



Deployable Structures: Structural Design and Static/Dynamic Analysis

Xiao Zhang^{1,2} · Rui Nie^{1,2} · Yan Chen^{1,2}  · Baiyan He^{1,2}

Received: 1 September 2021 / Accepted: 27 September 2021 / Published online: 27 October 2021
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

Abstract

Deployable structures can realize the transformation from a folded configuration to a deployed configuration to satisfy the requirements of applications. They have been widely used in aerospace structures, civil temporary components, medical devices, transformable robotics and other engineering applications. A large amount of research has been carried out on the structural design ranging from rigid, rigid-flexible to flexible structures and the performance analysis including the static loading properties and structural stability, as well as the dynamics during deployment and in the deployed configuration. However, to date, there are no mature systematic approaches for the design and analysis of deployable structures due to diverted application demands. Therefore, in this review, efforts are made to find a common methodology from most existing successful cases and to propose the major challenges for the future applications of deployable structures.

Keywords Deployable structures · Structural design · Performance analysis · Statics · Dynamics

Mathematics Subject Classification 52C25 · 70Bxx · 70Exx · 74Gxx · 74Hxx · 74Kxx · 74Pxx · 74Sxx

1 Introduction

A deployable structure is a type of transformable structure that can vary in shape from a compact, packaged configuration to an operational, expanded configuration. In most cases, the packaged configuration is used for storage and transportation, while the expanded configuration is used for working requirements. Deployable structures widely exist in nature, such as blooming flowers, unfolding leaves, foldable insect wings, and the opening mechanisms of the mouths of angler fish [1]. During the long history of human culture development,

✉ Y. Chen
yan_chen@tju.edu.cn

B. He
hebaiyan@tju.edu.cn

¹ School of Mechanical Engineering, Tianjin University, Tianjin 300350, China

² Key Laboratory of Mechanism Theory and Equipment Design of Ministry of Education, Tianjin University, Tianjin 300350, China

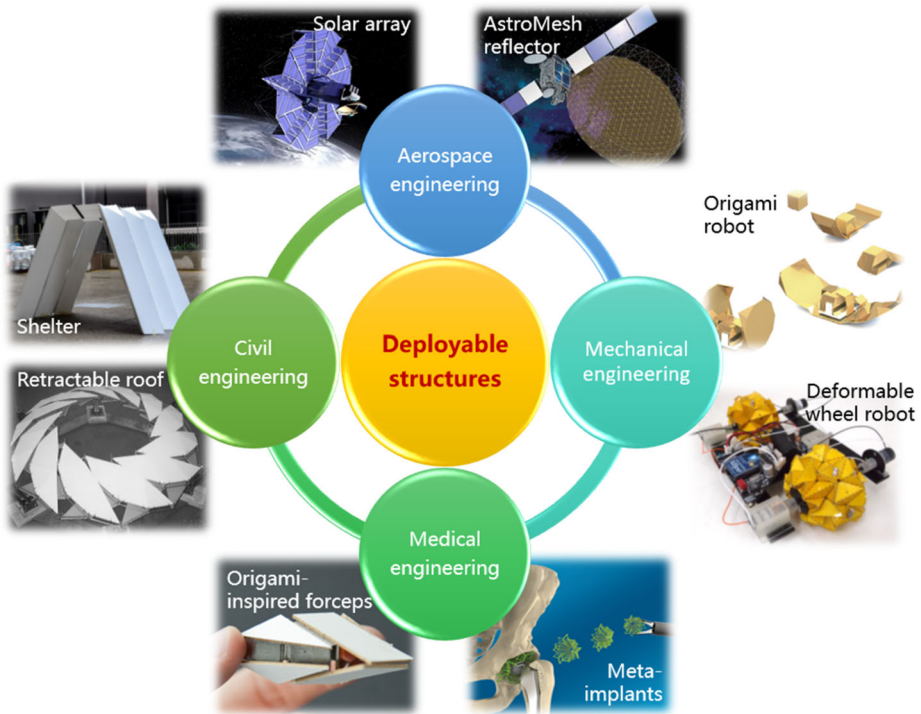


Fig. 1 Examples of deployable structures in engineering applications. Solar array [6], AstroMesh reflector [26], origami robot [23], deformable wheel robot [24], meta-implants [21], origami-inspired forceps [22], retractable roof [17], and shelter [12]

folding and deploying processes have always been present in daily life, such as foldable furniture, oriental fans, umbrellas, expandable balloons, and so on.

Currently, deployable structures are being developed to be used in various engineering fields (see Fig. 1). Aerospace has become the main field for cutting-edge research in the field of deployable structures accompanied by exploration in outer space in order to address the contradiction between the multifunction and large-scale requirements of aerospace equipment and the limited effective size of the launching vehicle. Deployable structures have been applied to a human lunar base [2], the in-space robotic assembly of a modular space telescope [3], space antennas [4], parabolic solid reflectors [5], solar arrays [6, 7], solar sails [8], and sunshields [9]. In aerospace applications, the bearing capacity, structural stability, shape accuracy and retention, deployment reliability, and dynamic behaviours in deployment and the deployed configurations should be fully considered. In civil engineering, to meet the needs of disaster relief regarding tents and road bridges, foldable plate structures and foldable bar structures [10, 11] with the characteristics of quick construction and convenient transportation, such as origami shelters [12–14], bridges [15, 16], are produced accordingly. To obtain a good lighting effect and to realize deployment according to weather conditions, retractable roof structures [17] are constructed. In the medical field, many medical devices can be regarded as deployable structures, such as stents [18–20] that fold to a small diameter in the human body and deploy in a shape suitable for the blood vessel, meta-implants that change from folded configurations to a full-size load-bearing shape [21], and origami-inspired forceps [22] that fold and unfold in a medical interventional catheter. In the above

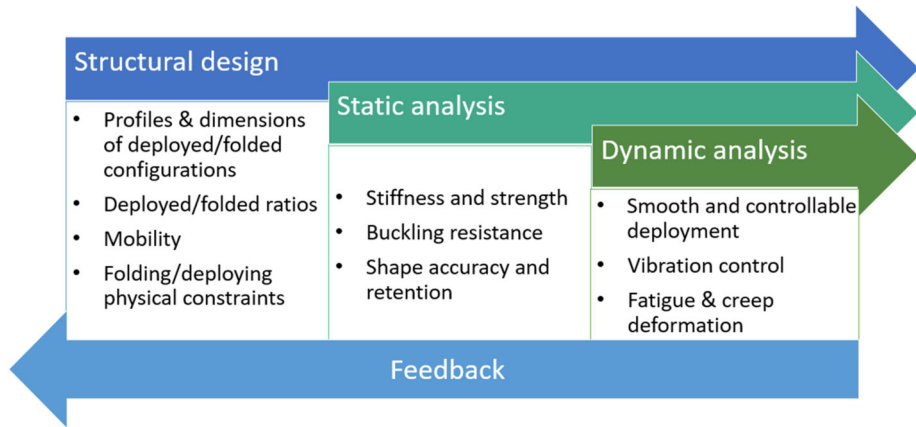


Fig. 2 The development process of deployable structures

two fields, in addition to the folded and unfolded configuration constraints, their static properties, such as strength, stiffness and buckling resistance, should be considered. Recently, the demand for deployable structures in mechanical engineering has increased rapidly, especially with the appearance of multifunctional robots fitting various environments [23–25]. A robot with morphologies using different self-folded origami exoskeletons was created to enable the manipulation of objects and locomotion on ground and in air and water [23]. A deformable-wheel robot [24] was proposed based on a waterbomb origami pattern, where the diameter of the wheel could be changed. A reconfigurable modular robot (Mori) [25] that can fold into any 3D configuration was designed by assembling modules to have different functions.

A typical development process of deployable structures includes two main aspects: structural design and performance analysis. As shown in Fig. 2, with the application demands, the initial structural design of the deployable structure is normally proposed first, followed by static and dynamic analysis to evaluate the design. Next, feedback is given to the structural design to further modify or require a new design proposal. After several such design cycles, an optimized structure is formed with all the expected functions. However, to date, there are no mature systematic approaches for the design and analysis of deployable structures due to diverted application demands. Therefore, in this review, efforts are made to find a common methodology from most existing successful cases and to propose the major challenges for the future application of deployable structures.

The paper is laid out as follows. First, the structural design of deployable structures with different configurations ranging from one dimension to three dimensions and different structural components from rigid, rigid-flexible, to flexible are described in detail, while driving-locking modes are briefly reviewed. Second, a performance analysis including the static bearing properties, structural stability, and dynamics during deployment or at the deployed configuration is performed. Finally, further discussion concludes the review.

2 Design of Deployable Structures

Most deployable structures have two functional configurations: the fully folded configuration for storage and transportation and the fully deployed configuration for services. The

transformation between these two configurations should have reliable intermediate motion, while maintaining the stability of two distinct configurations. Hence, the research on the structural design of deployable structures normally includes the geometric design of configurations, selection of the constituent elements (rigid and/or flexible elements, rods, panels and/or membranes), the driving and locking mechanisms, which is the foundation for the subsequent performance analysis of the deployable structure.

2.1 Structural Design of Deployable Structures

To adapt to different application environments, the features of the deployable structure vary, including a large deployable ratio for ultra-large flexible solar wings and antennas, high-precision with solid working surfaces for phased array antennas and parabolic or cylindrical antennas, and light-weight structures for foldable tents. According to whether the components are rigid or not, the deployable structures can be classified into three categories, rigid, flexible and rigid-flexible deployable structures, which has their own design challenge and advances for application scenarios.

2.1.1 Rigid Deployable Structures

A rigid deployable structure is a combination of bodies that have high stiffness and can be regarded as rigid connected by joints to form kinematic chains with one or multiple degrees of freedom (DOFs). This type of structure can easily realize the reciprocating movement for deployment and retraction, while the rigid bodies can provide high stiffness for the working configuration. To obtain the large folding ratios and improve the efficiency of manufacture and assembly, this type of deployable structure is generally designed as mobile assemblies of unit mechanisms through specific tessellations and mobile assemblies inheriting the characteristics of unit mechanisms [27]. Hence, the structural design of rigid deployable structures mainly focuses on the unit and its mobile tessellation.

To create novel deployable structures and to satisfy the demands of applications, unit mechanisms are proposed based on typical planar and spatial linkages through mechanism synthesis, combination [28–32], origami inspiration [33–36], and bionic methods [37]. In the aspect of the mechanism, Chen proposed a threefold-symmetric Bricard linkage based on the general plane-symmetric and trihedral Bricard linkages [28, 38], based on which a family of one-DOF deployable units were created by replacing its three alternate revolute joints with one-DOF mechanisms [31]. Ding constructed a family of two-layer and two-loop spatial linkages to assemble umbrella-like deployable structures [32]. Han proposed deployable basic units through type synthesis for hoop truss deployable structures [39, 40]. A Myard $6R$ linkage was derived from the combination of Myard $5R$ linkages [29]. Inspired by origami, five Miura-derivative patterns were constructed based on geometric modelling approaches [33], four types of four-crease origami patterns with geometric compatibility conditions were derived by Liu based on the matrix method from rigid origami corresponding to mobile assemblies of spherical linkages [34], and rigidly foldable origami tubes were constructed from the combination of original origami tubes according to compatibility analysis [35, 41]. Meanwhile, by applying bionics principles, petal-inspired deployable units were designed and analysed [37].

According to the geometry of folded and deployed configurations and the deployed/folded ratio in length, (projected) area or volume, deployable structures can be classified into one-, two- and three-dimensional (1D, 2D and 3D) deployable structures, respectively.

1D rigid deployable structures can realize a large deployed/folded ratio in length and do not change much in the other two dimensions. This kind of deployable structure can be

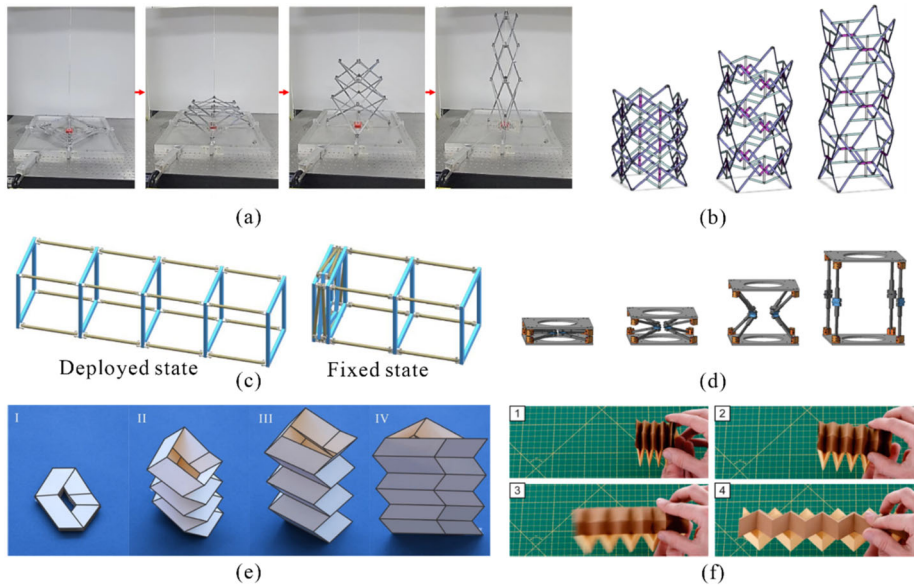


Fig. 3 1D rigid deployable structures. (a) A deployable mast based on scissor-like linkages [45], (b) prism mast based on Hoekens linkages [46], (c) self-lockable mast based on a 4-UU parallel mechanism [47], (d) deployable space telescope based on Sarrus linkage [48], (e) a rigid origami tube [35], and (f) a combination of two origami tubes [50]

used to design mobile bridges [42] for civil engineering and deployable/collapsible masts, for space applications [43]. This type of deployable structures can be subdivided into two types according to the different morphologies of their components: deployable truss structures composed of bar elements and plate structures composed of continuous surface elements. Based on planar unit mechanisms such as scissor-like linkages [44, 45] (Fig. 3a) and Hoekens linkages (Fig. 3b) [46], one-DOF prism masts can be constructed with two-joint connections where axes are perpendicular to the plane of each planar unit mechanism. Spatial unit mechanisms have been used to design deployable truss structures, such as 4-UU parallel mechanisms connected by H-joints for a self-lockable deployable mast [47] (Fig. 3c) and Sarrus linkages for deployable space telescopes [48] (Fig. 3d). On the other hand, 1D rigid deployable plate structures are mainly derived from rigid origami tubes [35, 41, 49, 50] (Fig. 3e). Here, a rigid origami pattern consists of facets rotating around a crease and no deformation occurring on the facets. An origami pattern can be considered a mobile assembly of linkages by regarding the crease lines and the rigid panels as revolute joints and links, respectively [51, 52]. Mechanism theories were introduced to obtain the compatibility conditions for the design of rigid foldability and to carry out kinematic analysis of origami tubes [35, 41]. Multiple tubes can be connected to form rigid tubes with different sectional shapes [35] and to improve the stiffness of the structure (Fig. 3f) in the deployed configuration [50].

2D deployable structures can realize a large deployed/folded ratio in the (projected) area and do not change much in the third dimension, such as deployable ring structures for antennas [39, 40, 53–56] (Fig. 4a) and deployable solar arrays [6, 57]. Similar to 1D deployable structures, they can be classified into truss structures and plate structures. For rigid truss deployable structures, there are two design methods: the tessellation method and the mov-

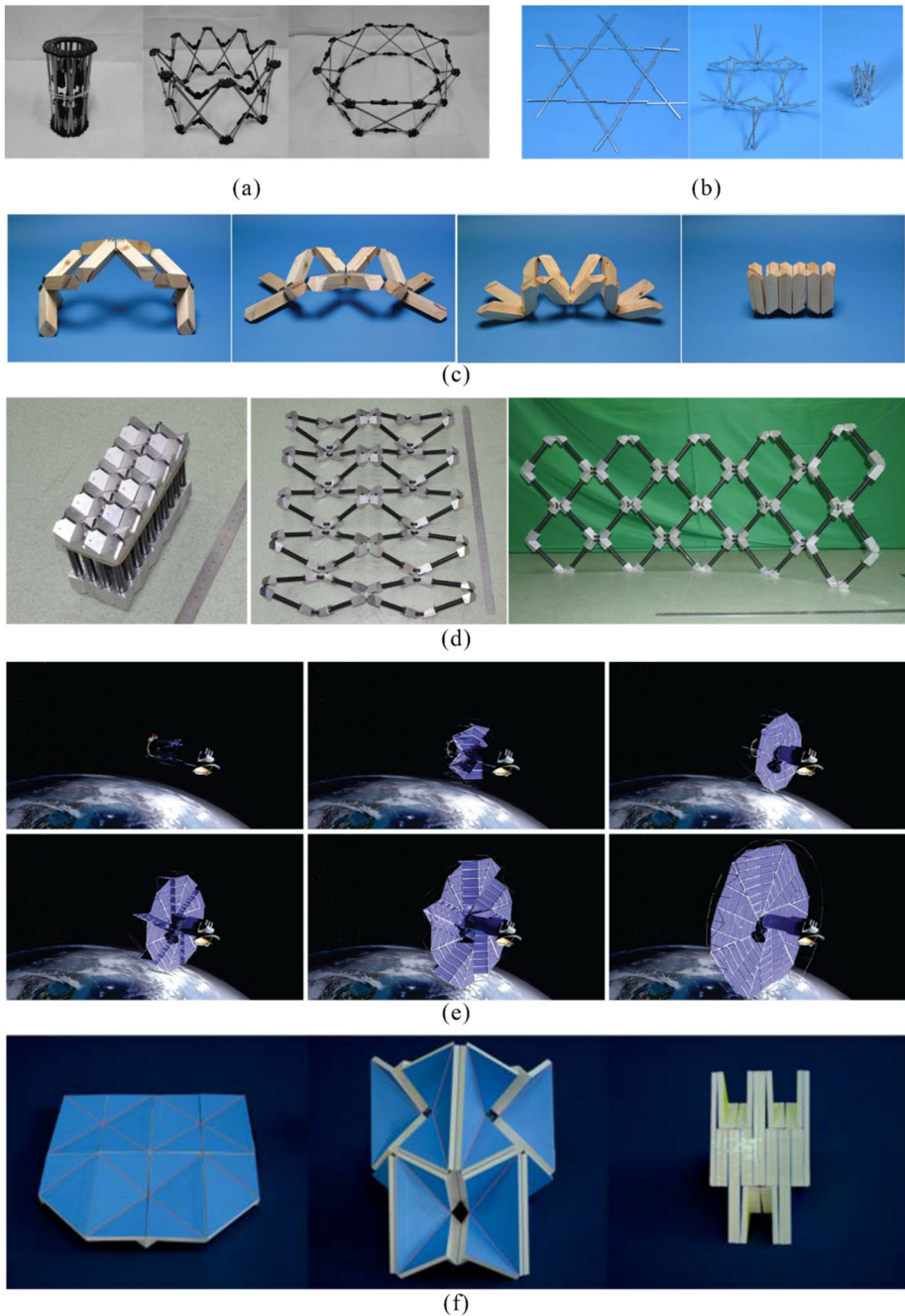


Fig. 4 2D rigid deployable structures. (a) A deployable ring structure based on scissor-like linkages [40], (b) a planar deployable structure based on threefold-symmetric Bricard linkages [38], (c) an arc deployable structure based on Bennett linkages [38], (d) a parabolic cylindrical deployable structure based on Bennett linkages [72], (e) origami-inspired solar arrays [6], and (f) a thick-panel origami structure with a flat deployed configuration [79]

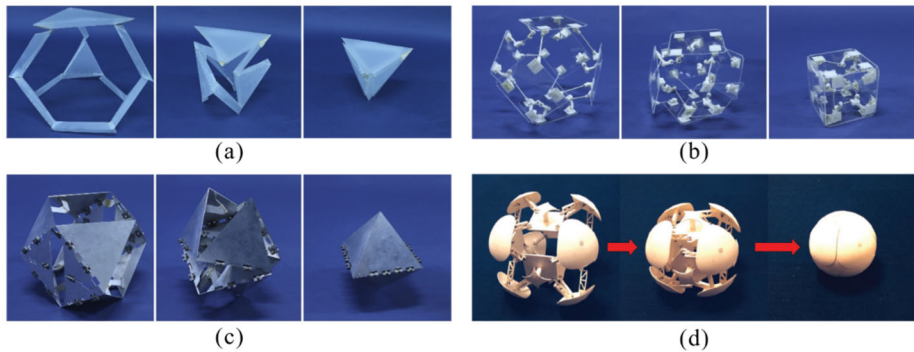


Fig. 5 3D rigid deployable structures. (a) A deployable polyhedron between a tetrahedron and a truncated tetrahedron based on Bricard linkages [83], (b) a deployable polyhedron between a truncated octahedron and a cube based on Bricard linkages [84], (c) a deployable polyhedron between a cuboctahedron and an octahedron based on Bennett linkages [84], and (d) a deployable Fulleroid-like structure [87]

able connection method. The tessellation method includes the selection of a suitable tiling, the construction of units using overconstrained linkages and validation of the compatibility [38, 58]. The movable connection method includes three connection schemes, common part-chain connections, common link connections and flexible connections, to connect deployable units [59]. According to the two methods, overconstrained linkages such as Bennett linkages [60, 61], Myard linkages [61, 62] and Bricard linkages (e.g., plan-symmetric Bricard linkages [63] and threefold-symmetric Bricard linkages [28, 64]) were regarded as unit mechanisms for assembling deployable structures with different deployed configurations such as planar [38, 65–69] (Fig. 4b), arc [38] (Fig. 4c), cylindrical [70], saddle [71] and parabolic cylindrical surfaces (Fig. 4d) [72]. However, most of them have not realized engineering applications due to their overconstraints improving the difficulty for manufacture and reducing the reliability for application. Meanwhile, scissor-like linkages are a type of famous unit that can be tessellated to design foldable shelters [73], stairs [74] and convertible roofs [17, 75]. To satisfy the requirements of deployable solar panels [6, 57, 76] and solid surface antennas [77, 78], a thick plate should be folded into a small volume with few panels. Zirbel constructs an origami-based deployable array using a membrane technique to construct a thick-panel flasher pattern with a deployed-to-stowed diameter ratio of 9.2 [6, 57] (Fig. 4e). Chen proposed the offset hinge technique to construct thick-panel origami and constructed a large family of deployable structures from typical origami patterns, such as the Miura-ori, the diamond, the waterbomb (Fig. 4f) and the hybrid thick-panel origami [79, 80], which has great potential in the design deployable structures with a large folding ratio. However, these deployable plate structures have stairs in the deployed configuration. Design of thick-panel origami with flat unfolded profiles would be more useful for deployable structures [81].

3D deployable structures consist of units that can expand with a large volume ratio, such as the Hoberman ball [82]. Due to the complex topology and inner constraints of 3D rigid deployable structures, the design of new types of structures with mobility is a challenge. Yang created three types of deployable polyhedrons by properly setting a movable joint at each vertex of polyhedrons and calculated their mobilities based on the truss method [83–85] (Fig. 5a–c). Wei proposed the virtual-center-based method for synthesizing deployable polyhedrons [86] and integrating an eight-bar linkage into a platonic polyhedron for constructing Fulleroid-like deployable structures under kinematic analysis with numerical

Table 1 Rigid deployable structures

	Morphology	Application/configuration	Unit mechanism/ origami pattern	Deployed/ folded ratio	DOF
1D rigid deployable structures	Truss structures with elements or lattices	A triangular mast [44]	Scissor-like linkage	1.41 m/0.078 m	1
		A self-lockable mast [47]	4-UU parallel mechanism	–	–
		A space telescope [48]	Sarrus linkage	0.3 m/0.08 m	–
	Plate structures	An origami shelter [41]	Origami tube	–	1
		A combination of two origami tubes [50]	Origami tubes	–	1
2D rigid deployable structures	Truss structures with elements or lattices	A deployable ring [40]	Scissor-like linkage	–	1
		A back structure for deployable panels [90]	Planar linkage	–	–
		An arc deployable structure [38]	Bennett linkage	–	1
		A parabolic cylindrical antenna [72]	Bennett linkage	–	1
	Plate structures	Origami-inspired solar arrays [6]	Flasher thick-panel origami	9.2	> 1
		Planar thick-panel origami [79]	Waterbomb pattern, diamond pattern, etc.	–	1
3D rigid deployable structures	Deployable polyhedron	A tetrahedron and a truncated tetrahedron [83]	Bricard linkage	23	1
		A truncated octahedron and a cube [84]	Bricard linkage	11.3	1
		A cuboctahedron and an octahedron [84]	Bennett linkage	5	1
		A Fulleroid-like structure [87]	Spatial eight-bar linkage	–	1
		One-DOF compactly foldable cubes [88]	Spherical linkage	–	1

simulations [87] (Fig. 5d). Gu constructed one-DOF compactly foldable cubes by introducing creases to square facets of origami cubes [88] and a thick-panel origami cube by using a plane-symmetric Bricard linkage to replace a spherical $4R$ linkage corresponding to a four-crease vertex [89].

Most rigid deployable structures have one DOF are summarised in Table 1. The above analysis shows that the research mainly focuses on 1D and 2D deployable structures for foldable masts, deployable antennas and solar panels. These rigid deployable structures consist of unit mechanisms derived from planar linkages and spatial linkages based on mobile tessellations [38, 59]. However, 3D deployable structures are difficult to ensure mobility with the two methods, due to the complex topology. Hence, a systemic design method for 3D deployable structures with movement to target deployed configurations should be proposed.

2.1.2 Flexible Deployable Structures

A flexible deployable structure consists of flexible elements, such as flexible rods, shells and thin membranes, which is suitable only for the one-time deployment cases. The flexible rods or shells can be folded in a small volume by external constraints and store potential energy with elastic deformations. When the external constraints are removed, the potential energy is released and the structure is deployed rapidly, which realizes self-deployment, the component-joint-drive integration, and the decrease of weight. Thin membranes have the advantage to be packaged in a very small volume to make lightweight deployable structures with an ultra-large deployed/folded ratio (high packing efficiency), which has been widely used to design ultra-large solar arrays [91] and solar sail [92] for deep space exploration. As deformations of flexible elements could generate material damage and reduce their lives, exploring reliable packaging schemes of flexible deployable structures for the predefined 1D-, 2D- and 3D-dimensional configurations with large deployed/folded ratios is the main research challenge of the structural design.

The typical 1D flexible deployable structures is based on the flexible rod, such as carbon-fibre-reinforced polymer (CFRP) helical antennas [93, 94] similar to spiral springs constructed (Fig. 6a), and a coilable longeron extendible mast [95, 96] twisted to buckle a longeron for folding (Fig. 6b). Flexible shells have two packaging schemes, coiling for tape springs and origami folding for nonrigid origami tubes. The former has been used to construct lightweight extendable booms (e.g., the boom in Fig. 6c) based on bistable shells [97, 98] and two cobonded omega-shaped carbon fibre half shells [1, 99], whose cross-section geometry is determined by shell theory and the maximum volume demand [99]. For the nonrigid origami tubes, such as Kresling patterns [100], star shape patterns [101] and Yoshimura patterns [102], has been used to design crawling robots [103, 104], protection drill shafts on the Mars Rover [105] (Fig. 6d), a sunshield for a space telescope [9] and inflatable mast [101] (Fig. 6e).

2D flexible deployable structures generally consisting of thin membranes can expand/fold with a large deployable ratio in area. There are two main packaging schemes, Miura-ori folding and wrapping. The Miura-ori pattern can be simultaneously deployed in two orthogonal directions, which has been applied in solar array for Space Flyer Unit (Fig. 7a) and rapid folding map [106]. The wrapping scheme winds a membrane around a hub and has two crease patterns: a wrapping crease pattern analysed by Pellegrino [107, 108] (Fig. 7b) and a flasher pattern invented by Shafer [109]. Comparing the two wrapping patterns, the height of the former in the folded configuration increases with deployment size, while that of the latter is approximately constant [110]. The latter has been used to fold a multifunctional deployable membrane for 3U CubeSat OrigamiSat-1 [91] (Fig. 7c). The family of wrapping origami inspired by organic patterns proposed by Nojima [111] have been selected to design conical spiral antennas [112]. Multiple membrane units wrapping to hubs can realize biaxial expansion (Fig. 7d) [113, 114]. Furthermore, packaging schemes with two stages of packaging for membranes were proposed, such as z-folding and symmetric wrapping scheme [115], folding and coiling scheme [116]. Meanwhile, most 3D flexible deployable structures are inflatable, such as balloons and airbags. They can be used to design large enclosed deployable surfaces, such as inflatable plug for sealing of rail tunnels [117] (Fig. 8), buffer devices for landing [118], inflatable reflector [110] and automotive airbags.

Table 2 indicates that flexible deployable structures have an ultra-large deployed/folded ratio, which can solve many problems regarding size and mass minimization. Finding efficient and reliable packaging schemes is still a challenge for the structural design of flexible

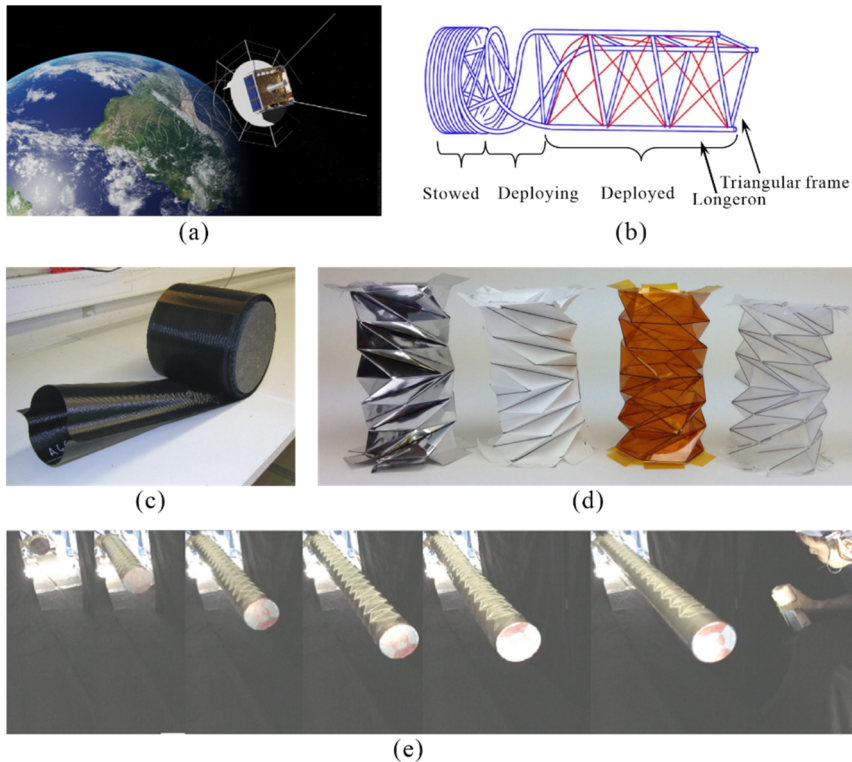


Fig. 6 1D flexible deployable structures. (a) AISat with a helical antenna in space [93], (b) a coilable longeron extendible mast [96], (c) a coiled carbon fibre boom [92], (d) Kresling fold patterns with different materials [105], and (e) an inflatable tube with star shape folding (this figure has been reprinted from [101] with a permission of the authors holding the copyright)

deployable structures. For 1D and 2D flexible deployable structures, multiple packaging schemes such as coiling, wrapping and origami folding methods are proposed. However, 3D flexible deployable structures with motions in three directions are rarely studied. The folding of 3D flexible deployable structure (undevelopable surfaces) is still being further studied for the applications, such as habitats on Mars and the Moon. As the thin membrane has low stiffness which affects the stiffness of the deployable structure, it will be a major challenge to apply a thin membrane for applications with high accuracy.

2.1.3 Rigid-Flexible Deployable Structures

Rigid-flexible deployable structures consist of rigid and flexible elements. They have high stiffness inherited from rigid elements, high flexibility and lightness acquired from the flexible elements, and a large folding rate creates a broad application space from aerospace to medical fields. Under the classification according to the dimensions, this kind of deployable structure can be classified into different subcategories according to the types of component elements: a rigid truss and flexible joints (compliant mechanisms), a rigid truss and flexible cables (e.g., tensegrity structures), a rigid deployable truss with flexible functional membranes or meshes.

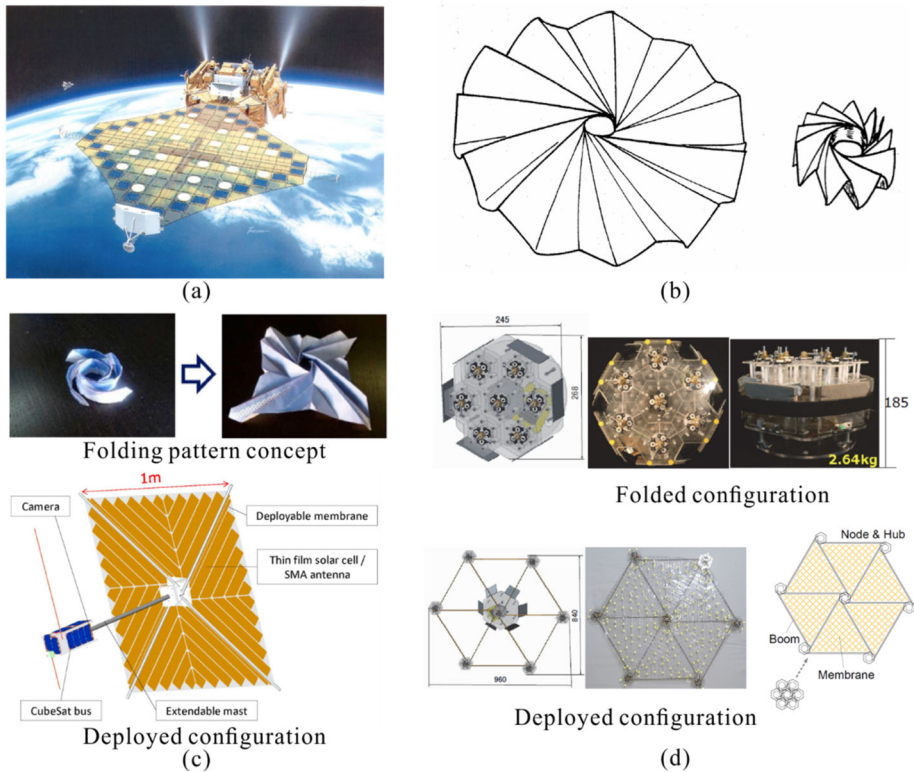


Fig. 7 2D flexible deployable structures. (a) The *Miura-ori* folding scheme for a solar array [106], (b) the wrapping crease pattern [108], (c) a deployable membrane based on a flasher pattern [91], and (d) the 2D deployment of membranes based on flexible booms coiled to hubs [114]

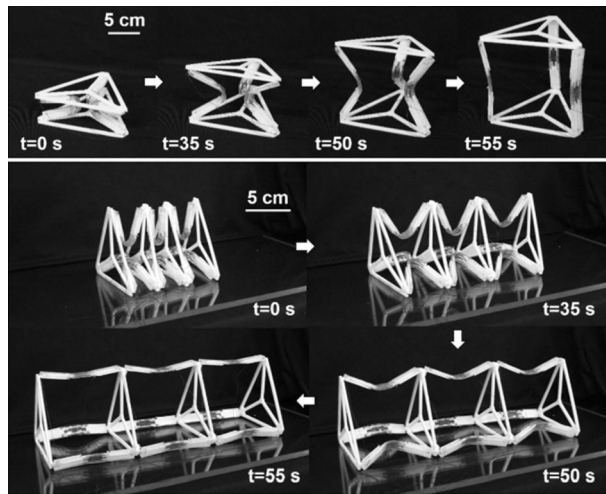
Most 1D rigid-flexible deployable structures are prism deployable masts consisting of rigid truss with flexible joints [119] or flexible cables [120]. The introduction of flexible joints can assist in driving the deployment of the truss structure. For example, Guo developed a triangular prism mast with tape-spring hyperelastic hinges arranged in the middle of a longitudinal link [119], and Wang constructed a triangular mast consisting of a rigid skeleton and smart joints [121] (Fig. 9). The combination of flexible cables and rigid links with the topology of three struts per stage was used to form deployable tensegrity masts [120]. When pretensioned cables are introduced to a rigid deployable truss structure, a cable-stiffened triangular pantographic mast can be constructed to improve the stiffness [122].

2D rigid-flexible deployable structures are generally 2D rigid deployable structures with flexible joints or flexible membranes or meshes attached [123]. The solar array inspired from Yoshimura origami (Fig. 10a) is composed of lattice support structure attached functional membranes and elastic hinges on the two central compression columns [124]. Two types of most applied rigid-flexible deployable reflectors are rigid deployable ring frameworks with reflective meshes [125] and umbrella-type rigid deployable structures with flexible membranes for reflectors [126]. A famous example of the former is the deployable *AstroMesh* reflector [125, 127] (Fig. 10b), which consists of a reflective mesh, cable nets, a tension tie array, and a ring-truss structure [128]. Multiple such modules can be connected to design large-scale deployable reflectors, such as the antenna on the Engineering Test Satellite VIII



Fig. 8 Inflatable Plug: Folding and packing sequence [117]

Fig. 9 A 1D deployable triangular mast consisting of a rigid skeleton and smart joints [121]



(ETS-VIII) satellite [129]. This type of deployable structure focus on the design of rigid deployable ring frameworks and the form-finding design of cable-mesh reflector. For the form-finding design, Morterolle proposed a method based on the force density strategy considering geometrical constraints [130] and Yang constructed an iterative design technique by combining surface stress density method and force density method [131]. Umbrella-type folding schemes have been used for deployable reflectors which are mainly composed of

Table 2 The flexible deployable structures

	Morphology	Application/configuration	Packaging scheme	Deployed/folded ratio
1D flexible deployable structures	Flexible rod	A CFRP helical antenna [94]	Coiling and compressing	4 m/0.1 m
		Extendible masts [95, 96]		–
	Flexible shell	Lightweight extendable booms [97, 98]	Coiling	–
The protection drill shafts on Mars Rover [105]		Origami pattern: Kresling pattern	–	
An inflatable mast based on Pentalpha folding [101]		Origami pattern: pentalpha folding	Deployed configuration: $\Phi 0.15 \text{ m} \times 2 \text{ m}$ [101]	
2D flexible deployable structures	Membrane	A solar array for Space Flyer Unit [106]	Miura-ori pattern	–
		Solar array and antenna for OrigamiSat-1 [91]	Wrapping scheme: flasher pattern	$1 \text{ m}^2/0.01 \text{ m}^2$ [91]
		Deployable spacecraft [116]	Folding and coiling	Deployed: $60 \text{ m} \times 60 \text{ m}$ Folded: $\Phi 1 \text{ m} \times 1.5 \text{ m}$
3D flexible deployable structures	Flexible membrane	The inflatable deployable reflector of Echo 1 [118]	–	Deployed configuration: 30 m -diameter sphere [110]
		An inflatable Plug [117]	Rolling or coiling	Deployed: 151.9 m^3

radial beams and flexible membranes [126, 132] (Fig. 10c). As some umbrella reflectors consist of cable net supported by radial beams, designing geometric topology and the internal tension of cable-net structure is necessary. For deployable umbrella reflectors, Tang developed several geometric-shape and internal-tension design methods for the double-layer cable-net structures (triangular, quadrilateral and wedge-shaped nets) [133]. A comparison of the two folding schemes for the deployable structure with the membrane shows that the AstroMesh type structures can obtain a large-scale deployed area with a slight change in the sizes in the folded configuration, while the umbrella-type structures need extended radial beam length, which affects the sizes in the folded configuration.

3D rigid-flexible deployable structures are mainly deployed to a space capsule with the focus of deployed/folded ratio in volume. The lunar habitat with a z-folding flexible partial tube [134] and the Bigelow Expandable Activity Module (BEAM) at the International Space Station [118] demonstrated space-deployable capsule technology. Hong designed deployable habitat modules based on flexible composite shells and deployable trusses consisting of two types of scissor-like elements [135]. Dronadula designed a hybrid lunar inflatable structure consists of rigid beams and flexible membranes [136] (Fig. 11). With the development of human habitats on planets, 3D rigid-flexible deployable structures would represent a research trend, where the compatibility of rigid and flexible elements should be considered.

The deployable structures mixed with rigid and flexible elements are summarised in Table 3 with a large number of application cases. However, most research was carried out on rigid structures and flexible elements separately, although there are many rigid deployable structures, few of which has the potential to be attached to membranes or networks. To construct new rigid-flexible deployable structures, the compatibility between the movement of rigid structures and the deformation of membranes or meshes for high accuracy is in urgent demands.

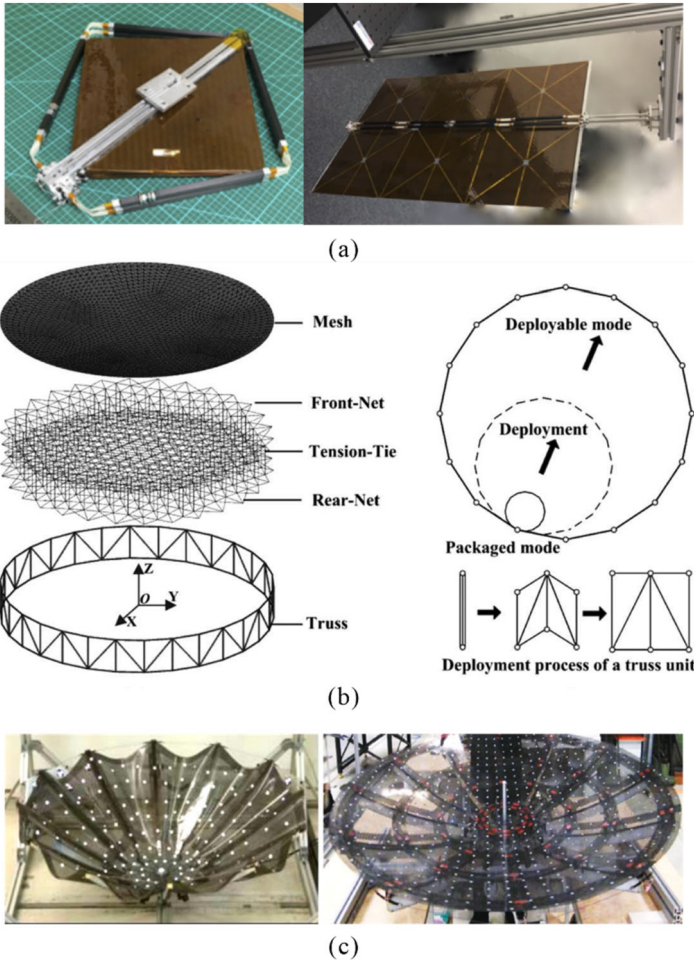


Fig. 10 2D rigid-flexible deployable structures. (a) A solar array based on the Yoshimura pattern with compliant hinges [124], (b) AstroMesh deployable mesh reflectors [125], and (c) an umbrella-type deployable structure [132]

Fig. 11 Fully deployed hybrid lunar inflatable structure with inflated and rigidized fabric dome [136]

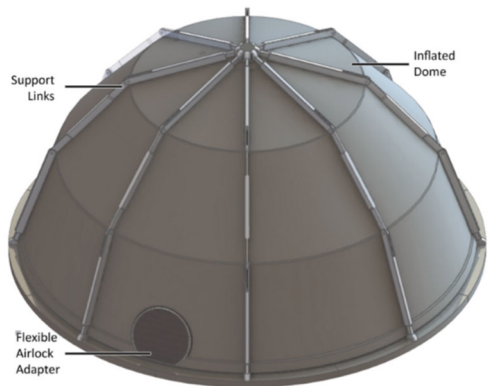


Table 3 Rigid-flexible deployable structures

	Morphology	Application/configuration	Components	Folding ratio
1D rigid-flexible deployable structures	1D rigid truss structure with flexible joints	Triangular mast [119]	1D rigid truss structure with tape-spring hinges	5.278 m/0.475 m
		Triangular mast [121]	1D rigid truss structure with smart joints	0.13 m/0.03 m
	1D rigid truss structure with flexible cables	A deployable tensegrity mast [120] Cable-stiffened deployable structures [122]	Tensegrity structure 1D rigid truss structure with pretensioned cables	Deployed height: 1.275 m Deployed height: 1.77 m
2D rigid-flexible deployable structures	2D rigid truss structure with flexible joints	Planar hexagonal deployable truss structure [123]	2D rigid truss structure with torsional-spring hinges	Deployed sizes: inscribed circle $\Phi 1.386$ m Stowed size: $0.2 \text{ m} \times 0.2 \text{ m}$ Ratio: 37.7
		Solar array [124]	Lattice support structure attached functional membranes	Deployed sizes: $0.52 \text{ m} \times 0.78 \text{ m}$ Stowed size: $0.2 \text{ m} \times 0.2 \text{ m}$ Ratio: 10.14
	2D rigid truss structure with flexible membranes or networks	AstroMesh reflector [128]	Deployable rigid ring frameworks with reflective mesh	Deployed size: $\Phi 6$ m
		Antenna reflector for the ETS-VIII satellite [129]		Deployed sizes: $19.2 \text{ m} \times 16.7 \text{ m}$ Stowed size: $\Phi 1$ m
		Structurally adaptive fibre-reinforced surface (SAFIRS) reflector [126]	Umbrella-type deployable structure with flexible shell-membrane	A scaled model with deployed size: $\Phi 1.6$ m
3D rigid-flexible deployable structures	Inflatable capsules	An expandable lunar habitat [134]	Two hard endcaps and a softgoods section	1.92
		The Bigelow Expandable Activity Module (BEAM) [118]	Two metal bulkheads, an aluminium structure, and multiple layers of soft fabric [137]	$16 \text{ m}^3/3.6 \text{ m}^3$

2.2 Deployment Actuation and Configuration Locking Schemes of Deployable Structures

After the structural design, the packaging scheme of a deployable structure is determined. Driving and locking are necessary functions for deployable structures to realize unfolding and to maintain the normal working configuration, which can be classified into three main modes: motor-cable-driven modes with mechanical locking devices (pin-type joints [43], latch spheres and grooves), spring-driven modes with self-locking, inflation-driven modes with work hardening or light curing, and combinations of these modes.

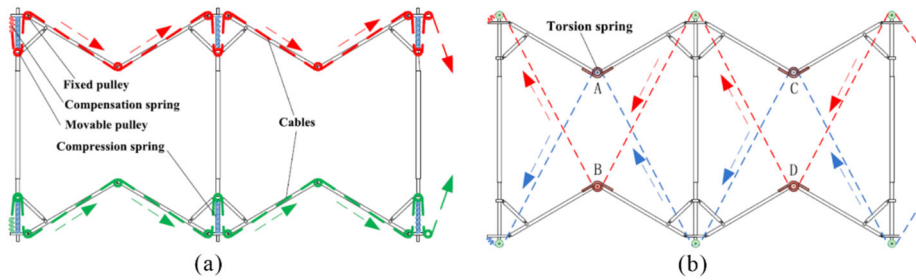


Fig. 12 The driving modes. (a) A motor-cable driven mode [53], (b) a spring-driven mode [53]

The motor-cable-driven mode is a common method for deploying rigid and rigid-flexible deployable structures with specially arranged motors and cables. Kam designed motors and two cables running over the hinges of a solar array with rigid panels in an accordion type structure and realized deployment and retraction [1]. Qi used a synchronization cable system to achieve the synchronous motion of sliders on the vertical rods of a ring-truss structure, and a cable drive mode was designed with compression springs to provide some driving resistance to protect the motor from overload and keep the tension on the cables [53, 138] (Fig. 12a). Tserodze used a motor-cable-driven mode based on the synchronization mechanism with a pair of gear wheels on the brackets and V-folding rods for a developable reflector [54]. After that, paired levers were introduced to the central joints of V-folding bars, which realized automatic fixation in the deployed configuration [56].

The spring-driven mode represents the deployment of structures that rely on elastic potential energy from the deformation of flexible elements, such as torsion springs in joints [123], taped springs [139] (elastic shells) on rods, and elastic rods in the deployable structure [96]. When the flexible elements are released, the structures are self-locked in the deployed configuration. Springs and anchors can be arranged with universal joints to drive the disk deployable structure of panels to realize self-deployment [77]. Qi used a spring-driven mode with torsion springs in joints for the deployment of a ring structure where two cables and a motor are introduced to control the deployment rate to avoid collisions from the influence of the torsion spring [53] (Fig. 12b). Flexible joints made of steel cables were designed by Bettini to store potential energy in a folded configuration and drive an antenna frame structure to the deployed configuration [140]. A coilable longeron extendible boom formed by bistable cylindrical shells can be deployed to a mast and wrapped to be a storage reel by a mechanical device consisting of a drive motor and rollers [141].

An inflation-driven mode is deploying structures by inflation, which is used for deployable structures with a closed cavity that consists of flexible membranes, such as flexible tubes, flexible capsules and rigid-flexible habitats. The deployed configuration can be locked by keeping the internal air pressure or self-hardening. Senda designed inflated tubes that are rigidized by work hardening in the deployed configuration [101]. Ronald proposed a carbon-reinforced isogrid inflatable boom that can be rigidized by UV [142].

Of the three driving and locking modes, the motor-cable driven mode and spring-driven mode can be independently or jointly applied to rigid and rigid-flexible deployable structures to drive and protect deployable systems. The inflation-driven mode is limited for flexible deployable structures, such as deployable masts and capsules. For the design of driving and locking modes, the topology, mobility and friction should be considered. For example, the arrangement of motors and cables requires comprehensive consideration of the DOFs of the deployable structure, as well as the resistance problem during deployable movement.

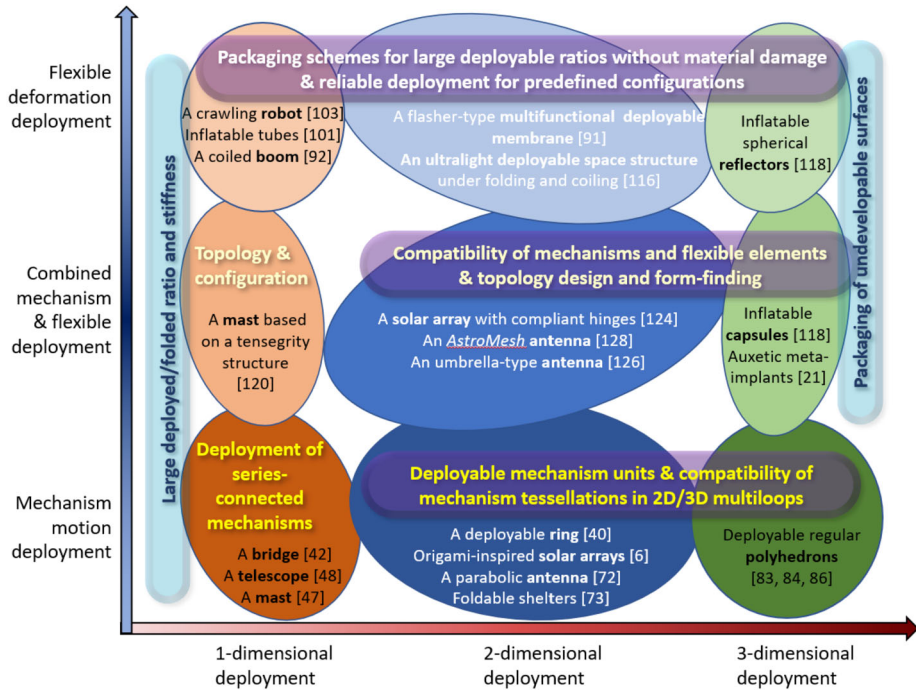


Fig. 13 Summary of the challenges in the structural design of deployable structures

Furthermore, optimization of the mode should be carried out for the static or dynamic performance of deployable structures.

2.3 Summary

From the above analysis, we can tell that the challenges in the design of deployable structures depend on the configurations, component properties and deployment operation process (Fig. 13). For deployable structures under mechanism motion deployment, 1D deployable structures focus on the deployment of series-connected mechanisms, while in 2D and 3D structures, the design of the deployable mechanism units and the realization of the compatibility of mechanism tessellations in 2D and 3D multiple loops have to be dealt with. Packaging schemes with large deployable ratios without material damage and reliable deployment for predefined configurations are the main tasks for deployable structures with flexible deformation deployment regardless of the dimensions. For the rigid-flexible deployable structures, the topology and configuration design should be considered for 1D case, while for 2D and 3D cases, the compatibility between the mechanism and flexible elements as well as topology design and form-finding should be considered. To obtain the advantages for functionalities, 1D deployable structures are expected to obtain a large deployed/folded ratio and stiffness, and 2D/3D deployable structures with flexible elements have to overcome the packaging of undevelopable surfaces.

Table 4 Static properties of deployable structures

Category	Performance evaluation	Deployable structures
Bearing capacity and stability	Strength	Solar panels/Sails, sunshields, deployable shipping container houses, deployable bridges, retractable roofs and domes, space capsules, airbags
	Stiffness	Deployable bridges, retractable roofs and domes, large space-deployable structures, minimally invasive surgery instruments
	Buckling resistance	Shelters, space deployable masts, large span roofs
Static deformation	Surface accuracy	Space antennas, space telescopes, phased array radars
	Shape retention	Space telescopes, radio telescopes, space antennas
	Shape adjustment	Morphing wings, morphing skin

3 Performance Analysis

After the functional configuration design is complete, performance analysis should be conducted to ensure the static and dynamic properties during deployment and in service. The static properties refer to not only the load-bearing capacities and stability depicted by stiffness, strength, and buckling resistance but also the surface accuracy under static loads, while the dynamic properties concern the deployment reliability, deployment speed, acceleration, inherent frequency, fatigue, etc.. These two aspects have to be considered simultaneously to achieve the successful performance of the deployable structures. In this section, they will be reviewed separately according to the theory and methodology.

3.1 Static Properties

The requirements for static properties vary with the applications (see Table 4), and the focus of static analysis and optimization design varies accordingly. For general deployable structures, more attention is given to their strength, stiffness, and buckling resistance under service loads.

3.1.1 Load-Bearing Capacity and Structural Stability

Generally, the geometrical configuration and material properties determine the failure modes. It is difficult to predict the governing failure mode before static analysis, so all three modes have to be considered in the design and analysis [143]. Unlike traditional structures, deployable structures can be transformed between a closed stage or compact configuration and a predetermined, stable expanded form. In some cases, the retraction ability may affect the load-bearing capacity and stability to some extent. When the applied service load exceeds the critical value but has not yet reached the yield limit, they will be destroyed due to instability, and its configuration and accuracy cannot be guaranteed [144]. Therefore, more attention should be given to the load-bearing capacity and stability. At present, relevant studies mainly concentrate on two aspects: modelling, analysis, and verification of the static performance for the determined configuration and design parameters; optimization of the parameters (geometric or material) with the objectives of good static properties for the determined topologies.

Analytical, numerical, and experimental methods are commonly used in static modelling and analysis. Analytical methods are based on the theory and methodologies of elastic mechanics and theoretical mechanics focusing on the modelling and analysis of the stiffness,

strength, and buckling characteristics under static loads. Schimmels [145] and Zhao [47] conducted stiffness matrix derivation of deployable structures. Raskin [146] studied the nonlinear characteristics of a uniform pantographic column in compression. Ge [147] formulated the local coil and helix mode's critical buckling forces of hingeless deployable mast structures based on the elastic stability theorem and Castigliano energy principle, respectively. Lyu [148] theoretically analysed the buckling modes of the folding articulated square truss mast (FASTmast) deployable structure and stiffness characteristics of the flex batten. Li [149] derived a stability model based on linear elastic analysis and the energy method to investigate the buckling load of a fully deployed linear array deployable structure under its weight. These methods can not only obtain the static characteristics of deployable structures with determined geometric and material parameters but can also be used to analyse the mapping relationship between the design parameters and static properties, which is essential for design and optimization. Although they can be easily applied to simple configurations, the derivation is quite complicated for structures with cables, membranes, or complex configurations with no apparent symmetry.

In contrast, numerical methods are relatively straightforward and easy to apply, especially for complicated deployable structures with cables and membranes. In recent decades, numerical methods have been widely applied to static analysis with the gradual improvement in computing abilities and the finite element analysis theory development. Song [150] evaluated the stability and capacity of a deployable structure composed of scissor composite members through numerical analysis using the finite element method (FEM). Vu [151] developed a finite element procedure using commutative algebra to analyse deployable tension-strut structures. Chen [152] presented a computational method for in situ finite element modelling of inflatable membrane structures based on geometrical shape measurements. Commercial FEM software is commonly used in the static analysis of deployable structures [153, 154]. Numerical methods are mostly used for structures with determined configurations, design parameters, and material properties, and they cannot directly reflect the correspondence between the design parameters and the structural static properties.

It should be pointed out that with the wide application of deployable structures in engineering, prototypes experimental methods and test technologies have become increasingly mature [155–157]. However, for space-deployable structures, there are still great challenges in ground tests, such as distributed gravity offload approaches, extreme temperature experiments, thermal vacuum environment simulations, and weak/zero magnetic environments.

The optimization design mainly includes optimal configuration selection, parameter and configuration optimization. Optimal configuration selection refers to selecting configurations that meet the load-bearing capacity and structural stability requirements through static analysis among several alternative designs [158]. Parameter optimization is usually conducted for deployable structures with the determined topology. The desired geometrical or material parameters are obtained through an optimization algorithm based on an optimization model aiming at static structural properties, such as stiffness, strength, and stability [159, 160]. Configuration optimization means optimization that starts from a reference configuration and takes the static performance as the goal. The configuration and design parameters are adjusted continuously according to the optimization results until the requirements for the static properties are met [161–163]. Both analytical and numerical methods can be applied in the optimization design. The difference is that the static models established by analytic methods are easy to combine with optimization algorithms to achieve parameter optimization [164, 165]. Numerical methods are mostly used in configuration selection and optimization. The correspondence between the design parameters and static performance can be established through the numerical fitting, and then parameter optimization can be

conducted [166]. Certainly, parameters can be optimized through a large number of iterations between design parameters and numerical calculation [160, 167, 168].

3.1.2 Surface Accuracy

Attention should be drawn to a type of special deployable structures with functional surfaces, which are required to form the desired shape in the deployed configuration and to maintain the shape under service loads. Thus, the surface accuracy of deployable structures that rely on the prescribed shape to achieve tasks is extremely important [169–171]. The shape deviations of these structures are mainly caused by design errors, manufacturing errors, assembly errors, and structural deformation due to service loads [172]. For Earth-based deployable structures, these shape deviations can be evaluated by measurement and decreased by adjustment methods. For space deployable structures, the shape errors caused by design, manufacture, and assembly can be measured and adjusted in ground tests [173–175]. While shape errors in service can be compensated only by preliminary design and analysis, there are currently no effective on-orbit adjustment methods [176, 177]. The relevant research mainly includes surface accuracy analysis, shape design, shape control, and adjustment.

The effects of various factors on the structural shape vary with configurations and service loads, and surface accuracy analysis should be conducted case by case [178]. Meguro [179] and Mehran [180] studied the surface precision degradation of mesh antennas due to cable length errors. Tibert [181], Hedgepeth [182], and Zong [172] investigated the effects of manufacturing errors on the surface accuracy of tensegrity antennas, geodesic domes, and mesh reflector antennas, respectively. Ding [183] and Nie [184] analysed the influences of joint clearances and flexibility on the shape precision of deployable panels and mesh reflector antennas. Ponomarev [185], Guo [125], Fang [186] and Lu [187] analysed the influences of thermal deformation on the surface accuracy of space antennas. For deployable structures consisting of bars and hinges, the influences of design errors on the surface accuracy are small, and the research mainly focuses on measurement and adjustment methods [188, 189], as well as static deformation and surface accuracy analysis [182, 190]. For deployable structures containing cables and membranes, the key to ensuring surface accuracy is to control design errors within a certain range. Due to the strong geometric nonlinearity of cables and membranes, the shape and the internal force distribution cannot be dealt with as separate issues, and the shape is heavily dependent on the forces and vice versa. Therefore, for these form-active structures, finding a shape that is in (or approximates) a state of static equilibrium, called form-finding, plays an essential role in surface accuracy analysis [191]. Enormous efforts have been made on the form-finding of cable and membrane structures [192], and these methods can be divided into stiffness matrix methods, geometric stiffness methods, and dynamic equilibrium methods [191]; see Table 5. Stiffness matrix methods include unnecessary material properties, which are computationally costly and may lead to difficult convergence. Geometric stiffness methods applied in their linear form produce results that are not constructionally practicable and can serve only as a preliminary result [191]. Dynamic equilibrium methods require many parameters to control stability and convergence.

Shape design is conducted to obtain desired shapes or surfaces in service. For deployable structures composed of bars and hinges, the required shapes can be achieved basically by geometric structural design [202–204]. For deployable structures containing cables or membranes, pretension design is indispensable [205, 206], and optimization and iterations are generally involved in these processes. Optimization models are established that take the desired shapes in equilibrium states as objectives, and then the design parameters are obtained through optimization algorithms [184, 207–209]. The iterative method modifies the

Table 5 A summary of form-finding methods

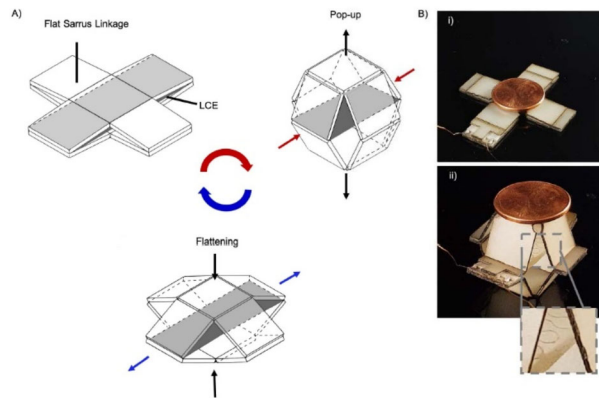
Category	Methods	Literature
Stiffness matrix methods	Stiffness matrix (SM) method Natural shape finding (NSF)	Siev and Eidelman, 1964 [193] Argyris, 1974 [194]
Geometric stiffness methods	Force density method (FDM) Geometric stiffness method (GSM) Updated reference strategy (URS) Multistep FDM Natural FDM	Linkwitz and Schek, 1971 [195] Haber and Abel, 1982 [196] Bletzinger and Ramm, 1999 [197] Sánchez, 2007 [198] Pauletti and Pimenta, 2008 [199]
Dynamic equilibrium methods	Dynamic relaxation (DR) Particle spring (PS) system	Barnes, 1977 [200] Kilian and Ochsendorf, 2005 [201]

design parameters according to the residuals of the adjacent iteration steps (form-finding) to achieve the required shapes [210–213]. As cables and membranes are mainly supported by deployable structures, small deformation of supporting frames may lead to large influences on the equilibrium forms of cables and membranes due to their high geometric nonlinearity [184, 210–212]. Thus, research on cables and membranes with flexible supports has been conducted [214]. The optimization methods considering the influences of error uncertainty on the surface accuracy have been developed to improve the surface accuracy [172, 215]. On-orbit thermal deformation is also considered in the optimization design to ensure high shape retention in space environments [177, 216, 217].

The shape of deployable structures may be affected by fabricating errors and assembly misalignments, so these structures are deliberately designed to be adjustable by changing the length of the support links or cables to obtain a high surface accuracy. Many studies are presented to provide concrete resizing suggestions for shape adjustment. Mitsugi [170] and Tanaka [171] utilized Monte Carlo simulation and the direct mode method to conduct shape control and adjustment. Du [218, 219] and Zhao [189] took the shape adjustment of mesh reflector antennas and planar closed-loop overconstrained deployable structures as optimization problems and used sequential quadratic programming and an improved successive Taguchi approach to solve the problem. Yoon performed shape control of reconfigurable reflector antennas as unconstrained minimization problems and used the analytical method to obtain solutions [220]. Zhang [221] proposed a shape control algorithm based on the pseudoinverse of the sensitivity matrix. In addition to fabrication and assembly errors, static deformation under service loads affects the surface accuracy in service. Researchers carried out shape adjustment investigations to compensate for the shape deviations caused by static deformation in service environments. Tabata et al. [222] conducted active shape adjustment with limited information on the surface shape and a limited number of actuators. Tanaka [223] introduced a surface adjustment mechanism for reconfigurable antenna systems to estimate and correct surface errors. Wang [224, 225] and Xun [226] studied the active shape adjustment method for cable network antennas by introducing piezoelectric (PZT) actuators.

Above all, the surface accuracy of deployable structures in service can be effectively ensured by surface accuracy analysis, shape design, control, and adjustment. However, for space-deployable structures, due to the limitations of on-orbit measurement and control techniques, on-orbit monitoring and adjustment are still in the theoretical stages and cannot be applied in engineering. At present, surface accuracy is still ensured by preliminary design, analysis, and adjustment on Earth.

Fig. 14 Reversible self-folding of the Sarrus linkage mechanism with a LCE actuator [234]



3.2 Dynamic Properties

The dynamics of deployable structures include deployment dynamics and structural dynamics. Deployment should generally be smooth, stable, and controllable. Damage caused by a sudden change in load at the end of deployment should be avoided. In the deployed configuration, vibrations under service loads should be controlled within the allowable range, and resonance with external excitations is not permitted.

3.2.1 Deployment Dynamics

Deployment is related to the success of services, and deployment studies have mainly concentrated on two aspects. The first aspect is deployment reliability, that is, the study of whether the mechanism can be deployed successfully and reliably. The other is the analysis and control of the dynamic behaviour. Whether deployable structures can be deployed successfully and smoothly is the key to configuration design and is related to deployment analysis. Therefore, research on deployment reliability is indispensable for newly designed configurations. Generally, dynamic simulations by commercial software [227–229] and prototype experiments [230, 231] are usually used to analyse and verify deployment. In recent years, smart materials, such as shape memory alloys, shape memory polymers, liquid crystal elastomers, and optical/electric/magnetic driven materials, have been increasingly applied in deployable structures [232, 233]. Figure 14 shows a reversible actuation for self-folding modular machines using liquid crystal elastomer [234]. Figure 15 shows a shape memory composite structure for self-deployable solar sails [235]. Figure 16 is a kirigami/origami-based soft deployable reflector for optical beam steering [236]. For these structures that rely on smart materials to unfold, although commercial software and numerical simulation can be used to analyse the deployment, prototype experiments are still required to further verify the deployment capacity and reliability due to the lack of accurate and robust models at present.

Deployment is a complex transition process from a mechanism to a structure, during which the performance estimate is important. The complexity has motivated a large number of studies on deployment modelling, analysis, and control to achieve the desired deployment process. Bars and hinges are assumed to be rigid bodies to simplify the modelling and analysis in some cases [145, 237–239]. However, elastic vibration, component deformation, asynchronous deployment, etc., may be ignored due to the rigid body assumption.

Fig. 15 Manufacturing and shape recovery of small laboratory-scale sail prototypes [235]

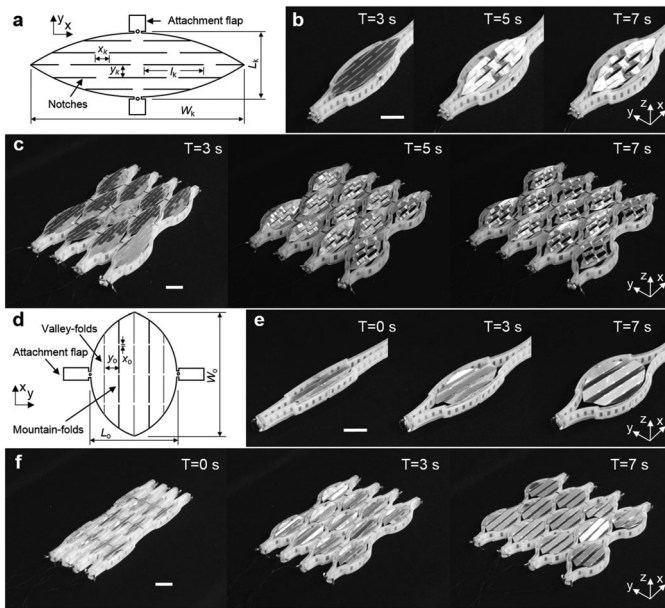
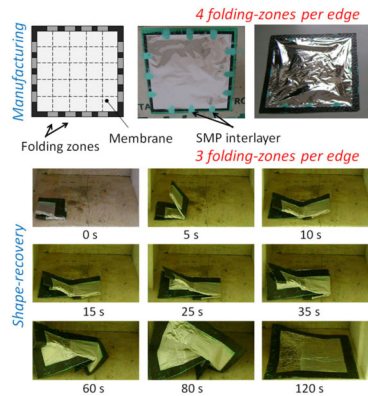


Fig. 16 Soft deployable reflectors. (a) The cut shape and pattern of kirigami reflective films, (b) the deployment process of an assembly composed of two soft actuators and one kirigami reflective film, (c) the deployment process of an extended kirigami reflector, (d) the cut shape and folding pattern of origami reflective films, (e) the deployment process of an assembly composed of two soft actuators and one origami reflective film, (f) the deployment process of the extended origami reflector. Scale bars: 30 mm [236]

Figure 17 shows the differences between the rigid and flexible models for the deployment of an AstroMesh. The rigid model cannot capture asynchronous deployment. Thus, flexible multibody dynamics and rigid-flexible coupling dynamics methods are investigated to accurately forecast the dynamic features during deployment [240–243]. Deployable structures usually contain large numbers of hinges, and the friction [244], damping [245], clearance [246–248], and hysteresis [249] of the hinges affect the deployment dynamics. Thus, hinge dynamics were studied to capture the dynamic behaviours of deployable structures during deployment accurately. The deployment studies of cables and membranes have increased

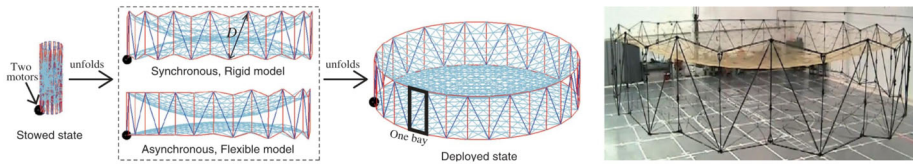


Fig. 17 Representations of (a) two different types of deployment processes of AstroMesh and (b) the asynchronous deployment of a 12 m AstroMesh (courtesy of Astro Aerospace) [240]

gradually with their wide application in deployable structures. The control volume (CV) method [250, 251], corpuscular (CP) method [252, 253], coupled fluid structure approach [254], comparative finite element method [255], and experimental methods were used to study the inflation of thin membrane structures. In the deployment of cables, the generalized inverse method [256], catenary elements [257], quasi-static analysis [258], etc., were utilized to model and analyse the whole process.

Besides the dynamics modelling and analysis above, structural design, such as installing auxiliary springs [241], designing time-controlled spring-driven hinges [259] or other braking systems [260], optimizing driving modes, and conducting optimal control [261], are effective ways to achieve a smooth and stable unfolding process. However, overall, accurately capturing the dynamic behaviours of deployable structures is still a key problem for deployment modelling, analysis, and control.

3.2.2 Structural Dynamics

As deployable structures mainly work in the deployed configuration, the structural dynamic performance is related to the accuracy and reliability in service. Thus, the structural dynamic characteristics are investigated to avoid vibration, resonance, loss of precision, and component damage under service loads.

Dynamic modelling and analysis are essential for ensuring the dynamic properties under service loads. Noor presented the equivalent continuum model and analysed the dynamics of beamlike and platelike structures [262]. Salehian presented a homogenization method for the dynamic analysis of truss structures motivated by large satellite applications [263]. Guo established an equivalent dynamic model of a beamlike space-deployable mast considering the mass of the joints and latch mechanisms [264]. These are analytical methods with complex derivations. The FEM is commonly used in structural dynamics analysis and is easy to conduct [265–267]. However, the FEM is a numerical algorithm and does not directly reflect the correspondence between structural parameters and dynamic performance. When used to analyse the influence of various factors on the structural dynamics, it is necessary to discretize the variables and to carry out several calculations. Therefore, the analytical method is more effective when nonlinear effects are apparent or when dealing with dynamic problems with continuously varying parameters, such as the effects of hinge friction, damping, and clearance on the structural dynamics [248, 268, 269]. For space-deployable structures used in aerospace engineering, temperature saltation may occur because of the heat flux from solar radiation, which leads to thermally induced vibrations [270, 271]. The decoupling method was first used in the thermally induced dynamics of deployable structures for simplification [272], and currently, coupled thermostructural modelling and analysis for space-deployable structures are developing [273]. Besides the above dynamic modelling and analysis, parameter optimization aimed at structural dynamic properties is an effective way to achieve good dynamic performance [274]. Numerous studies have been conducted

to eliminate vibration induced by nondestructive impacts, and various passive, active, and semiactive methods have been presented for different deployable structures [275]. These dynamic modelling, analysis, optimization, and vibration control methods help to ensure the dynamic performance of deployable structures in service.

Experimental methods are commonly used to test and verify dynamic characteristics. The experimental identification of the nonlinear dynamics of joints is well developed [276], and the link between nonlinear joint behaviour and the global dynamic response has been well documented [277]. However, to date, most attempts to link nonlinearities at the component level with overall dynamic behaviour have had only limited success [122]. In order to gain a thorough and accurate insight into the structural dynamic properties of deployable structures, prototypes were made, and vibration modal experiments and modal analysis were conducted for various configurations. Tan studied the nonlinear vibration of cable-stiffened pantographic deployable structures and conducted preliminary broadband modal tests to determine the natural frequencies and mode shapes [122]. Siriguleng investigated vibration modal experiments and modal interactions for a large space-deployable antenna with a ring-truss structure [278]. Wei conducted modal analysis and identification of deployable membrane structures [279].

For current and future precision space structures, the vibration environment must be known and controlled down to the nanometre level. Warren [280] and Moser [281] studied the submicron mechanical stability and microdynamic events of deployable optical structures through experiments. Ingham conducted microdynamic modal parameter characterization experiments for deployable space structures [282]. The signal processing methods for extracting weak transient signals from vibration experiments on deployable structures have been investigated [283–285]. With the demand for highly accurate and reliable deployable structures in the future, vibration modal experiments are required to be more precise, which creates new challenges for the corresponding tests and signal processing.

3.3 Summary

The main task of performance analysis is to ensure the static and dynamic properties of deployable structures during the deployment process and in the deployed state. The challenges for the performance analysis of deployable structures depend on the application conditions, performance requirements, and component properties (Fig. 18). Most deployable structures work in the deployed configuration, and the stiffness, strength, and buckling resistance under static loads are basic requirements. Thus, for general deployable structures, the key to static analysis is to provide quick and effective evaluation and feedback about the load-bearing capacity and stability for structural design. For deployable structures with functional surfaces, the design methodology for achieving high surface accuracy under service loads is the core problem to be solved. The dynamic performances of deployable structures concern reliable deployment and safe operation under dynamic loads. The deployment dynamics focus on accurate dynamic behaviour evaluation and driving scheme design for smooth, stable, and controllable deployment. The structural dynamics deal with the accurate structural dynamic performance analysis under dynamic loads and the effective dynamic characteristic tests under working conditions.

4 Future Work

In conclusion, with the wide application of deployable structures in engineering, scholars have carried out intensive and extensive studies on design and analysis and formed systematic theories and methods on structural design, statics and dynamics analysis. However,

Fig. 18 Summary of the challenges in the performance analysis of deployable structures

Statics	
<p><i>Quick and effective evaluation and feedback of load-bearing capacity and stability for structural design</i></p>	<p><i>Design methodology for achieving high surface accuracy under service loads</i></p>
<ul style="list-style-type: none"> • Static modelling and analysis Analytical methods [125–129], numerical methods [130–134], experimental methods [135–137] • Static optimization Optimal configuration selection [138], parameters optimization [139–140], configuration optimization [141–143] 	<ul style="list-style-type: none"> • Surface accuracy analysis Stiffness matrix methods [173–174], geometric stiffness methods [175–179], dynamic equilibrium methods [180–181] • Shape design Optimization method [187–189], iteration [190–193] • Shape control/adjustment Monte Carlo simulation [150], optimization method [198–199], sensitivity matrix method [201]
Dynamics	
<p><i>Driving scheme for smooth, stable, and controllable deployment & accurate dynamic behaviour evaluation</i></p>	<p><i>Accurate structural dynamic performance analysis under dynamic loads & effective dynamic characteristic tests under working conditions</i></p>
<ul style="list-style-type: none"> • Deployment reliability Dynamic simulation [207–209], prototype experiments [210–211] • Deployment behaviour analysis Multibody dynamics [220], rigid-flexible coupling dynamics [221–223] • Deployment process control Structural design for deployment control [239–240], control optimization [241] 	<ul style="list-style-type: none"> • Structural dynamic modelling/analysis/optimization FEM [245–247], thermostructural modelling and analysis method [252–253] • Dynamic characteristic tests Vibration modal experiments [258], modal identification and analysis [259] • Vibration control [260–261]

at present, structural design and performance analysis are usually independent. Combining them effectively to design structures with optimal performance and to achieve the integrated design of structure-function-performance is a prospective challenge.

Rigid skeletons and flexible skins are increasingly combined to design lightweight deployable structures with high rigidity. Realizing coordinated motion without interference between the rigid and flexible components and realizing the coupling effects in the deployment and deployed configurations are still significant tasks to be solved. Further breakthroughs are still required in the design and analysis of cables and membranes, such as efficient and orderly folding and unfolding, shape forming and retention, accurate modelling, distributed gravity offload, modal analysis, and tests.

In the near future, space-deployable structures with ultra-large folding ratio are urgently required to further explore and utilize cosmic resources, which poses great challenges in designing 3D deployable structures with reliable performances. Meanwhile, micro-deployable structures are being developed for high accuracy and reliability to apply in miniature ultra-precision medical devices, microsattellites, etc. Deployable structures with multiple folding

and unfolding modes are in great demand for multi-task application scenarios. The integration of structure and function will be achieved with the further development of novel smart materials, which leads to a multi-disciplinary research.

Acknowledgements The authors acknowledge the support of the National Natural Science Foundation of China (Projects 51825503, 51721003, 52035008, 52105032, 52175027, 52175242).

Author Contribution Xiao Zhang and Rui Nie contributed equally to this work.

References

1. Pellegrino, S.: Deployable Structures. Springer, Italy (2014)
2. Gruber, P., Häuplik, S., Imhof, B., Özdemir, K., Waclavicek, R., Perino, M.A.: Deployable structures for a human lunar base. *Acta Astronaut.* **61**, 484–495 (2007)
3. Lee, N., Backes, P., Burdick, J., Pellegrino, S., Fuller, C., Hogstrom, K., Kennedy, B., Kim, J., Mukherjee, R., Seubert, C., Wu, Y.: Architecture for in-space robotic assembly of a modular space telescope. *J. Astron. Telesc. Instrum. Syst.* **2**, 041207 (2016)
4. You, Z.: Deployable structure of curved profile for space antennas. *J. Aerosp. Eng.* **13**, 139–143 (2000)
5. Nassehpour, S., Kwan, A.S.K.: New concepts in large deployable parabolic solid reflectors. In: Proceedings of the AECEF Symposium, pp. 162–171. Vilnius Gediminas Technical University, Department of Construction Economics & Property, Vilnius (2008)
6. Zirbel, S.A., Lang, R.J., Thomson, M.W., Sigel, D.A., Walkemeyer, P.E., Trease, B.P., Magleby, S.P., Howell, L.L.: Accommodating thickness in origami-based deployable arrays. *J. Mech. Des.* **135**, 111005 (2013)
7. Murphy, D.M., Eskenazi, M.I., McEachen, M.E., Spink, J.W.: Ultraflex and megaflex-development of highly scalable solar power. In: 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC), pp. 1–8. IEEE, New Orleans (2015)
8. Johnson, L., Whorton, M., Heaton, A., Pinson, R., Laue, G., Adams, C.: NanoSail-D: a solar sail demonstration mission. *Acta Astronaut.* **68**, 571–575 (2011)
9. Wilson, L., Pellegrino, S., Danner, R.: Origami sunshield concepts for space telescopes. In: The 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, p. 1594. AIAA, Boston (2013)
10. Doroftei, I.A., Bujoreanu, C., Doroftei, I.: An overview on the applications of mechanisms in architecture. Part I: bar structures. In: The 8th International Conference on Advanced Concepts in Mechanical Engineering, p. 052018. IOP Publishing, Bristol (2018)
11. Doroftei, I.A., Bujoreanu, C., Doroftei, I.: An overview on the applications of mechanisms in architecture. Part II: foldable plate structures. In: The 8th International Conference on Advanced Concepts in Mechanical Engineering, p. 052019. IOP Publishing, Bristol (2018)
12. Lee, T.U., Gattas, J.M.: Geometric design and construction of structurally stabilized accordion shelters. *J. Mech. Robot.* **8**, 031009 (2016)
13. De Temmerman, I.A.N., Mollaert, M., Van Mele, I.A.T., De Laet, I.A.L.: Design and analysis of a foldable mobile shelter system. *Int. J. Space Struct.* **22**, 161–168 (2007)
14. Liu, X., Gattas, J.M., Chen, Y.: One-DOF superimposed rigid origami with multiple states. *Sci. Rep.* **6**, 36883 (2016)
15. Chikahiro, Y., Ario, I., Pawlowski, P., Graczykowski, C., Nakazawa, M., Holnicki-Szulc, J., Ono, S.: Dynamics of the scissors-type mobile bridge. *Proc. Eng.* **199**, 2919–2924 (2017)
16. Zhu, L., Zhang, D., Shao, F., Xu, Q., Zhao, Q.: Structural evaluation of torsional rigidity of new FRP-aluminum space truss bridge with rigid transverse braces. *KSCE J. Civ. Eng.* **23**, 3021–3029 (2019)
17. Kassabian, P., You, Z., Pellegrino, S.: Retractable roof structures. *Proc. Inst. Civ. Eng. Struct. Build.* **134**, 45–56 (1999)
18. Ozaki, Y., Violaris, A.G., Serruys, P.W.: New stent technologies. *Prog. Cardiovasc. Dis.* **39**, 129–140 (1996)
19. Duda, S.H., Wiskirchen, J., Tepe, G., Bitzer, M., Kaulich, T.W., Stoeckel, D., Claussen, C.D.: Physical properties of endovascular stents: an experimental comparison. *J. Vasc. Interv. Radiol.* **11**, 645–654 (2000)
20. Kuribayashi, K., Tsuchiya, K., You, Z., Tomus, D., Umamoto, M., Ito, T., Sasaki, M.: Self-deployable origami stent grafts as a biomedical application of Ni-rich TiNi shape memory alloy foil. *Mater. Sci. Eng. A* **419**, 131–137 (2006)

21. Bobbert, F.S.L., Janbaz, S., Zadpoor, A.A.: Towards deployable meta-implants. *J. Mater. Chem. B* **6**, 3449–3455 (2018)
22. Edmondson, B.J., Bowen, L.A., Grames, C.L., Magleby, S.P., Howell, L.L., Bateman, T.C.: Oriceps: origami-inspired forceps. In: *ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, p. V001T01A027. ASME, Utah (2013)
23. Miyashita, S., Guitron, S., Li, S., Rus, D.: Robotic metamorphosis by origami exoskeletons. *Sci. Robot.* **2**, eaao4369 (2017)
24. Lee, D.Y., Kim, J.S., Kim, S.R., Koh, J.S., Cho, K.J.: The deformable wheel robot using magic-ball origami structure. In: *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, p. V06BT07A040. ASME, Portland (2013)
25. Banerjee, H., Pusalkar, N., Ren, H.: Single-motor controlled tendon-driven peristaltic soft origami robot. *J. Mech. Robot.* **10**, 064501 (2018)
26. <https://spaceflightnow.com/news/n0403/29mbsat/>. Accessed 16 May 2021
27. Zhang, X., Chen, Y.: Mobile assemblies of Bennett linkages from four-crease origami patterns. *Proc. Math. Phys. Eng. Sci.* **474**, 20170621 (2018)
28. Chen, Y., You, Z., Tarnai, T.: Threefold-symmetric Bricard linkages for deployable structures. *Int. J. Solids Struct.* **42**, 2287–2301 (2005)
29. Chen, Y., You, Z.: An extended Myard linkage and its derived 6R linkage. *J. Mech. Des.* **130**, 052301 (2008)
30. Chen, Y., You, Z.: Two-fold symmetrical 6R foldable frame and its bifurcations. *Int. J. Solids Struct.* **46**, 4504–4514 (2009)
31. Huang, H., Li, B., Zhu, J., Qi, X.: A new family of Bricard-derived deployable mechanisms. *J. Mech. Robot.* **8**, 034503 (2016)
32. Cao, W.A., Yang, D., Ding, H.: A new family of deployable mechanisms derived from two-layer and two-loop spatial linkages with five revolute pair coupling chains. *J. Mech. Robot.* **9**, 061016 (2017)
33. Gattas, J.M., Wu, W., You, Z.: Miura-base rigid origami: parameterizations of first-level derivative and piecewise geometries. *J. Mech. Des.* **135**, 111011 (2013)
34. Liu, S., Chen, Y., Lu, G.: The rigid origami patterns for flat surface. In: *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, p. V06BT07A039. ASME, Portland (2013)
35. Chen, Y., Lv, W., Li, J., You, Z.: An extended family of rigidly foldable origami tubes. *J. Mech. Robot.* **9**, 021002 (2017)
36. Feng, H.J., Peng, R., Ma, J.Y., Chen, Y.: Rigid foldability of generalized triangle twist origami pattern and its derived 6R linkages. *J. Mech. Robot.* **10**, 051003 (2018)
37. Wang, R., Sun, J., Dai, J.S.: Design analysis and type synthesis of a petal-inspired space deployable-foldable mechanism. *Mech. Mach. Theory* **141**, 151–170 (2019)
38. You, Z., Chen, Y.: *Motion Structures: Deployable Structural Assemblies of Mechanisms*. Spon Press, New York (2014)
39. Han, B., Xu, Y., Yao, J., Zheng, D., Guo, X., Zhao, Y.: Configuration synthesis of hoop truss deployable mechanisms for space antenna based on screw theory. *AIP Adv.* **9**, 085201 (2019)
40. Han, B., Xu, Y., Yao, J., Zheng, D., Guo, L., Zhao, Y.: Type synthesis of deployable mechanisms for ring truss antenna based on constraint-synthesis method. *Chin. J. Aeronaut.* **33**, 2445–2460 (2020)
41. Liu, S., Lv, W., Chen, Y., Lu, G.: Deployable prismatic structures with rigid origami patterns. *J. Mech. Robot.* **8**, 031002 (2016)
42. Ario, I., Nakazawa, M., Tanaka, Y., Tanikura, I., Ono, S.: Development of a prototype deployable bridge based on origami skill. *Autom. Constr.* **32**, 104–111 (2013)
43. <https://www.northropgrumman.com/space-old/astro-aerospace-products-telescopic-tube-masts/>. Accessed 16 May 2021
44. You, Z., Pellegrino, S.: Cable-stiffened pantographic deployable structures part I-triangular mast. *AIAA J.* **34**, 813–820 (1996)
45. Kim, T.H., Suh, J.E., Han, J.H.: Deployable truss structure with flat-form storability using scissor-like elements. *Mech. Mach. Theory* **159**, 104252 (2021)
46. Lu, S., Zlatanov, D., Ding, X., Molfino, R.: A new family of deployable mechanisms based on the Hoekens linkage. *Mech. Mach. Theory* **73**, 130–153 (2014)
47. Zhao, L., Wang, H., Chen, G., Huang, S.: Sequentially assembled reconfigurable extended joints: self-lockable deployable structure. *J. Aerosp. Eng.* **31**, 04018103 (2018)
48. Choi, J., Lee, D., Hwang, K., Kim, B.: Design, fabrication, and evaluation of a passive deployment mechanism for deployable space telescope. *Adv. Mech. Eng.* **11**, 1–14 (2019)
49. Mousanezhad, D., Kamrava, S., Vaziri, A.: Origami-based building blocks for modular construction of foldable structures. *Sci. Rep.* **7**, 1–8 (2017)

50. Filipov, E.T., Tachi, T., Paulino, G.H.: Origami tubes assembled into stiff, yet reconfigurable structures and metamaterials. *Proc. Natl. Acad. Sci. USA* **112**, 12321–12326 (2015)
51. Dai, J.S., Rees Jones, J.: Mobility in metamorphic mechanisms of foldable/erectable kinds. *J. Mech. Des.* **121**, 375–382 (1999)
52. Wang, K., Chen, Y.: Folding a patterned cylinder by rigid origami. In: Wang, I.P., Lang, R.J., Mark, Y. (eds.) *Origami*, vol. 5, pp. 265–276. AK Peters/CRC Press, New York (2011)
53. Qi, X., Huang, H., Li, B., Deng, Z.: A large ring deployable mechanism for space satellite antenna. *Aerosp. Sci. Technol.* **58**, 498–510 (2016)
54. Tserodze, S., Prowald, J.S., Gogilashvili, V., Chkhikvadze, K.: Transformable reflector structure with V-folding rods. *CEAS Space J.* **8**, 291–301 (2016)
55. Han, B., Zheng, D., Xu, Y., Yao, J., Zhao, Y.: Kinematic characteristics and dynamics analysis of an overconstrained scissors double-hoop truss deployable antenna mechanism based on screw theory. *IEEE Access* **7**, 140755–140768 (2019)
56. Tserodze, S., Prowald, J.S., Chkhikvadze, K., Nikoladze, M., Muchaidze, M.: Latest modification of the deployable space reflector structure with V-folding bars. *CEAS Space J.* **12**, 163–169 (2020)
57. Zirbel, S.A., Trease, B.P., Thomson, M.W., Lang, R.J., Magleby, S.P., Howell, L.H.: Hanaflex: a large solar array for space applications. In: *Micro-and Nanotechnology Sensors, Systems, and Applications VII*, p. 94671C. SPIE, Maryland (2015)
58. Liu, S.Y., Chen, Y.: Myard linkage and its mobile assemblies. *Mech. Mach. Theory* **44**, 1950–1963 (2009)
59. Huang, H., Deng, Z., Li, B.: Mobile assemblies of large deployable mechanisms. *J. Space Eng.* **5**, 1–14 (2012)
60. Baker, J.E.: The Bennett linkage and its associated quadric surfaces. *Mech. Mach. Theory* **23**, 147–156 (1988)
61. Baker, J.E.: The Bennett, Goldberg and Myard linkages—in perspective. *Mech. Mach. Theory* **14**, 239–253 (1979)
62. Myard, F.E.: Contribution à la géométrie des systèmes articulés. *Bull. Soc. Math. Fr.* **59**, 183–210 (1931)
63. Feng, H., Chen, Y., Dai, J.S., Gogu, G.: Kinematic study of the general plane-symmetric Bricard linkage and its bifurcation variations. *Mech. Mach. Theory* **116**, 89–104 (2017)
64. Yang, F., You, Z., Chen, Y.: Foldable hexagonal structures based on the threefold-symmetric Bricard linkage. *J. Mech. Robot.* **12**, 011012 (2020)
65. Gan, W., Pellegrino, S.: Closed-loop deployable structures. In: *The 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 1450. AIAA, Norfolk (2003)
66. Ma, B., Huang, H.: Large deployable networks constructed by interconnected Bricard linkages. *Adv. Mater. Res.* **338**, 723–726 (2011)
67. Song, X., Guo, H., Li, B., Liu, R., Deng, Z.: Large deployable network constructed by Altman linkages. *Proc. Inst. Mech. Eng., Part C, J. Mech. Eng. Sci.* **231**, 341–355 (2017)
68. You, Z., Chen, Y.: Mobile assemblies based on the Bennett linkage. *Proc. R. Soc. A, Math. Phys. Eng. Sci.* **461**, 1229–1245 (2005)
69. Chen, Y., You, Z.: Square deployable frames for space applications. Part 2: realization. *Proc. Inst. Mech. Eng., G J. Aerosp. Eng.* **221**, 37–45 (2007)
70. Lu, S., Zlatanov, D., Ding, X.: Approximation of cylindrical surfaces with deployable Bennett networks. *J. Mech. Robot.* **9**, 021001 (2017)
71. Yang, F.F., Li, J.M., Chen, Y., You, Z.: A deployable Bennett network in saddle surface. In: *Proceedings of the 14th IFToMM World Congress, IFToMM, Taiwan*, pp. 428–434 (2015)
72. Song, X., Deng, Z., Guo, H., Liu, R., Li, L., Liu, R.: Networking of Bennett linkages and its application on deployable parabolic cylindrical antenna. *Mech. Mach. Theory* **109**, 95–125 (2017)
73. Alegria Mira, L., Thrall, A.P., De Temmerman, N.: Deployable scissor arch for transitional shelters. *Autom. Constr.* **43**, 123–131 (2014)
74. Zhao, J.S., Wang, J.Y., Chu, F., Feng, Z.J., Dai, J.S.: Structure synthesis and statics analysis of a foldable stair. *Mech. Mach. Theory* **46**, 998–1015 (2011)
75. Akgün, Y., Gantes, C.J., Sobek, W., Korkmaz, K., Kalochairetis, K.: A novel adaptive spatial scissor-hinge structural mechanism for convertible roofs. *Eng. Struct.* **33**, 1365–1376 (2011)
76. Holland, A., Straub, J.: Development of origami-style solar panels for use in support of a Mars mission. In: *Energy Harvesting and Storage: Materials, Devices, and Applications VII*, p. 98650D. SPIE, Maryland (2016)
77. Kanemitsu, T., Matsumoto, S., Namba, H., Sato, T., Tadokoro, H., Oura, T., Takagi, K., Aoki, S., Kaya, N.: *Self-Deployable Antenna Using Centrifugal Force* pp. 173–182. Springer Netherlands, Dordrecht (2000)

78. Huang, H., Guan, F., Pan, L., Xu, Y.: Design and deploying study of a new petal-type deployable solid surface antenna. *Acta Astronaut.* **148**, 99–110 (2018)
79. Chen, Y., Peng, R., You, Z.: Origami of thick panels. *Science* **349**, 396–400 (2015)
80. Chen, Y., Feng, H., Ma, J., Peng, R., You, Z.: Symmetric waterbomb origami. *Proc. R. Soc. A, Math. Phys. Eng. Sci.* **472**, 20150846 (2016)
81. Zhang, X., Chen, Y.: The diamond thick-panel origami and the corresponding mobile assemblies of plane-symmetric Bricard linkages. *Mech. Mach. Theory* **130**, 585–604 (2018)
82. Hoberman, C.: Connections to make foldable structures. EP20010300695 (2002)
83. Yang, F., Chen, Y.: One-DOF transformation between tetrahedron and truncated tetrahedron. *Mech. Mach. Theory* **121**, 169–183 (2018)
84. Chen, Y., Yang, F., You, Z.: Transformation of polyhedrons. *Int. J. Solids Struct.* **138**, 193–204 (2018)
85. Yang, F., You, Z., Chen, Y.: Mobile assembly of two Bennett linkages and its application to transformation between cuboctahedron and octahedron. *Mech. Mach. Theory* **145**, 103698 (2020)
86. Wei, G., Chen, Y., Dai, J.S.: Synthesis, mobility, and multifurcation of deployable polyhedral mechanisms with radially reciprocating motion. *J. Mech. Des.* **136**, 091003 (2014)
87. Xiu, H.H., Wang, K.Y., Wei, G.W., Ren, L., Dai, J.S.: A Sarrus-like overconstrained eight-bar linkage and its associated Fulleroid-like platonic deployable mechanisms. *Proc. Inst. Mech. Eng., Part C, J. Mech. Eng. Sci.* **234**, 241–262 (2020)
88. Gu, Y., Chen, Y.: Origami cubes with one-Dof rigid and flat foldability. *Int. J. Solids Struct.* **207**, 250–261 (2020)
89. Gu, Y., Wei, G., Chen, Y.: Thick-panel origami cube. *Mech. Mach. Theory* **164**, 104411 (2021)
90. Xu, Y., Lin, Q., Wang, X., Li, L., Cong, Q., Pan, B.: Mechanism design and dynamic analysis of a large-scale spatial deployable structure for space mission. In: Seventh International Conference on Electronics and Information Engineering, p. 1032226. SPIE, Nanjing (2017)
91. Ikeya, K., Sakamoto, H., Nakanishi, H., Furuya, H., Tomura, T., Ide, R., Iijima, R., Iwasaki, Y., Ohno, K., Omoto, K., Furuya, T., Hayashi, T., Kato, M., Koide, S., Kurosaki, M., Nakatsuka, Y., Okuyama, S., Kashiwaya, R., Nakamura, J., Nio, W., Tsunemitsu, T., Yamazaki, Y., Taga, K., Hohmann, B., Amamoto, T., Chubachi, T., Tamura, S., Okada, H., Watanabe, A., Kawabata, N., Hori, T., Ito, H., Kuratomi, T., Shimoda, Y., Hidaka, N., Watanabe, K., Torisaka, A., Yamazaki, M.: Significance of 3U cubesat Origamisat-1 for space demonstration of multifunctional deployable membrane. *Acta Astronaut.* **173**, 363–377 (2020)
92. Block, J., Straubel, M., Wiedemann, M.: Ultralight deployable booms for solar sails and other large gossamer structures in space. *Acta Astronaut.* **68**, 984–992 (2011)
93. Block, J., Bäger, A., Behrens, J., Delovski, T., Hauer, L.C., Schütze, M., Schütze, R., Sprowitz, T.: A self-deploying and self-stabilizing helical antenna for small satellites. *Acta Astronaut.* **86**, 88–94 (2013)
94. Sprewitz, T., Reershemius, S., Hauer, L.C., Fexer, S., Schütze, M., Suhr, B.: Development, testing and in-orbit verification of a large CFRP helical antenna on the Alsat mission. In: 2020 IEEE Aerospace Conference, pp. 1–9. IEEE, MT (2020)
95. Crawford, R.: Strength and efficiency of deployable booms for space applications. In: The 12th Structures, Structural Dynamics and Materials Conference, pp. 1–13. AIAA, CA (1971)
96. Li, H., Yu, Z., Guo, S., Cai, G.: Investigation of joint clearances in a large-scale flexible solar array system. *Multibody Syst. Dyn.* **44**, 277–292 (2018)
97. Mao, H., Ganga, P.L., Ghiozzi, M., Ivchenko, N., Tibert, G.: Deployment of bistable self-deployable tape spring booms using a gravity offloading system. *J. Aerosp. Eng.* **30**, 04017007 (2017)
98. Fujioka, E., Yokozeki, T., Watanabe, A., Aoki, T.: Analysis on temperature-dependent deployment behavior of bi-stable composite rods. *Adv. Compos. Mater.* **28**, 245–257 (2019)
99. Chu, Z., Lei, Y., Li, D.: Dynamics and robust adaptive control of a deployable boom for a space probe. *Acta Astronaut.* **97**, 138–150 (2014)
100. Kresling, B.: Natural twist buckling in shells: from the hawkmoth's bellows to the deployable Kresling-pattern and cylindrical. In: Miura-ori Proceedings of the 6th International Conference on Computation of Shell and Spatial Structures, pp. 12–32. IASS-IACM, Ithaca (2008)
101. Senda, K., Ohta, S., Igarashi, Y., Watanabe, A., Hori, T., Ito, H., Tsunoda, H., Watanabe, K.: Deploy experiment of inflatable tube using work hardening. In: The 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, p. 1808. AIAA, Rhode Island (2006)
102. Schenk, M., Viquerat, A.D., Seffen, K.A., Guest, S.D.: Review of inflatable booms for deployable space structures: packing and rigidization. *J. Spacecr. Rockets* **51**, 762–778 (2014)
103. Pagano, A., Yan, T., Chien, B., Wissa, A., Tawfick, S.: A crawling robot driven by multi-stable origami. *Smart Mater. Struct.* **26**, 094007 (2017)
104. Bhowad, P., Kaufmann, J., Li, S.: Peristaltic locomotion without digital controllers: exploiting multi-stability in origami to coordinate robotic motion. *Extreme Mech. Lett.* **32**, 100552 (2019)

105. Morgan, J., Magleby, S.P., Howell, L.L.: An approach to designing origami-adapted aerospace mechanisms. *J. Mech. Des.* **138**, 052301 (2016)
106. Miura, K., Miura, K.: Triangles and quadrangles in space. In: *Symposium of the International Association for Shell and Spatial Structures*, pp. 27–38. IASS, Valencia (2009)
107. Guest, S.D., Pellegrino, S.: Inextensional wrapping of flat membranes. In: *Proceedings of the First International Seminar on Structural Morphology*, Montpellier, pp. 203–215 (1992)
108. Pellegrino, S., Vincent, J.F.: How to fold a membrane. In: Pellegrino, S. (ed.) *Deployable Structures*, pp. 59–75. Springer, New York (2001)
109. Lang, R.J.: *Origami in Action: Paper Toys that Fly, Flag, Gobble and Inflate*. Macmillan, London (1997)
110. Miura, K., Pellegrino, S.: *Forms and Concepts for Lightweight Structures*. Cambridge University Press, Cambridge (2020)
111. Nojima, T.: Origami modeling of functional structures based on organic patterns. Presentation Manuscript at Vipsi Tokyo (1996)
112. Yao, S., Liu, X., Georgakopoulos, S.V.: Study and design of Nojima origami conical spiral antenna. In: *IEEE International Symposium on Antennas & Propagation*, pp. 1431–1432. IEEE, Fajardo (2016)
113. Miyazaki, Y.: Deployable techniques for small satellites. *Proc. IEEE* **106**, 471–483 (2018)
114. Miyazaki, Y., Fukunaga, M., Kousaka, D.: Membrane structure supported by self-deployable truss for space applications. In: *2018 AIAA Spacecraft Structures Conference*, p. 1201. AIAA, Florida (2018)
115. Arya, M., Lee, N., Pellegrino, S.: Wrapping thick membranes with slipping folds. In: *2nd AIAA Spacecraft Structures Conference*, p. 0682. AIAA, Kissimmee (2015)
116. Arya, M., Lee, N., Pellegrino, S.: Ultralight structures for space solar power satellites. In: *3rd AIAA Spacecraft Structures Conference*, p. 1950. AIAA, San Diego (2016)
117. Sosa, E.M., Thompson, G.J., Barbero, E.J.: Experimental investigation of initial deployment of inflatable structures for sealing of rail tunnels. *Tunn. Undergr. Space Technol.* **69**, 37–51 (2017)
118. Litteken, D.A.: Inflatable technology: using flexible materials to make large structures. In: *Proc. SPIE 10966, Electroactive Polymer Actuators and Devices (EAPAD) XXI*, p. 1096603. SPIE, Denver (2019)
119. Yang, H., Guo, H.W., Wang, Y., Liu, R.Q., Li, M.: Design and experiment of triangular prism mast with tape-spring hyperelastic hinges. *Chin. J. Mech. Eng.* **31**, 1–10 (2018)
120. Tibert, G., Pellegrino, S.: Deployable tensegrity masts. In: *44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 1978. AIAA, Norfolk (2003)
121. Wang, W., Rodrigue, H., Ahn, S.H.: Deployable soft composite structures. *Sci. Rep.* **6**, 20869 (2016)
122. Tan, G.E.B., Pellegrino, S.: Nonlinear vibration of cable-stiffened pantographic deployable structures. *J. Sound Vib.* **314**, 783–802 (2008)
123. Wu, M., Zhang, T., Xiang, P., Guan, F.: Single-layer deployable truss structure driven by elastic components. *J. Aerosp. Eng.* **32**, 04018144 (2019)
124. Jeon, S.K., Footdale, J.N.: Scaling and optimization of a modular origami solar array. In: *2018 AIAA Spacecraft Structures Conference*, p. 2204. AISS, Kissimmee (2018)
125. Guo, W., Li, Y., Li, Y.-Z., Tian, S., Wang, S.: Thermal-structural analysis of large deployable space antenna under extreme heat loads. *J. Therm. Stresses* **39**, 887–905 (2016)
126. Datashvili, L., Baier, H., Wehrle, E., Kuhn, T., Hoffmann, J.: Large shell-membrane space reflectors. In: *The 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 2504. AIAA, Orlando (2010)
127. <https://www.northropgrumman.com/space/astro-aerospace-products-astromesh>. Accessed 28 August 2021
128. Mobrem, M., Kuehn, S., Spier, C., Slimko, E.: Design and performance of AstroMesh reflector onboard soil moisture active passive spacecraft. In: *2012 IEEE Aerospace Conference*, pp. 1–10. IEEE, Big Sky (2012)
129. Meguro, A., Tsujihata, A., Hamamoto, N., Homma, M.: Technology status of the 13 m aperture deployment antenna reflectors for engineering test satellite VIII. *Acta Astronaut.* **47**, 147–152 (2000)
130. Morterolle, S., Maurin, B., Quirant, J., Dupuy, C.: Numerical form-finding of geotensoid tension truss for mesh reflector. *Acta Astronaut.* **76**, 154–163 (2012)
131. Yang, G., Duan, B., Zhang, Y., Yang, D.: Uniform-tension form-finding design for asymmetric cable-mesh deployable reflector antennas. *Adv. Mech. Eng.* **8**, 1687814016672367 (2016)
132. Santiago-Prowald, J., Baier, H.: Advances in deployable structures and surfaces for large apertures in space. *CEAS Space J.* **5**, 89–115 (2013)
133. Tang, Y., Shi, Z., Li, T., Wang, Z.: Double-layer cable-net structures for deployable umbrella reflectors. *J. Aerosp. Eng.* **32**, 04019068 (2019)
134. Hinkle, J., Dixit, A., Lin, J., Whitley, K., Watson, J., Valle, G.: Design development and testing for an expandable lunar habitat. In: *AIAA SPACE 2008 Conference & Exposition*, p. 7634. AIAA, San Diego (2008)

135. Hong, Y., Yao, W., Xu, Y.: Structural design and impact analysis of deployable habitat modules. *Int. J. Aerosp. Eng.* **2018**, 3252104 (2018)
136. Dronadula, R., Benaroya, H.: Hybrid lunar inflatable structure. *Acta Astronaut.* **179**, 42–55 (2021)
137. <https://www.nasa.gov/feature/beam-facts-figures-faqs>. Accessed 28 August 2021
138. Li, B., Qi, X., Huang, H., Xu, W.: Modeling and analysis of deployment dynamics for a novel ring mechanism. *Acta Astronaut.* **120**, 59–74 (2016)
139. Chang, W., Cao, D., Lian, M.: Simulation and analysis of tape spring for deployed space structures. In: *Young Scientists Forum 2017*, p. 1071022. SPIE, Shanghai (2018)
140. Bettini, W., Quirant, J., Averseng, J., Maurin, B.: Self-deployable geometries for space applications. *J. Aerosp. Eng.* **32**, 04018138 (2019)
141. Chu, Z., Hu, J., Yan, S., Zhou, M.: Experiment on the retraction/deployment of an active-passive composited driving deployable boom for space probes. *Mech. Mach. Theory* **92**, 436–446 (2015)
142. Allred, R.E., Hoyt, A., Mcelroy, P.M., Scarborough, S., Cadogan, D.P.: UV rigidizable carbon-reinforced isogrid inflatable booms. In: *The 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 1202. AIAA, Denver (2013)
143. Gantes, C.: A design methodology for deployable structures. Massachusetts Institute of Technology (1991)
144. Gantes, C.J.: Design strategies for controlling structural instabilities. *Int. J. Space Struct.* **15**, 167–188 (2000)
145. Huang, S.G., Schimmels, J.M.: The bounds and realization of spatial stiffnesses achieved with simple springs connected in parallel. *IEEE Trans. Robot. Autom.* **14**, 466–475 (1998)
146. Raskin, I., Roorda, J.: Nonlinear analysis of uniform pantographic columns in compression. *J. Eng. Mech.* **125**, 1344–1348 (1999)
147. Ge, D.M., Chen, W.J., Fu, G.Y., Dong, S.L.: Buckling theoretical analysis of coilable hingeless extendible/retractable space mast. *Chin. J. Comput. Mech.* **24**, 615–619 (2007)
148. Jin, Y., Liu, T., Lyu, R., Ji, B., Cui, Q.: Theoretical analysis and experimental investigation on buckling of fastmast deployable structures. *Int. J. Struct. Stab. Dyn.* **15**, 1450075 (2015)
149. Li, B., Wang, S.M., Zhi, C.J., Xue, X.Z., Makis, V.: Analytical and numerical study of the buckling of planar linear array deployable structures based on scissor-like element under its own weight. *Mech. Syst. Signal Process.* **83**, 474–488 (2017)
150. Song, Y., Ho Chi, O., Qing, Z.: A study of new deployable structure. *Adv. Mater. Res.* **1049**, 1083–1089 (2014)
151. Vu, K.K., Liew, J.Y., Krishnapillai, A.: Commutative algebra in structural analysis of deployable tension-strut structures. *J. Int. Assoc. Shell Spat. Struct.* **46**, 173–178 (2005)
152. Zhao, B., Hu, J., Chen, W., Chen, J., Qiu, Z., Jing, Z.: Computational method for in-situ finite element modeling of inflatable membrane structures based on geometrical shape measurement using photogrammetry. *Comput. Struct.* **224**, 106105 (2019)
153. Ye, H., Li, B., Shi, X., Zhang, Y.: Quasi-static folding mechanical behavior analysis and optimization design for composite tube hinge. *J. Mech. Eng.* **56**, 172–180 (2020)
154. Cai, J., Ma, R., Deng, X., Feng, J.: Static behavior of deployable cable-strut structures. *J. Constr. Steel Res.* **119**, 63–75 (2016)
155. Teixeira, A.M.A.J., Pfeil, M.S., Battista, R.C.: Structural evaluation of a GFRP truss girder for a deployable bridge. *Compos. Struct.* **110**, 29–38 (2014)
156. Zhang, D., Yuan, J., Li, F., Lv, Y., Zhao, Q., Gao, Y., Mo, C., Yang, J.: Experimental characterization of static behavior of a new GFRP-metal space truss deployable bridge: comparative case study. *J. Bridge Eng.* **26**, 05020011 (2021)
157. Mao, H., Zhang, D., Chen, L., Zhao, Q., Su, X., Yuan, J.: Flexural behaviour of a new lightweight glass fibre-reinforced polymer-metal string bridge with a box-truss composite girder. *Adv. Struct. Eng.* **23**, 104–117 (2020)
158. Shi, C., Guo, H., Liu, R., Deng, Z.: Configuration optimization and structure design of the double-layer hoop deployable antenna mechanism. *J. Astronaut.* **37**, 869–878 (2016)
159. Martínez-Martín, F.J., Thrall, A.P.: Honeycomb core sandwich panels for origami-inspired deployable shelters: multi-objective optimization for minimum weight and maximum energy efficiency. *Eng. Struct.* **69**, 158–167 (2014)
160. Kaveh, A., Talatahari, S.: A particle swarm ant colony optimization for truss structures with discrete variables. *J. Constr. Steel Res.* **65**, 1558–1568 (2009)
161. Thrall, A.P., Adriaenssens, S., Paya-Zaforteza, I., Zoli, T.P.: Linkage-based movable bridges: design methodology and three novel forms. *Eng. Struct.* **37**, 214–223 (2012)
162. Arnouts, L.I.W., Massart, T.J., De Temmerman, N., Berke, P.Z.: Multi-objective optimisation of deployable bistable scissor structures. *Autom. Constr.* **114**, 103154 (2020)

163. Thrall, A.P., Zhu, M., Guest, J.K., Paya-Zaforteza, I., Adriaenssens, S.: Structural optimization of deploying structures composed of linkages. *J. Comput. Civ. Eng.* **28**, 04014010 (2014)
164. Kaveh, A., Shojaee, S.: Optimal design of scissor-link foldable structures using ant colony optimization algorithm. *Comput.-Aided Civ. Infrastruct. Eng.* **22**, 56–64 (2007)
165. You, Z.: Sensitivity analysis based on the force method for deployable cable-stiffened structures. *Eng. Optim.* **29**, 429–441 (1997)
166. Ye, H., Zhang, Y., Yang, Q., Xiao, Y., Grandhi, R.V., Fischer, C.C.: Optimal design of a three tape-spring hinge deployable space structure using an experimentally validated physics-based model. *Struct. Multidiscip. Optim.* **56**, 973–989 (2017)
167. Song, Z., Chen, C., Jiang, S., Chen, J., Liu, T., Deng, W., Lin, F.: Optimization analysis of microgravity experimental facility for the deployable structures based on force balance method. *Microgravity Sci. Technol.* **32**, 773–785 (2020)
168. Koumar, A., Tysmans, T., Coelho, R.F., De Temmerman, N.: An automated structural optimisation methodology for scissor structures using a genetic algorithm. *Appl. Comput. Intell. Soft Comput.* **2017**, 6843574 (2017)
169. Hafika, R.T., Adelman, H.M.: Selection of actuator locations for static shape control of large space structures by heuristic integer programming. *Comput. Struct.* **20**, 575–582 (1985)
170. Mitsugi, J., Yasaka, T., Miura, K.: Shape control of the tension truss antenna. *AIAA J.* **28**, 316–322 (1990)
171. Tanaka, H., Natori, M.C.: Shape control of space antennas consisting of cable networks. *Acta Astronaut.* **55**, 519–527 (2004)
172. Zong, Y., Hu, N., Duan, B., Yang, G., Cao, H., Xu, W.: Manufacturing error sensitivity analysis and optimal design method of cable-network antenna structures. *Acta Astronaut.* **120**, 182–191 (2016)
173. Maji, A.K., Starnes, M.A.: Shape measurement and control of deployable membrane structures. *Exp. Mech.* **40**, 154–159 (2000)
174. Ukita, N., Saito, M., Ezawa, H., Ikenoue, B., Ishizaki, H., Iwashita, H., Yamaguchi, N., Hayakawa, T.: Design and performance of the ALMA-J prototype antenna. In: *Ground-Based Telescopes*, pp. 1085–1093. SPIE, Glasgow (2004)
175. Wiktowy, M., O’Grady, M., Atkins, G., Singhal, R.: Photogrammetric distortion measurements of antennas in a thermal-vacuum environment. *Can. Aeronaut. Space J.* **49**, 65–71 (2003)
176. Yang, G., Duan, B., Du, J., Zhang, Y.: Shape pre-adjustment of deployable mesh antennas considering space thermal loads. *Proc. Inst. Mech. Eng., G J. Aerosp. Eng.* **232**, 143–155 (2018)
177. Nie, R., He, B., Yan, S., Ma, X.: Design optimization of mesh antennas for on-orbit thermal effects. *Int. J. Mech. Sci.* **175**, 105547 (2020)
178. John, M.: Hedgepeth: accuracy potentials for large space antenna reflectors with passive structure. *J. Spacecr. Rockets* **19**, 211 (1982)
179. Meguro, A., Harada, S., Watanabe, M.: Key technologies for high-accuracy large mesh antenna reflectors. *Acta Astronaut.* **53**, 899–908 (2003)
180. Mobrem, M.: Methods of analyzing surface accuracy of large antenna structures due to manufacturing tolerances. In: *The 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 1453. AIAA, Norfolk (2013)
181. Tibert, G.: Deployable tensegrity structures for space applications. *Royal Institute of Technology* (2002)
182. Hedgepeth, J.M.: Influence of fabrication tolerances on the surface accuracy of large antenna structures. *AIAA J.* **20**, 680–686 (1982)
183. Li, X., Ding, X., Chirikjian, G.S.: Analysis of angular-error uncertainty in planar multiple-loop structures with joint clearances. *Mech. Mach. Theory* **91**, 69–85 (2015)
184. Nie, R., He, B., Hodges, D.H., Ma, X.: Integrated form finding method for mesh reflector antennas considering the flexible truss and hinges. *Aerosp. Sci. Technol.* **84**, 926–937 (2019)
185. Ponomarev, V.S., Gerasimov, A.V., Ponomarev, S.V.: Thermomechanical analysis of large deployable space reflector antenna. In: *Conference on Heat and Mass Transfer in the Thermal Control System of Technical and Technological Energy Equipment*, p. 01059. MATEC Web of Conferences, Tomsk (2015)
186. Fang, H., Sunada, E., Chaubell, J., Estebanfernandez, D., Thomson, M., Nicaise, F.: Thermal deformation and RF performance analyses for the SWOT large deployable Ka-band reflectarray. In: *The 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 2502. AIAA, Orlando (2010)
187. Lu, G., Zhou, J., Cai, G., Fang, G., Lv, L., Peng, F.: Studies of thermal deformation and shape control of a space planar phased array antenna. *Aerosp. Sci. Technol.* **93**, 105311 (2019)
188. Wu, M., Zhang, Z., Guan, F.: Analysis and measurement of flatness of a single-layer deployable truss structure driven by elastic components. *Manned Spacefl.* **23**, 529–535 (2017)

189. Zhao, Q., Guo, J., Yu, D., Hong, J., Chen, F.: An enhanced method of resizing support links for a planar closed-loop overconstrained deployable structure considering kinematic reliability and surface accuracy. *Aerosp. Sci. Technol.* **104**, 105988 (2020)
190. Yang, Y., Luo, J., Zhang, W., Xie, S., Sun, Y., Li, H.: Accuracy analysis of a multi-closed-loop deployable mechanism. *Proc. Inst. Mech. Eng., Part C, J. Mech. Eng. Sci.* **230**, 611–621 (2016)
191. Veenendaal, D., Block, P.: An overview and comparison of structural form finding methods for general networks. *Int. J. Solids Struct.* **49**, 3741–3753 (2012)
192. Tibert, A.G., Pellegrino, S.: Review of form-finding methods for tensegrity structures. *Int. J. Space Struct.* **18**, 209–223 (2003)
193. Siev, A., Eidelman, J.: Stress analysis of prestressed suspended roofs. *J. Struct. Div.* **90**, 103–121 (1964)
194. Argyris, J.H., Angelopoulos, T., Bichat, B.: A general method for the shape finding of lightweight tension structures. *Comput. Methods Appl. Mech. Eng.* **3**, 135–149 (1974)
195. Linkwitz, K., Schek, H.J.: Einige bemerkungen zur berechnung von vorgespannten seilnetzkonstruktionen. *Ing.-Arch.* **40**, 145–158 (1971)
196. Harber, R.B.: Initial equilibrium solution methods for cable reinforced membranes part I-formulations. *Comput. Methods Appl. Mech. Eng.* **30**, 263–284 (1982)
197. Bletzinger, K.U., Ramm, E.: A general finite element approach to the form finding of tensile structures by the updated reference strategy. *Int. J. Space Struct.* **14**, 131–145 (1999)
198. Sanchez, J., Serna, M.A., Morer, P.: A multi-step force-density method and surface-fitting approach for the preliminary shape design of tensile structures. *Eng. Struct.* **29**, 1966–1976 (2007)
199. Pauletti, R.M.O., Pimenta, P.M.: The natural force density method for the shape finding of taut structures. *Comput. Methods Appl. Mech. Eng.* **197**, 4419–4428 (2008)
200. Barnes, M.R.: *Form Finding and Analysis of Tension Space Structures by Dynamic Relaxation*. City University London, London (1977)
201. Kilian, A., Ochsendorf, J.: Particle-spring systems for structural form finding. *J. Int. Assoc. Shell Spat. Struct.* **46**, 77–84 (2005)
202. Inoyama, D., Sanders, B.P., Joo, J.J.: Topology synthesis of distributed actuation systems for morphing wing structures. *J. Aircr.* **44**, 1205–1213 (2007)
203. Inoyama, D., Sanders, B.P., Joo, J.J.: Topology optimization approach for the determination of the multiple-configuration morphing wing structure. *J. Aircr.* **45**, 1853–1862 (2008)
204. Wu, J., Li, J., Yan, S.: Design of deployable bistable structures for morphing skin and its structural optimization. *Eng. Optim.* **46**, 745–762 (2014)
205. Bletzinger, K.U., Wuchner, R., Daoud, F., Camprubi, N.: Computational methods for form finding and optimization of shells and membranes. *Comput. Methods Appl. Mech. Eng.* **194**, 3438–3452 (2005)
206. Lewis, W.J.: *Tension Structures: Form and Behavior*. Thomas Telford, London (2006)
207. Tibert, G.: Optimal design of tension truss antennas. In: *The 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 1629. AIAA, Norfolk (2003)
208. Yang, D., Liu, J., Zhang, Y., Zhang, S.: Optimal surface profile design of deployable mesh reflectors via a force density strategy. *Acta Astronaut.* **130**, 137–146 (2017)
209. Liu, R., Guo, H., Liu, R., Wang, H., Tang, D., Song, X.: Shape accuracy optimization for cable-rib tension deployable antenna structure with tensioned cables. *Acta Astronaut.* **140**, 66–77 (2017)
210. Ma, X., Song, Y., Li, Z., Li, T., Wang, Z., Deng, H.: Mesh reflector antennas: form finding analysis review. In: *The 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, p. 1576. AIAA, Boston (2013)
211. Li, T., Jiang, J., Deng, H., Lin, Z., Wang, Z.: Form-finding methods for deployable mesh reflector antennas. *Chin. J. Aeronaut.* **26**, 1276–1282 (2013)
212. Liu, W., Li, D.X., Yu, X.Z., Jiang, J.P.: Exact mesh shape design of large cable-network antenna reflectors with flexible ring truss supports. *Acta Mech. Sin.* **30**, 198–205 (2014)
213. Lu, C., Zhu, H., Li, S.: Initial form-finding design of deployable tensegrity structures with dynamic relaxation method. *J. Intell. Fuzzy Syst.* **33**, 2861–2868 (2017)
214. Nie, R., He, B., Hodges, D.H., Ma, X.: Form finding and design optimization of cable network structures with flexible frames. *Comput. Struct.* **220**, 81–91 (2019)
215. Li, T., Deng, H., Tang, Y., Jiang, J., Ma, X.: Accuracy analysis and form-finding design of uncertain mesh reflectors based on interval force density method. *Proc. Inst. Mech. Eng., G J. Aerosp. Eng.* **231**, 2163–2173 (2017)
216. Nie, R., He, B., Yan, S., Ma, X.: Optimization design method for the cable network of mesh reflector antennas considering space thermal effects. *Aerosp. Sci. Technol.* **94**, 105380 (2019)
217. Nie, R., He, B., Yan, S., Ma, X.: Optimization design method for mesh reflector antennas considering the truss deformation and thermal effects. *Eng. Struct.* **208**, 110253 (2020)
218. Du, J., Gu, Y., Bao, H., Wang, C., Chen, X.: Shape adjustment optimization and experiment of cable-membrane reflectors. *Acta Astronaut.* **146**, 192–201 (2018)

219. Du, J., Zong, Y., Bao, H.: Shape adjustment of cable mesh antennas using sequential quadratic programming. *Aerosp. Sci. Technol.* **30**, 26–32 (2013)
220. Yoon, H.S., Washington, G.: An optimal method of shape control for deformable structures with an application to a mechanically reconfigurable reflector antenna. *Smart Mater. Struct.* **19**, 105004 (2010)
221. Zhang, S., Du, J., Yang, D., Zhang, Y., Li, S.: A combined shape control procedure of cable mesh reflector antennas with optimality criterion and integrated structural electromagnetic concept. *Struct. Multidiscip. Optim.* **55**, 289–295 (2017)
222. Tabata, M., Natori, M.C.: Active shape control of a deployable space antenna reflector. *J. Intell. Mater. Syst. Struct.* **7**, 235–240 (1996)
223. Tanaka, H.: Surface error estimation and correction of a space antenna based on antenna gain analyses. *Acta Astronaut.* **68**, 1062–1069 (2011)
224. Wang, Z., Li, T., Deng, H.: Form-finding analysis and active shape adjustment of cable net reflectors with PZT actuators. *J. Aerosp. Eng.* **27**, 575–586 (2014)
225. Wang, Z., Li, T., Cao, Y.: Active shape adjustment of cable net structures with PZT actuators. *Aerosp. Sci. Technol.* **26**, 160–168 (2013)
226. Xun, G., Peng, H., Wu, S., Wu, Z.: Active shape adjustment of large cable-mesh reflectors using novel fast model predictive control. *J. Aerosp. Eng.* **31**, 04018038 (2018)
227. Zuo, Y., Li, Z., Jin, G., Xie, P.: Spontaneously deployable structure for space diffractive telescope. *Optoelectron. Lett.* **13**, 245–249 (2017)
228. Zheng, T., Fei, Z., Rui, X., Yan, L.: A novel space large deployable paraboloid structure with power and communication integration. *Int. J. Antennas Propag.* **2019**, 3980947 (2019)
229. Zhang, H., Zhou, C., Xie, X., Li, T.: Analysis and simulation of a new type of radial deployable structures. *Adv. Mater. Res.* **753**, 1128–1132 (2013)
230. Zareei, A., Deng, B., Bertoldi, K.: Harnessing transition waves to realize deployable structures. *Proc. Natl. Acad. Sci.* **117**, 4015–4020 (2020)
231. Choi, J., Lee, D., Hwang, K., Kim, B.: A mechanism for a deployable optical structure of a small satellite. *Int. J. Precis. Eng. Manuf.* **16**, 2537–2543 (2015)
232. Leng, J., Yu, K., Sun, J., Liu, Y.: Deployable morphing structure based on shape memory polymer. *Aircr. Eng. Aerosp. Technol.* **87**, 218–223 (2015)
233. Li, F., Liu, L., Lan, X., Zhou, X., Bian, W., Liu, Y., Leng, J.: Preliminary design and analysis of a cubic deployable support structure based on shape memory polymer composite. *Int. J. Smart Nano Mater.* **7**, 106–118 (2016)
234. Minori, A.F., He, Q., Glick, P.E., Adibnazari, I., Stopol, A., Cai, S., Tolley, M.T.: Reversible actuation for self-folding modular machines using liquid crystal elastomer. *Smart Mater. Struct.* **29**, 105003 (2020)
235. Santo, L., Bellisario, D., Iorio, L., Quadri, F.: Shape memory composite structures for self-deployable solar sails. *Astrodynamic* **3**, 247–255 (2019)
236. Wang, W., Li, C., Rodrigue, H., Yuan, F., Han, M.W., Cho, M., Ahn, S.H.: Kirigami/origami-based soft deployable reflector for optical beam steering. *Adv. Funct. Mater.* **27**, 1604214 (2017)
237. Sun, Y., Wang, S., Mills, J.K., Zhi, C.: Kinematics and dynamics of deployable structures with scissor-like-elements based on screw theory. *Chin. J. Mech. Eng.* **27**, 655–662 (2014)
238. Wang, D., Liu, R., Wang, Y., Guo, H., Cong, Q., Zhang, C.: Deployment analysis of a planar deployable support truss structure. In: 2013 IEEE International Conference on Mechatronics and Automation, pp. 1287–1292. IEEE, Takamatsu (2013)
239. Suh, J., Jeong, S., Han, J.: Conceptual design and dynamic analysis of bistable deployable structure. In: *Active and Passive Smart Structures and Integrated Systems XII*, p. 105950J. SPIE, Denver (2018)
240. Peng, Y., Zhao, Z., Zhou, M., He, J., Yang, J., Xiao, Y.: Flexible multibody model and the dynamics of the deployment of mesh antennas. *J. Guid. Control Dyn.* **40**, 1499–1506 (2017)
241. Wang, Y., Guo, H., Yang, H., Liu, R., Deng, Z.: Deployment analysis and optimization of a flexible deployable structure for large synthetic aperture radar antennas. *Proc. Inst. Mech. Eng., G J. Aerosp. Eng.* **230**, 615–627 (2016)
242. Zhang, Y., Li, N., Yang, G., Ru, W.: Dynamic analysis of the deployment for mesh reflector deployable antennas with the cable-net structure. *Acta Astronaut.* **131**, 182–189 (2017)
243. Peng, Q., Wang, S., Zhi, C., Li, B.: A new flexible multibody dynamics analysis methodology of deployable structures with scissor-like elements. *Chin. J. Mech. Eng.* **32**, 1–10 (2019)
244. Hachkowski, M.R., Peterson, L.D., Lake, M.S.: Friction model of a revolute joint for a precision deployable spacecraft structure. *J. Spacecr. Rockets* **36**, 591–598 (1999)
245. Dewalque, F., Rochus, P., Bruls, O.: Importance of structural damping in the dynamic analysis of compliant deployable structures. *Acta Astronaut.* **111**, 323–333 (2015)
246. Li, B., Wang, S., Yuan, R., Xue, X., Zhi, C.: Dynamic characteristics of planar linear array deployable structure based on scissor-like element with joint clearance using a new mixed contact force model. *Proc. Inst. Mech. Eng., Part C, J. Mech. Eng. Sci.* **230**, 3161–3174 (2016)

247. Li, B., Wang, S., Makis, V., Xue, X.: Dynamic characteristics of planar linear array deployable structure based on scissor-like element with differently located revolute clearance joints. *Proc. Inst. Mech. Eng., Part C, J. Mech. Eng. Sci.* **232**, 1759–1777 (2018)
248. Ma, X., Li, T.: Wave analysis of planar deployable structures with revolute clearance joints based on spectral element method. *Int. J. Appl. Mech.* **10**, 1850090 (2018)
249. Dewalque, F., Schwartz, C., Denoel, V., Croisier, J.L., Forthomme, B., Bruls, O.: Experimental and numerical investigation of the nonlinear dynamics of compliant mechanisms for deployable structures. *Mech. Syst. Signal Process.* **101**, 1–25 (2018)
250. Salama, M., Kuo, C.P., Lou, M.: Simulation of deployment dynamics of inflatable structures. *AIAA J.* **38**, 2277–2283 (2000)
251. Haug, E., Protard, J.B., Milcent, G., Herren, A., Brunner, O.: The numerical simulation of the inflation process of space rigidized antenna structures. *ESA SP* **2**, 861–869 (1991)
252. Lian, W., Bhalsod, D., Olovsson, L.: Benchmark study on the airbag particle method for out-of-position applications. In: 10th International LS-DYNA Users Conference, pp. 11–21. LSTC, Dearborn (2008)
253. Hirth, A., Haufe, A., Olovsson, L.: Airbag simulation with LS-DYNA: past-present-future. In: The 6th European LS-DYNA Conference, pp. 23–45. LSTC, Gothenburg (2007)
254. Marklund, P.O., Nilsson, L.: Simulation of airbag inflation processes using a coupled fluid structure approach. *Comput. Mech.* **29**, 289–297 (2002)
255. Glaser, R., Caccese, V., Shahinpoor, M.: Comparative finite element and experimental analysis of a quasi-static inflation of a thin deployable membrane space structure. *Finite Elem. Anal. Des.* **138**, 48–65 (2018)
256. Mitsugi, J., Ando, K., Senbokuya, Y., Meguro, A.: Deployment analysis of large space antenna using flexible multibody dynamics simulation. *Acta Astronaut.* **47**, 19–26 (2000)
257. Zhang, Y., Ru, W., Yang, G., Li, N.: Deployment analysis considering the cable-net tension effect for deployable antennas. *Aerosp. Sci. Technol.* **48**, 193–202 (2016)
258. Nie, R., He, B., Zhang, L., Fang, Y.: Deployment analysis for space cable net structures with varying topologies and parameters. *Aerosp. Sci. Technol.* **68**, 1–10 (2017)
259. Peng, Q.a., Wang, S., Zhi, C.: The design and simulation of a new time-controlled spring driven hinge for deployable structures. *Mech. Mach. Sci.* **408**, 761–772 (2017)
260. Chu, Z., Deng, Z., Qi, X., Li, B.: Modeling and analysis of a large deployable antenna structure. *Acta Astronaut.* **95**, 51–60 (2014)
261. Peng, H., Fei, L., Kan, Z., Liu, P.: Symplectic instantaneous optimal control of deployable structures driven by sliding cable actuators. *J. Guid. Control Dyn.* **43**, 1114–1128 (2020)
262. Noor, A.K.: Continuum modeling for repetitive lattice structures. *Appl. Mech. Rev.* **41**, 285–296 (1988)
263. Salehian, A., Inman, D.J.: Dynamic analysis of a lattice structure by homogenization: experimental validation. *J. Sound Vib.* **316**, 180–197 (2008)
264. Guo, H., Liu, R., Deng, Z.: Dynamic analysis and nonlinear identification of space deployable structure. *J. Cent. South Univ.* **20**, 1204–1213 (2013)
265. Glassman, T., Warwick, S., Lo, A., Casement, S.: Starshade starlight-suppression performance with a deployable structure. In: *Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave*, p. 990425. SPIE, Edinburgh (2016)
266. Li, F., Liu, L., Lan, X., Wang, T., Li, X., Chen, F., Bian, W., Liu, Y., Leng, J.: Modal analyses of deployable truss structures based on shape memory polymer composites. *Int. J. Appl. Mech.* **8**, 1640009 (2016)
267. Zhao, C., Li, C., Zhou, N., Liao, H.: Self-deployable structure designed for space telescope for microsatellite application. In: 8th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Design, Manufacturing, and Testing of Micro- and Nano-Optical Devices and Systems; and Smart Structures and Materials, p. 96850B. SPIE, Suzhou (2016)
268. Guo, H., Zhang, J., Liu, R., Deng, Z.: Effects of joint on dynamics of space deployable structure. *Chin. J. Mech. Eng.* **26**, 861–872 (2013)
269. Song, Z., Yang, X., Huang, H., Li, B.: Dynamic analysis of planar mechanisms with revolute clearance joints based on two evaluation indices. *Mech. Based Des. Struct. Mach.* **44**, 231–249 (2016)
270. Shen, Z., Li, H., Liu, X., Hu, G.: Thermal shock induced dynamics of a spacecraft with a flexible deploying boom. *Acta Astronaut.* **141**, 123–131 (2017)
271. Shen, Z., Hu, G.: Thermally induced dynamics of a spinning spacecraft with an axial flexible boom. *J. Spacecr. Rockets* **52**, 1503–1507 (2015)
272. Boley, B.A.: Thermally induced vibrations of beams. *J. Aeronaut. Sci.* **23**, 179–181 (1956)
273. Thornton, E.A., Kim, Y.A.: Thermally induced bending vibrations of a flexible rolled-up solar array. *J. Spacecr. Rockets* **30**, 438–448 (1993)
274. Liu, R., Guo, H., Liu, R., Wang, H., Tang, D., Deng, Z.: Structural design and optimization of large cable-rib tension deployable antenna structure with dynamic constraint. *Acta Astronaut.* **151**, 160–172 (2018)

275. Mroz, A., Holnicki-Szulc, J., Biczuk, J.: Prestress accumulation-release technique for damping of impact-born vibrations: application to self-deployable structures. *Math. Probl. Eng.* **2015**, 720236 (2015)
276. Bullock, S.J., Peterson, L.D.: Nanometer regularity in the mechanics of a precision deployable spacecraft structure joint. *J. Spacecr. Rockets* **36**, 758–764 (1999)
277. Moon, F.C., Li, G.X.: Experimental study of chaotic vibrations in a pin-jointed space truss structure. *AIAA J.* **28**, 915–921 (2012)
278. Siriguleng, B., Zhang, W., Liu, T., Liu, Y.Z.: Vibration modal experiments and modal interactions of a large space deployable antenna with carbon fiber material and ring-truss structure. *Eng. Struct.* **207**, 109932 (2020)
279. Wei, J., Ma, R., Liu, Y., Yu, J., Eriksson, A., Tan, H.: Modal analysis and identification of deployable membrane structures. *Acta Astronaut.* **152**, 811–822 (2018)
280. Warren, P.A., Peterson, L.D., Hinkle, J.D.: Submicron mechanical stability of a prototype deployable space telescope support structure. *J. Spacecr. Rockets* **36**, 765–771 (1999)
281. Moser, R.L., Erwin, R.S., Schrader, K.N., Bell, K.D., Griffin, S.F., Powers, M.K.: Experimental control of microdynamic events observed during the testing of a large deployable optical structure. In: *UV, Optical, and IR Space Telescopes and Instruments*, pp. 715–726. SPIE, Munich (2000)
282. Ingham, M.D., Crawley, E.F.: Microdynamic characterization of modal parameters for a deployable space structure. *AIAA J.* **39**, 331–338 (2001)
283. Xun, J., Yan, S.: A revised Hilbert-Huang transformation based on the neural networks and its application in vibration signal analysis of a deployable structure. *Mech. Syst. Signal Process.* **22**, 1705–1723 (2008)
284. Liu, T., Yan, S., Zhang, W.: Time-frequency analysis of nonstationary vibration signals for deployable structures by using the constant-Q nonstationary gabor transform. *Mech. Syst. Signal Process.* **75**, 228–244 (2016)
285. Liu, T., Huang, J., Yan, S., Guo, F.: Extraction and analysis of transient signals of a deployable structure vibration based on the sparse decomposition with mixed norms. *Aerosp. Sci. Technol.* **105**, 106064 (2020)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.