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Leveraging Origami for Space Efficiency: A Comprehensive Review of Its Role in Aerospace

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Abstract

Originating in East Asia, origami has developed beyond its original artistic medium to play a significant role in the design of adjustable systems, especially in the sector of space engineering. Due to tight weight and space constraints, these structures which are essential for aviation and spacecraft make effective use of the geometric qualities of origami. This study provides a summary of recent research, emphasizing the benefits, technical applications, and uses of deployable structures made of origami in the aerospace industry. Additionally, it examines more current origami-based space instruments, including details on their principles and real-world uses. The ancient Japanese paper-folding technique known as origami has found new uses in aerospace engineering, providing creative answers for the creation of lightweight parts, deployable structures, and small storage systems. The integration of origami-based designs in aerospace engineering is examined in this article, along with how these designs advance solar arrays, radar antennae, and spacecraft. The importance of origami-inspired engineering in lowering payload weight, maximizing space utilization, and improving the performance of aerospace components is highlighted in the article. The paper also explores several origami-based systems that are being studied for potential future uses in aviation and space exploration. Engineers use origami principles to create more effective, adaptable aerospace components, such as deployable solar panels and antennae, and lightweight, shape-shifting materials. Origami's use in space exploration and aviation is expected to grow as research progresses, spurring inventions that improve the sustainability, efficiency, and usability of the next aerospace systems. This paper shows that origami has a bright future in contemporary engineering by highlighting its recent advancements and possible applications in aerospace.

Keywords: Origami, aerospace, structures, instruments, miniaturization, space exploration, inventions, solar panel, antennae

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INTRODUCTION

The term "origami" (from the Japanese words "*ori*" meaning folding and "kami" meaning paper) refers to the craft of using folding techniques to turn a flat sheet of paper into a three-dimensional item. Without the need for cuts or adhesives, paper can be folded into an infinite variety of forms and patterns using origami folding techniques.

Engineering professionals are interested in the following features of origami:

1. Retractability
2. Maneuverability
3. Easily carried
4. Reduces parts of the system

5. Ability to be manufactured from malleable metals or materials
6. Folding as a manufacturing process
7. Simplified assembly
8. Simplified miniaturization
9. Reduced material volume and bulk

LITERATURE REVIEW

We learn from these characteristics how important they are to the design of spacecraft and aviation machinery. Currently, an increasing number of origami folding patterns are being used to create various types of deployable structures. The various kinematic characteristics of these structures render them suitable for various equipment designs. An overview of origami folding patterns and their applications is crucial for researchers to understand their various configurations and properties. Thus, in this review, we discuss the design techniques and mathematical underpinnings of origami-based deployable mechanisms and investigate their current and future uses in aerospace engineering.

Yue summarized recent studies on origami-based deployable structures and their use in aerospace engineering. It primarily illustrates the geometric characteristics, technical applications, benefits, and uses of origami-based deployable structures in aerospace engineering [1].

The goal of the origami-adapted design process is to make it easier for designers to consistently transform origami into functional products with the desired qualities. Three preliminary design examples—a deployable parabolic antenna for space and Earth communication systems, an expandable habitat for the International Space Station, and origami bellows to shield Mars Rover's drill shafts—were used by Morgan et al. to demonstrate the origami-adapted design process. To satisfy certain requirements for an aerospace-based product, each of these instances begins with an origami fold pattern and modifies it [2].

An extension of origami geometry to the situation of "folding" a three-dimensional (3D) space along a plane was examined by J.C. Lucero. First, the geometry of the reflections was used to analyze all potential incidence limitations between specified points, lines, and planes. A collection of 3D elementary fold operations that have a finite number of solutions and satisfy combinations of constraints is then specified [3].

With an emphasis on research findings from 2015 to 2020, Meloni et al. reviewed contemporary origami-based applications in engineering, design techniques, and tools [4]. Given their extensive coverage, starshade blankets must be remarkably light compared with standard multi-layer insulated (MLI) spacecraft blankets. Additionally, the blankets must be stowed in a highly repeatable manner around the central core of the spacecraft using the deployable ring and petal components. Therefore, they are perfect origami folding patterns. Shigel et al. started with variations in the origami flasher to fold the central ring blanket, which was at least 20 m in diameter, based on earlier research on large deployable rigid arrays [5]. Turner et al. provided an overview of recent origami research in mechanical engineering. A foundation for important mathematical origami findings was provided, along with an introduction to basic terms and concepts frequently utilized in origami [6].

The principles of origami engineering and their use in both current and future industries have been covered by Fei and Sujan. A brief introduction is given to several key mathematical concepts, including the Huzita-Hatori axioms, Maekawa, and Kawasaki theorems [7]. By using origami design, which is produced by carefully combining two types of plane-symmetric thick-panel origami modules, Wang et al. developed a novel space-deployable structure with a curved surface. The network construction process is explained in detail [8]. These structures and their main advantages over other deployable and extensible structures already in use were explained by Sokolowski et al. [9] Ultra-lightweight shape memory rigidizable inflatable (RI) structures were identified by DARPA and NASA as a technology that will enable future space and interplanetary missions that call for huge space systems [10].

OBJECTIVE

To explore and analyze the various applications of origami principles and techniques in the field of aerospace engineering, focusing on their potential benefits in terms of lightweight design, compactness, and deployability of structures for space exploration, satellite technology, and other aerospace applications.

WORKING

An arrangement capable of folding and unfolding multiple times to achieve the intended form is called an origami configuration. The key advantages of origami construction in aerospace engineering stem from the following attributes.

1. Large setups are becoming smaller.
2. Accuracy is increasing.
3. Drive machinery is being used less frequently.
4. Components are becoming standard.

The advantage of compacting large configurations is their ability to transport numerous research instruments by using small artificial satellites. Additionally, most deployable structures designed in the origami style exhibit a diminished degree of freedom (DOF), resulting in the need for fewer servomotors to operate them.

RIGID ORIGAMI IMPLEMENTATION IN ENGINEERING

One branch of origami that is rigid is devoid of distortions. The origami of this type folds without deformation, resembling certain motion systems found in the study of machine engineering. Thus, mechanical links can be used to create stiff origami. Fold patterns of this type of origami can be divided into two categories based on their large planar structures: valley and mountain creases. Figure 1 shows an example.

When folded, the valley crease becomes concave, as shown in Figure 2, whereas the mountain crease becomes convex. It is feasible to demonstrate the flat foldability requirements of a crease pattern with a singular vertex.

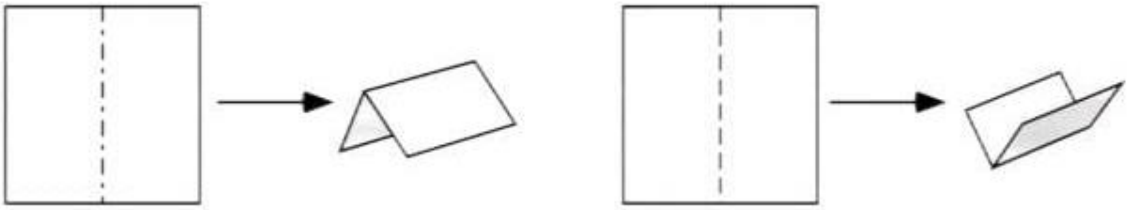

Figure 1. Mountain crease and valley crease.

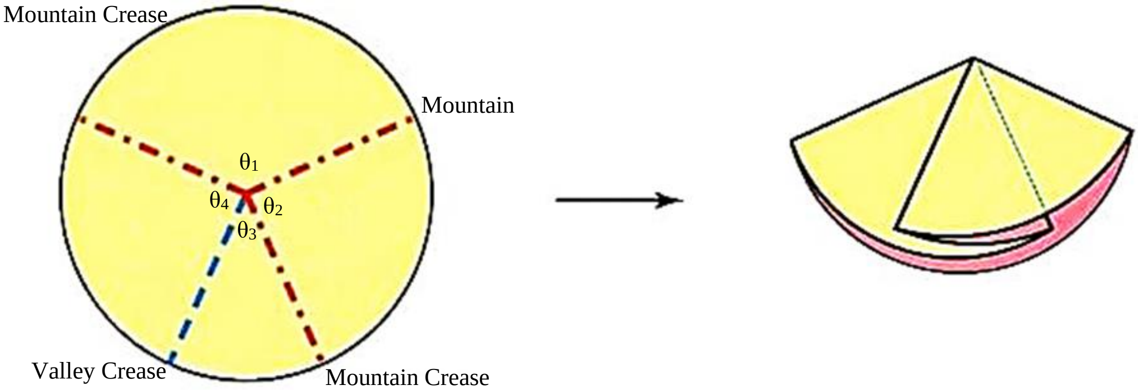

Figure 2. Crease pattern (single vertex).

A flat sheet of paper with negligible thickness, shown in Diagram 2, has a single vertex crease pattern that is flat foldable if and only if the angles
$\theta 1 + \theta 2 + \cdots + \theta n = 360^\circ$ are met.

- The total number of wrinkles was consistent.
- The minimum number of creases was 2.
- The number of valleys and mountains varied by ±2.
- The angle relationship should satisfy Kawasaki's theorem conditions.

$$180^\circ = \theta 2 + \theta 4 + \cdots + \theta n = \theta 1 + \theta 3 + \cdots + \theta n - 1.$$

Origami's folds resemble revolute joints in machinery-related designs, enabling staff members to rotate around them. Similarly, considering the entire crease structure with a singular vertex as a circular connection is plausible. This equivalence arises from the consistent distance between the fold-edge intersections and vertex in the resulting 3D structure formed by folding papers, as shown in Figure 3.

APPLICATIONS OF VARIOUS FOLDING PATTERNS

Solar Array with Miura Folding Pattern

The Miura folding pattern shown in Figure 4 is widely used in mechanical engineering, particularly in aerospace engineering. In the early 1980s, a remarkably simple groundbreaking folding method was introduced to deploy expansive planar structures. Initially employed in the design of solar sails, it has proven to be highly effective.

Origami-based Solar Panel

"Flasher" is another folding pattern of origami as shown in Figure 5. It is a rotationally 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.

APPLICATIONS OF ORIGAMI

1st: Star Shade

The purpose of star shades is to prevent nearby light from affecting the image and description of a particular planet by blocking off the light that the stars send to the space telescope, as shown in Figure 6.

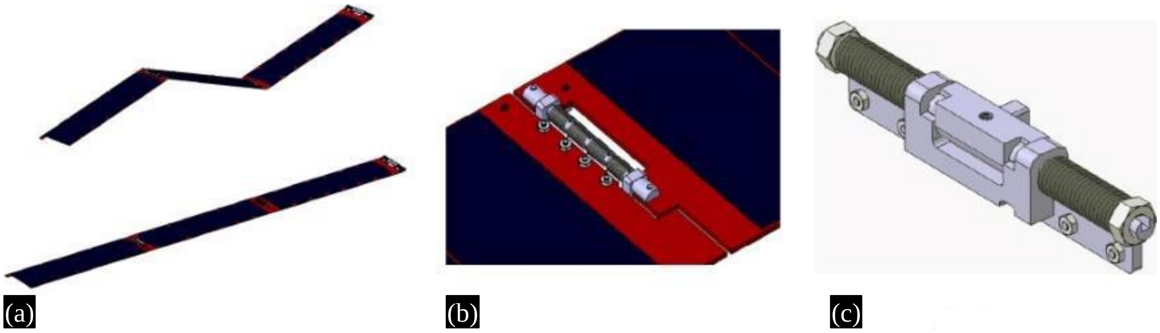

Figure 3. 3D structure formed by folding papers.

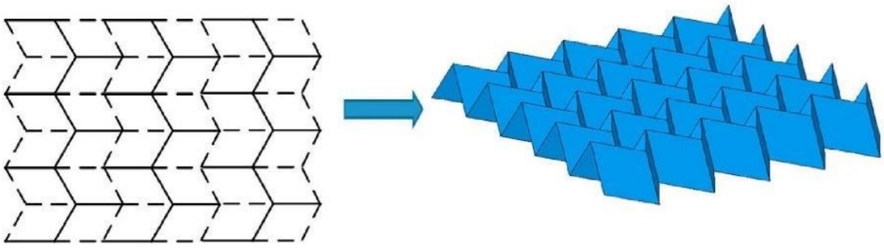

Figure 4. Diagram of Miura folding pattern.

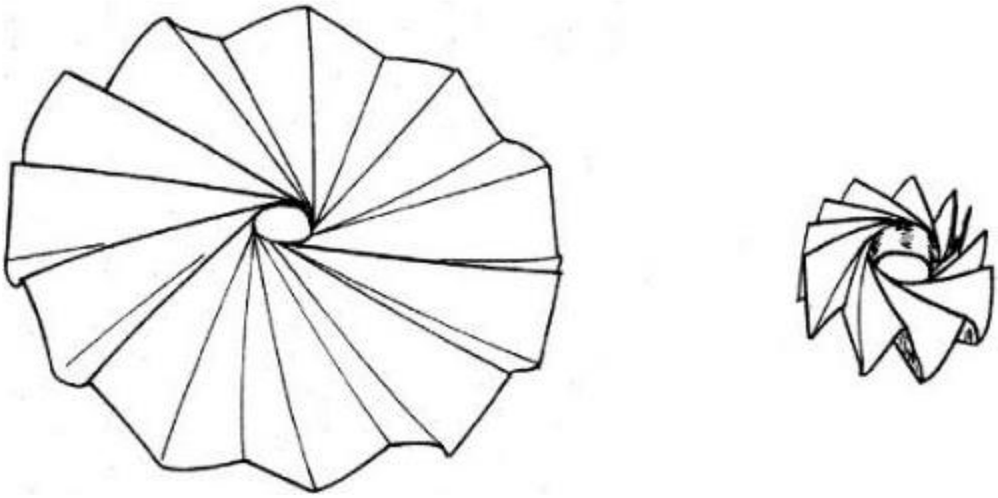

Figure 5. Flasher folding pattern: (a) Flasher before deployment; (b) Flasher after deployment.

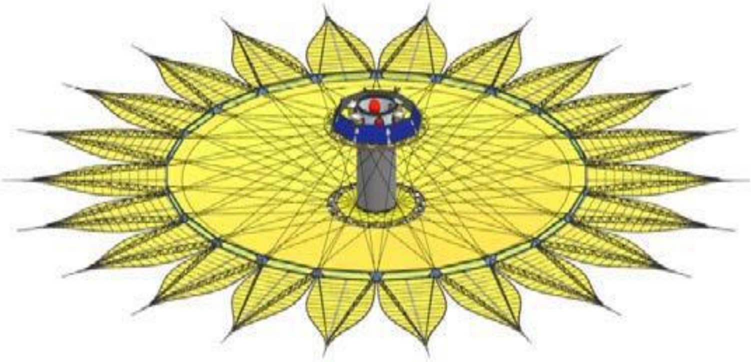

Figure 6. Flasher-inspired Starshade.

Star blinds must be lightweight and fully opaque, even after being punctured by micrometeorites, to increase dependability. Additionally, the star shade must be able to be stowed in a highly reproducible arrangement around the central hub of the spacecraft. Origami-based structures are ideal for designing star blinds because they exhibit these characteristics. Furthermore, some scientists have invented a simulation model to test the impact of articular rigidity and have suggested that a prototype design depends on the “flasher” fold architecture.

2nd: Space Telescopes

Origami concepts are being increasingly applied in space exploration technologies. Paper-folding techniques facilitate the reliable deployment of complex structures, transforming from compact shapes during storage and transportation. Consequently, origami has emerged as a pivotal technology for spaceflight scenarios, where constraints on mass and volume are paramount. A notable application is the development of lightweight high-resolution origami telescopes. These telescopes can be tightly packed into rocket fairings and unfolded in orbit as needed. Origami folding patterns enable precise control over the shape during the launch. For example, the James Webb Space Telescope features a mirror constructed from hexagon-shaped pieces mounted on a folding chassis designed to fit inside a rocket. Upon launch, the mirror unfolds seamlessly for complete deployment.

The James Webb Space Telescope (JWST) uses origami-inspired techniques in its sunshield design, as shown in Figure 7. The sunshield consists of five layers of special material that unfolds to the size of a tennis court once the telescope is in space. This origami-like deployment allows the sunshield to protect the telescope from the sun’s heat and light, thereby enabling it to maintain its operating temperature and conduct observations of the universe with remarkable precision.

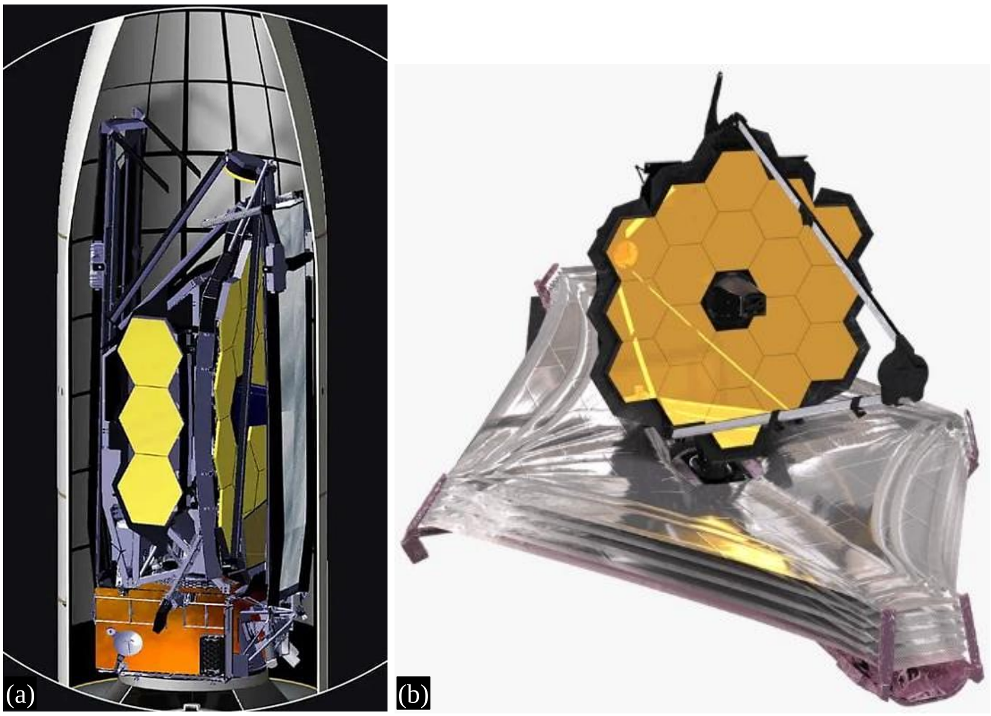

Figure 7. (a) The James Webb Space Telescope in unexpanded form; (b) the James Webb Space Telescope in expanded form.

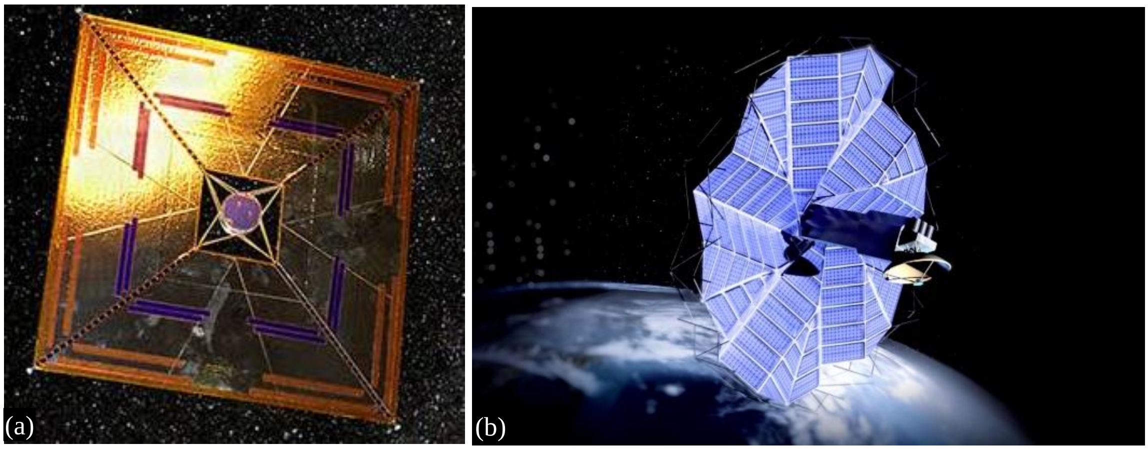

Figure 8. (a) Solar sail; (b) solar array.

3rd: Solar Array and Solar Sail

Another potential application of origami techniques is solar arrays, which harness solar energy to generate power. Accordion-folded multi-layer origami arrays can spread steadily in orbit after firmly retracting for launch. Compared with traditional rigid panel arrays, this offers higher power production from a larger surface area and more compact storage. Scholarly teams have shown origami solar panels that are 90% smaller when folded and almost as efficient as traditional designs, as shown in Figure 8.

4th: Critical Habitats

In addition to being portable, origami has the potential to be a promising space radiation shield. Origami shields that are multilayered and have specific folding patterns can create lightweight barriers that work well. Compared to traditional materials, folded Kevlar composites, in particular, show improved radiation blocking and thermal insulation. One day, critical instruments and astronauts may be shielded from harm during extended journeys by deployable origami enclosures and shelters.

Figure 9. Moon base.

Critical habitat needs can be addressed by using origami principles as space agencies plan for prolonged human presence beyond the Earth (Figure 9). Lightweight, flexible, and quickly deployable structures are made possible by origami, which makes them perfect for extraterrestrial construction. Origami-inspired modular space habitat designs offer room interiors and effective volume utilization for launches. Connecting small folding modules allows layout flexibility. Folding allows habitats to be reconfigured to accommodate crew sizes or change mission needs.

Reconfigurable origami shell panels and frames have been used by researchers to propose the lunar and Martian colony concepts. Effective radiation and debris protection are necessary for manned flight. Origami shields with several layers offer superior isotropic protection against space radiation compared with traditional materials. More radiation paths can be blocked by effectively using the mass owing to folded kinematics. In addition, during solar flares, astronauts or equipment can be protected by deployable origami shelters.

THE FUTURE ASPECTS OF ORIGAMI

Although the field of origami engineering has advanced rapidly, there is still a great deal of unrealized potential in the aerospace industry. Origami can revolutionize everything from medical equipment to deployable buildings in space by overcoming scale constraints. The practical applications of origami encounter challenges when they expand from paper models to fully functional, full-sized systems. It is essential to understand the fundamentals of fold kinematics and mechanics. The way weight, forces, and dynamics work is very different from paper origami art. For space and flight, robustness and dependability must also be incorporated. However, overcoming these obstacles will be made possible by developments in manufacturing, simulations, and materials. Better emulation of paper folds is possible with multi-material composites possessing distinct characteristics.

Complete working origami systems can be fabricated more easily using 3D printing and intelligent materials. Solutions to these problems could lead to an increase in aircraft applications. Deep-space transit habitats are incredibly tiny and employ self-deploying origami modules. Extremely agile airplanes use the concept of origami to change their wings.

CONCLUSION

In summary, the principles of origami engineering allow for revolutionary solutions that fulfill contemporary aerospace requirements. Even if there are still difficulties in converting abstract origami ideas into practical applications, essential elements are starting to come together. Origami, at the crossroads of science, design, mathematics, and engineering, has the potential to transform other technical sectors, such as aerospace, in the twenty-first century.

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