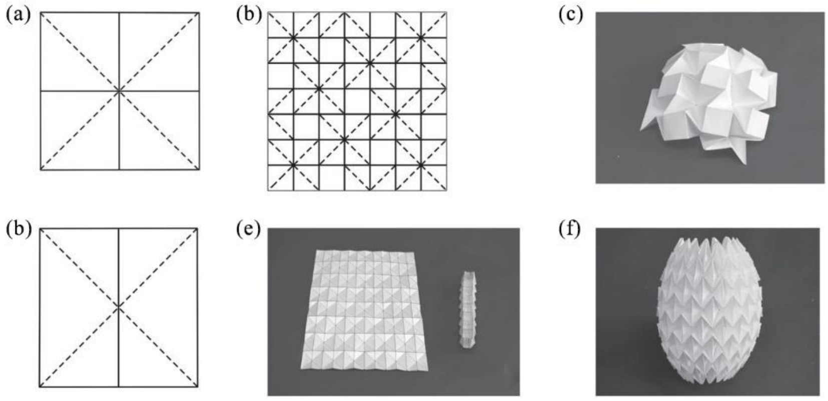

Figure 11. Waterbomb Base and Corresponding Tessellations [13]. (a). Eight-crease base; (b). Eight-crease tessellation; (c). Eight-crease partially folded model; (d). Six-crease base; (e). Six-crease tessellation; (f). Six-crease partially folded model

Generally, it can be categorized into two types: eight-crease base and six-crease base. Different bases and tessellation patterns will form different three-dimensional structures, which are all called the “magic origami ball”. Compared to traditional rigid grippers, soft-body grippers can provide a safer and more flexible way of interaction [25]. It has been reported that the waterbomb-based soft-body grippers (shown in Figure 12) have sufficient robustness and the ability to carry heavy items up to 140 times their weight of themselves [25]. Additionally, it has been shown that this type of gripper can be more reliable when grabbing objects. A 3-D print origami gripper with a DOF of 1 has been presented recently [26]. The four fingers of this origami-based gripper are highly synchronized with the single-driving motor. Furthermore, the use of 3-D printing can also reduce manufacturing complexity and improve precision, which makes the gripper more reliable and has more predictable kinematic properties.

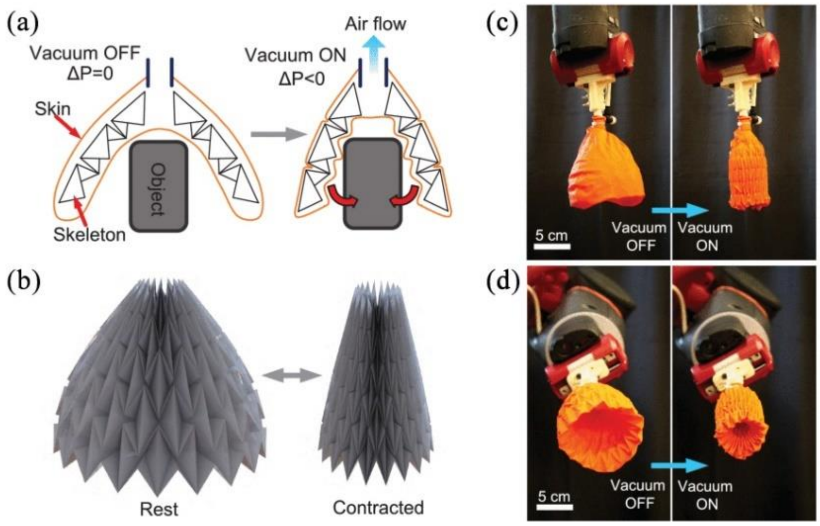

Figure 12. Vacuum-driven Waterbomb Gripper, figure reprinted from [25]. (a). Working principle of the gripper; (b). Waterbomb skeleton; (c)-(d). Views from different perspectives

3.5 Other Folding Patterns and Applications

In addition to Miura-ori, flasher, helix, and waterbomb folding patterns, other patterns such as the square-twist, and Yoshimura (diamond) (shown in Figures 13 and 14) also have extensive applications in aerospace engineering. Square-twist is a rotational symmetric folding pattern that has nine faces and twelve creases.

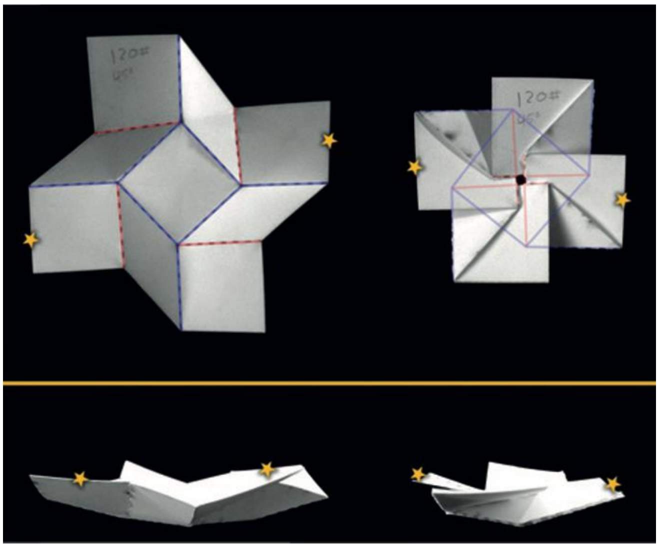

Figure 13. Square-twist Folding Pattern, figure reprinted from [27]

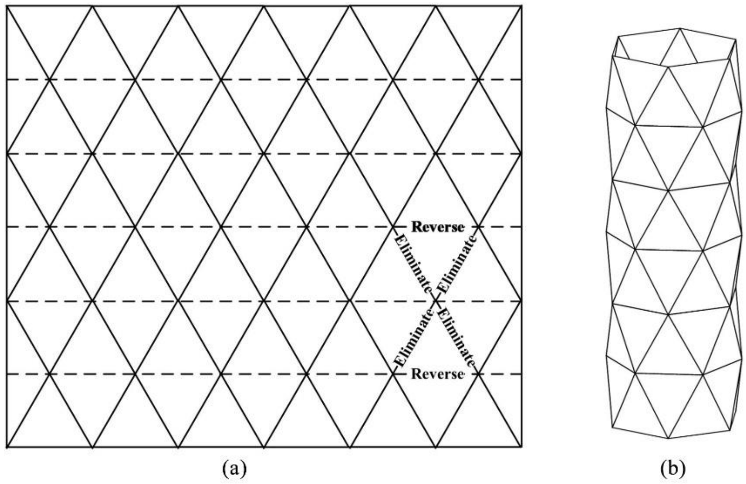

Figure 14. Yoshimura (Diamond) Folding Pattern, figure reprinted from [28]. (a). Yoshimura folding pattern; (b). Yoshimura inspired cylindrical structure

This folding pattern has been applied to the design of antennas to promote channel capacity and communication reliability [29]. Yoshimura is another folding pattern with valley creases of parallel diagonals and mountain creases of edges [30]. It has been reported that the implementation of this folding pattern in the CFRP (Carbon Fiber Reinforced Plastic) tube significantly improved the weight-specific energy absorption performance [31].

4. Future Developments and Potential Applications

In this section, we aim to discuss future developments and potential applications of origami-inspired deployable structures in aerospace engineering and the space industry. In recent decades, origami-inspired structures have attracted worldwide attention, and have been successfully applied to space instruments such as solar arrays, antennas, and robotic arms. The rapidly increasing number of space instruments, the variation of the space environment, the gradually tight budget, and the exceedingly limited space in spacecraft are pushing deployable structures toward the features of being lightweight, reliable, affordable, and compactable. For future developments and potential applications, Liu and co-workers have stated that ongoing research and innovation are promoting folding efficiency and expanding future capabilities and the practicality of space instruments [23].

4.1 Artificial Muscles

Nowadays, artificial muscles have become a crucial technology for designing and manufacturing myriad common machines and robots. It has been shown that the design, fabrication, and implementation of artificial muscles face some challenges such as material costs, operating principles, scalability, and single DOF contractile actuation motions [32]. With repeated basic units and multi-degree-of-freedom folding patterns, origami-based artificial muscles can reduce costs and achieve multiaxial motions such as contraction, bending, and torsion. It has been demonstrated a fluid-driven origami-based artificial muscle (FOAM) (shown in Figure 15) that generated stresses of 600 kpa and produced peak power densities over 2 kW/kg with the contraction of 90% of the initial length [32].

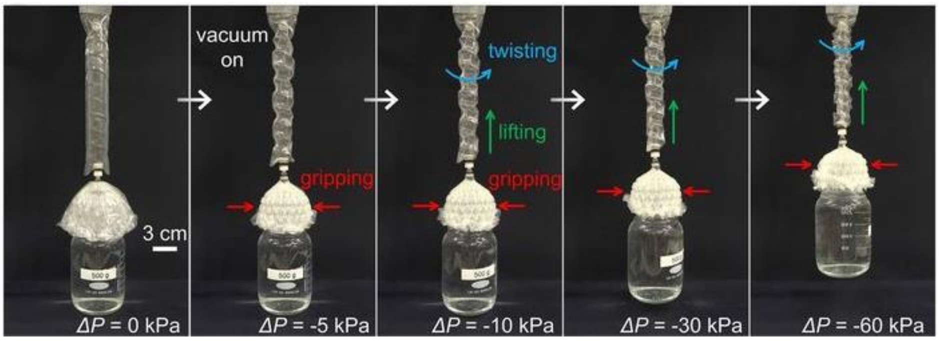

Figure15. Fluid-driven Origami-inspired Artificial Muscle, figure reprinted from [32]

This type of artificial muscle can generate powerful, efficient, programmable multi-dimensional actuation, which can be of widespread use in space exploration and human-robot interactions [32]. Also, Lee et al. presented an origami-based vacuum pneumatic artificial muscle (OV-PAM) (shown in Figure 16) which achieves over 400 N forces with a contraction of more than 90% of the initial length [33].

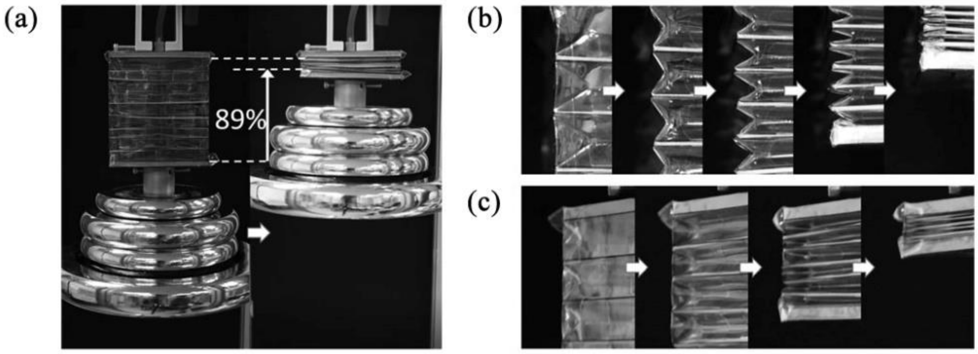

Figure 16. Origami-Based Vacuum Pneumatic Artificial Muscles, reprinted from [33]. (a). Contraction of this artificial muscle with a load of 10 kg; (b). Process of folding; (c). Process of compression

It has also been noted that future development will focus on applying OV-PAMs to space soft wearables due to their low weight and high specific actuation stress [33].

4.2 Star Shade

The star shades (shown in Figure 17) are the devices to block out the light emitted from the stars to the space telescope, to ensure the image and characterization of specific planets are free of impact by the light nearby. To improve reliability, the star shades are required to be light in weight and remain completely opaque even after perforation caused by micrometeorites [34]. Also, the star shade should be able to stow around the central hub of the spacecraft in a highly repeatable configuration [34]. The above requirements make origami-based structures ideal candidates for the design of star shades. Additionally, some researchers have proposed a design of the prototype that is based on the “flasher” folding pattern and further created a dynamic model to analyze the effect of joint stiffness on the forces and torques produced by the process of deployment [34,35].

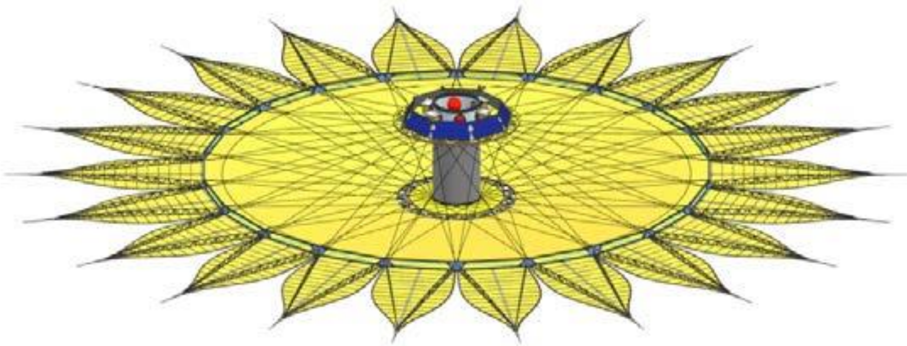

Figure 17. Flasher-inspired Starshade, figure reprinted from [35]

Constructing larger deployable star shades to match better space-orbiting telescopes is believed to be one possible direction of its future developments. The research on star shade holds promise to build star shades with up to 72 m-diameter in a 5 m-diameter fairing [36].

4.3 Energy Absorption Devices

Safety is a crucial factor in the design of spacecraft. To reduce the impact of micrometeorites, either buffering devices or energy absorption devices are needed to protect the spacecraft. Currently, origami-based energy absorption devices have been extensively employed in the design of car crash boxes and bulletproof shields (Ma et al. 2014; Kenny et al. 2018)]. Compared to conventional car crash boxes, origami-based crash boxes (shown in Figure 18) exhibit predictable and stable behaviors and achieve an energy absorption ratio of up to 92.1% [37]. Researchers noted that the origami-based crash box will absorb more energy than traditional thin-wall crash boxes without in-plane incurring stretching [37].

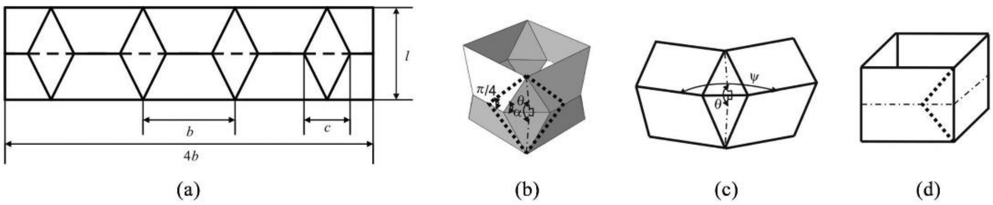

Figure 18. Origami-based Crash Box, figure reprinted from [37]. (a). Origami folding pattern; (b). Model of this crash box; (c). Partially folding of a quarter of the folding pattern; (d). A traditional square tube.

Similarly, energy absorption devices can also be applied to spacecraft design. It has been reported that bio-origami structures based on leaves, wings of insects, and durian shells showed great potential for future developments in aerospace engineering and civil engineering [35]. Future research topics will focus more on the energy absorption capabilities of biomimicry origami-based structures in the space industry [17].

5. Conclusion

This article provides an overview of the engineering implementations, potential applications, and future developments of origami-based deployable structures. The development of aerospace engineering has been stimulated by the contradiction between the increasing number of experimental instruments and the limited space in spacecraft. Accordingly, much attention has been drawn to the design of deployable structures. The emergence of thick panel origami theory made it possible to design origami-based deployable structures with zero-thickness sheets. Compared to traditional deployable structures, origami-based deployable structures have many remarkable advantages including easier manufacturing processes, lower cost, lightweight, lower storage volume, better stiffness, higher reliability, and more predictable and precise kinematic behaviors. Therefore, many origami folding patterns and origami-based deployable structures have been extensively used in aerospace engineering. Several folding patterns including Miura-ori, flasher, helix, and waterbomb are employed in the fields of solar sails, solar panels, larger space antennas, and robotic grippers. In the near future, these folding patterns and structures are believed to provide unique and valuable properties for star shades, artificial muscles, and energy absorption devices. Hopefully, this article provides insights for readers to understand the benefits of origami-based deployable structures.

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