

Research Progress on Extendable and Foldable Structures

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Abstract. Retractable and folding structures, as a key technology for addressing spatial constraints and achieving functional adaptability, are demonstrating increasingly broad and significant application prospects in aerospace engineering, modern architecture, and the development of various portable equipment. This paper aims to systematically trace the developmental trajectory and current research status of such structures within both academic and engineering circles globally, while thoroughly elucidating their core design principles. Through ingenious kinematic design and morphological configuration, these structures achieve controllable, reliable, and efficient morphological transitions between compact stowage and fully deployed operational states. This fundamentally enhances spatial resource utilization efficiency, alongside the structural system's functional adaptability and environmental responsiveness. Although notable progress and successful case studies have been achieved in specific engineering practices and application projects, substantial research challenges and academic frontiers remain at the fundamental level. These include developing systematic integrated design theories, elucidating dynamic operational mechanisms under complex conditions, characterizing performance under multi-physics coupling effects, and establishing comprehensive performance enhancement methods for global optimization. Subsequent sections of this paper will focus closely on core theoretical principles concerning the geometric composition, kinematic and dynamic analysis of scalable and foldable structures. Detailed discussions will be conducted in conjunction with their implementation forms, including grid-like structures, cable-rod systems, and folded plate configurations. The ultimate aim is to provide systematic, forward-looking, and reference-worthy academic support and literature basis for both theoretical innovation framework development and complex engineering application practice within this technological domain.

Keywords: Expandable structure; collapsible structure; structure engineering.

1. Introduction

With societal advancement, aerospace exploration, construction techniques and portable equipment have also progressed rapidly. Concurrently, demands for lightweight structures, adaptable configurations and high storage efficiency have intensified. Through specific mechanisms and form design, retractable and folding structures achieve controlled transitions from compact storage to fully deployed states, emerging as pivotal technologies for overcoming spatial constraints and enabling functional adaptability. Such structures can significantly enhance spatial efficiency and structural adaptability. Deployable and folding structures have found extensive application across numerous fields—including civil, military, and aerospace—due to their advantages of rapid construction, ease of assembly, convenient transport and storage, and reusability [1]. In the aerospace sector, they are extensively employed in components such as satellite solar panels and deployable antennas, effectively facilitating the successful execution of space missions. Within civil construction, they enable the rapid assembly of emergency shelters and temporary facilities, providing crucial support for disaster response operations. Within medical equipment, folding structures also play a pivotal role, facilitating the development of more portable and efficient diagnostic and therapeutic devices. With ongoing advancements in materials science and technology, retractable and folding structures will evolve further towards intelligent, multifunctional integration, paving the way for breakthroughs in deep space exploration, sustainable urban development, and healthcare.

In recent years, significant progress has been made domestically in the research of stretchable and foldable structures. Within the aerospace sector, space deployable structures have evolved from one-

dimensional deployable arms and two-dimensional planar array deployments to three-dimensional planar array deployments [2]. Internationally, numerous studies on stretchable and foldable structures have also been conducted. Within the field of retractable electronic component structures, Waseda University's innovative 'Kiri-origami' construction integrates traditional origami techniques with modern paper-cutting technology. This approach effectively resolves the technical conflict between electronic component assembly and structural retractability. Furthermore, they have successfully developed a retractable display prototype incorporating 145 LEDs. This technology will empower the future development of wearable smart devices and medical health assistance equipment, providing a key driving force [3]. North Carolina State University in the United States has proposed a variant origami superstructure scheme. This innovative approach integrates the concept of multi-stage transmission mechanisms with thick-plate origami techniques, enabling the realisation of over a thousand distinct configurations with the deployment of no more than three drive components. This lays a crucial technological foundation for expanding the functionalities of variant robots and developing rapidly assembled, reconfigurable structures [4].

In summary, deployable and foldable structures have been explored in diverse fields such as domestic and international construction projects, aerospace equipment, and emergency facilities, owing to their significant advantages of strong spatial adaptability and convenient transportation and storage. Moreover, various case studies demonstrate broad application prospects, accumulating rich engineering experience for subsequent technological development. However, current research predominantly focuses on application implementation in specific scenarios, with considerable scope remaining for investigation into core operational theories and the properties of different structural forms. The following discussion will explore the theoretical foundations and holistic design logic of expandable and foldable structures, alongside key technologies for representative configurations such as grid-type, cable-rod-type, and folding-panel-type structures. This aims to provide more comprehensive theoretical underpinnings and design references for technological breakthroughs and industrial applications within this field.

2. Research on structural theory

In theoretical methodology research, Tianjin University has proposed a systematic design approach based on the integration of over constrained mechanisms with geometric coverage. This methodology employs three-dimensional over constrained mechanisms as fundamental building blocks, constructing large-scale deployable structures through planar or spatial geometric coverage. It effectively resolves geometric and kinematic coordination challenges under highly non-linear conditions, enabling the systematic acquisition of all design solutions satisfying coverage requirements. Large-scale deployable structures featuring single degrees of freedom and geometric over constraint characteristics have been successfully designed, achieving precise transitions from compact folded states to multiple predefined configurations.

In the realm of structural typology expansion, Tianjin University's research into the motion coordination relationships of spatial multi-loop mechanisms, coupled with the introduction of truss transformation strategies, has enabled the team to propose a design methodology for single-degree-of-freedom polyhedral transformation structures. This approach achieves bifurcation-free single-degree-of-freedom transformation between disparate polyhedra, propelling deployable structures from two-dimensional planar configurations towards three-dimensional volumetric architectures.

In engineering applications, this work resolves the contradiction between morphological transformation and high load-bearing requirements in variant aircraft wings. It systematically elucidates the core engineering characteristics that deployable structures must possess—namely, 'efficient transport and rapid deployment'—while clarifying their applicable domains: large-scale deployable mechanisms primarily target space infrastructure such as space stations and satellite antennas, whereas compact foldable polyhedrons suit precision equipment including microsatellites and interventional medical robots. All design proposals have undergone high-fidelity physical

prototype validation to confirm their operational reliability and functional completeness, providing robust theoretical underpinnings and design paradigms for technological innovation within China's aerospace and advanced manufacturing sectors [5-7].

3. Retractable and folding structural design

3.1. Grid structure

A grid frame is a spatial structural system comprising a dense column grid and orthogonally arranged interlayer beams. This structure must not only bear vertical floor loads but also resist horizontal forces such as wind loads and seismic actions. Given the relatively small cross-sectional dimensions of its beams and columns, overall stability under combined vertical and horizontal loading becomes a critical issue in the engineering application of such structures [8]. Among grid structures, steel grid structures are the most prevalent. This system employs small-section members as energy-dissipating units, thereby reducing material consumption, and has been successfully applied in numerous projects [9].

3.2. Tie-rod structure

Cable-rod structures are designed around the principle of 'rigid rods providing support while flexible cables serve as traction or constraints'. Mobility is achieved through the tensioning and release of cables alongside the rotation and extension of rods. Among these, spatial cable-rod deployable mechanisms represent a widely adopted deployable system in aerospace engineering, exemplified by large antenna backstays. The entire deployment process of these mechanisms is particularly crucial, forming a key focus in the design and research of aerospace deployable systems. Research primarily examines the kinematic patterns exhibited during the transition from a stowed configuration to a fully deployed state, and vice versa from fully deployed to stowed, aiming to enhance both performance and manufacturing processes [10].

3.3. Folded plate structure

The folded plate system comprises multiple thin plates assembled at predetermined angles to form a thin-walled spatial structure with a zigzag profile. This system is assembled from flat plate units, simultaneously bearing loads and defining spatial enclosures while exhibiting high overall rigidity and favourable material economy. Furthermore, incorporating folded plate components into steel frameworks offers novel solutions for continuous collapse resistance design. This approach effectively reduces steel consumption while maintaining structural performance, balancing structural safety with construction costs [11]. Applications are extensive, including foldable container sidewalls, portable solar panel facings, and spacecraft solar array substructures. Certain designs employ laminated panels or honeycomb cores to reduce weight while maintaining structural integrity.

4. Summary

There are three primary types of common expandable structures, each suited to distinct scenarios. These are grid structures, cable-and-rod structures, and folded plate structures. Each configuration possesses its own advantages, enabling them to meet diverse practical requirements.

Looking ahead, deployable structures are becoming increasingly intelligent, multifunctional and cross-disciplinary. Future structures will not merely "fold"; they will integrate smart materials and sensing technologies to automatically adapt to environments, adjust their form, and even self-repair. In architecture, adaptive roof systems responsive to weather changes—such as foldable snow-removal devices[12]—are emerging. Within medicine, these technologies find application in minimally invasive surgical instruments or implantable devices. The future of retractable and foldable structures holds boundless potential, quietly transforming human life. From space exploration to everyday applications, these innovations will usher in a more flexible and intelligent future.

To achieve this future vision, current research must advance synergistically across multiple levels. Advanced digital design and simulation technologies require further development to more accurately model complex deployment processes and the impact of their operational environments. Concurrently, innovation in new materials and manufacturing processes is paramount, as this will directly determine the performance and reliability of future structures. Crucially, disciplinary barriers must be overcome to foster deep integration across structural engineering, materials science, information technology, and artificial intelligence. This convergence will collectively propel deployable structures from simple mechanical systems towards intelligent systems capable of perception, adaptation, and even autonomous decision-making.

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