

Development of Rigid-Foldable Thick Cylindrical Origami Structures and Their Tendon-Driven Deployment Mechanisms

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Contents

Abstract	1
Introduction	2
1.1 Origami-inspired structures	2
1.2 Origami with thick panels	3
1.3 Actuation strategies for origami-based applications	3
1.4 Goals	4
1.5 Thesis Organization	4
Rigid-Foldable Cylindrical Origami with Tunable Mechanical Behaviors	6
2.1 Introduction	6
2.2 Foldable prism origami	6
2.3 Geometry model	7
2.4 Mechanical behaviors of FP-ori with different parameters	10
2.4.1 Flat foldability	10
2.4.2 Self-locking	11
2.4.3 Bistability	11
2.5 Verification through finite element method and experiment	12
2.6 Programmable multi-unit FP-ori structure	14
2.6.1 Vertically stacked structure	14
2.6.2 Planar tessellation configuration	15
2.7 Discussion	16
2.8 Supplementary Materials	16
2.8.1 Crease patterns of triangular, pentagonal, and hexagonal foldable prism origami	16
2.8.2 Folding process by FEM simulation	17
2.8.3 Energy Model of the FP-ori truss structure	18
2.8.4 Multi-stable structure	19
2.8.5 Calculation of negative Poisson's ratio of tessellation structure	20
Foldable Cube Origami with Thick Panel and its Applications to Deployable Structure	22
3.1 Introduction	22
3.2 Rigid and flat foldable cubic origami	23
3.3 Kinematics of thick FC-ori structures	25
3.3.1 Linkage modeling method	25
3.3.2 Coordinate system method	28
3.4 3D-printed thick FC-ori module	31
3.5 Modular FC-ori module with programmable multistability	33
3.6 Modular deployable mobile robot	35
3.6.1 Various configuration modes of OriFlex	36
3.6.2 Functionalities of OriFlex under various modes	37
3.7 Discussion	39
3.8 Supplementary Materials	40
3.8.1 Calculation of the order of the FC-ori mechanism	40

3.8.2 Engineering drawings of components of FC-ori unit	42
3.8.3 Design of rotatable base used in mechanical testing	43
3.8.4 Self-locking capability of FC-ori	44
3.8.5 Spring-Magnet energy model theory	45
3.8.6 Modular, deployable mobile robot (OriFlex)	48
A Self-Locking Tendon-Driven Robotic Arm Inspired by Cubic Origami	50
4.1 Introduction	50
4.2.1 Rigid-foldable thick origami	51
4.2.2 Self-locking property of FC-ori	51
4.2.3 Force and moment transmission between the top panel and creases	53
4.3 Tendon-driven FC-ori unit	55
4.3.1 Kinematic relationship and mechanical testing	55
4.3.2 Optimization methods to reduce friction between the tendon and panel	57
4.3.3 Effect of Load on Tendon Tension and Structural Load-carrying Capacity ..	60
4.4 Origami robotic arm actuated by a single motor	62
4.4.1 Multi-unit serially connected robotic arm	62
4.4.2 Programmable parallel connected robotic arm	63
4.4.3 Comparison with existing tendon-driven origami robotic arms	64
4.5 Discussion	66
4.6 Supplementary Materials	67
4.6.1 Calculation method for rotating coordinates around an arbitrary vector in three-dimensional space.	67
4.6.2 Materials and methods	67
Conclusion and Future Work	70
5.1 Conclusion	70
5.2 Future work	71
Reference	73
List of publications	80
Acknowledgment	81

Abstract

Rigid-foldable origami structures offer significant advantages for deployable systems, including compactness, tunable mechanical behavior, and reconfigurable functionality. However, traditional cylindrical origami designs often suffer from limited rigid-foldability and mechanical robustness, constraining their broader engineering applications. This study systematically proposes a class of ideal rigid-foldable cylindrical origami structures characterized by programmable mechanical properties, regular prismatic configurations, and compact footprint. To address the challenges of thick panels and inconvenience of folding in practical, a modified crease method to remain rigid- and flat-foldability and an actuation method using only a single motor are developed, respectively, aiming to bridge the gap between theoretical foldability and practical applications. First, I propose a foldable prism origami (FP-ori) structure inspired by Kresling origami that achieves rigid-foldability and tunable features like flat-foldability, monostability, and bistability by adjusting geometric parameters. The relationship between geometric parameters and mechanical behaviors was validated through finite element simulations, energy model and paper model experiments. Furthermore, multi-unit structures with stackability and controllable rotation directions were constructed, incorporating kirigami concepts to realize configurations exhibiting significant negative Poisson's ratio. Next, to address thickness-induced limitations and enable cubic rigid-folding, I further introduce a sliding crease method which incorporates translational degrees of freedom along selected creases to foldable cube origami (FC-ori). FC-ori units exhibit programmable multistability when embedded with various magnets and springs, forming the frame for modular deployable robots capable of terrain adaptability and shape transformation. Finally, I develop a tendon-driven actuation strategy to overcome geometric self-locking constraints of FC-ori units. By optimizing tendon routes to reduce friction, I demonstrate multi-unit robotic arms that can switch between folded and deployed states within seconds, using only a single motor. These systems highlight the feasibility of compact, reconfigurable, and high-stiffness robotic structures for applications in aerospace, foldable shelters, and adaptive robotic systems. Overall, this work provides a unified framework for the geometric design, mechanical programming, and actuation of rigid-foldable origami, opening new avenues for advanced engineering applications requiring compactness, adaptability, and structural integrity.

Chapter 1

Introduction

1.1 Origami-inspired structures

In recent years, deployable structures have garnered significant attention due to their advantages in volume reduction, rapid deployment, and spatial adaptability. These features have made them highly valuable across various engineering domains, particularly in high-performance, compact scenarios such as metamaterials [1-6], aerospace structures [7, 8], disaster search and rescue [9], and medical devices [10, 11]. Compared to traditional rigid structures, these morphable systems achieve enhanced spatial efficiency and multifunctional integration through folding, deploying, or shape-morphing mechanisms.

Among various deployable structure configurations, origami-inspired structures, which derived from the ancient art of paper folding, have become a powerful tool in modern reconfigurable design, due to their intrinsic advantages including tunable mechanical properties, lightweight, compressibility, geometric versatility, scalability and modularity. Common origami structures include Miura origami, water-bomb origami, Kresling origami, twisted tower origami, Yoshimura origami, and Tachi-Miura origami. Due to differences in folding configurations and mechanical properties, each of these structures has found distinct applications in engineering fields. For instance, Miura origami allows a planar panel to be folded into a highly compact form; this is widely applied in origami robots [12] and solar panels due to its outstanding folding efficiency [13]. Waterbomb origami, which can transform between spherical and cylindrical configurations, has been utilized to develop wheels with variable diameters [14, 15] and vacuum grippers capable of grasping objects with diverse shapes [16]. Kresling origami, possessing multistability and adjustable height, is frequently applied in robotics, particularly for crawling robots driven by pneumatic actuators [17] or magnetic forces [18]. Twisted tower origami exhibits various modes of motion, such as bending, twisting, and compression, and has been applied in flexible robotic arms [19] and grippers [20]. Yoshimura origami is composed of diamond facets and is commonly used for an energy absorber [21]. Tachi-Miura origami, a type of rigid foldable cylindrical origami, can be applied in jumping mechanisms [22]. In addition, researchers have created modified origami by adding creases, incisions, or combining other origami patterns [23-25]. Compared to the original origami structures, the modified designs retain some original properties while introducing new and intriguing features. Therefore, to enable origami structures to support more advanced functions and better meet the demands of practical engineering applications, the development of new origami configurations is both necessary and imperative.

Among the key considerations in designing novel origami configurations, rigid-foldability and flat-foldability play particularly critical roles. Origami structures with rigid-foldability enable facets to rotate solely around the creases without undergoing deformation throughout the folding process [26] and origami structures with flat-foldability can be folded into a flat overlapped sheet [27]. Rigid-foldability ensures smooth folding and allows for the structure to maintain its shape when folded, which is essential for designing rigid-material origami robots. Flat-foldability

permits efficient storage and transportation of the deployable structure [28]. The single-vertex origami satisfying Kawasaki's theorem [29] (e.g., Miura origami) is a representative structure that possesses both rigid-foldability and flat-foldability. However, it is inherently a two-dimension(2D) configuration, which imposes certain limitations in applications requiring three-dimensional form. Compared to cylindrical origami structures, the 2D origami lacks volumetric enclosure capability, making it unsuitable for structural packaging or integration into deployable robotic arms. Moreover, its planar geometry is not conducive to achieving spatial stiffness, a property that is particularly important in engineering systems with high load-bearing or motion control requirements. Several origami structures have been identified that simultaneously exhibit three-dimension (3D) configuration, rigid-foldability, and flat-foldability. These include Miura origami tube [30], Tachi-Miura origami [31], Sarrus linkage [9], kirigami-inspired foldable cuboid [32] and some rigid-foldable cubes [33-35]. Different from Miura origami and Tachi-Miura origami, the latter types all feature regular prismatic configurations, which means that they are more easily applicable in robotics.

1.2 Origami with thick panels

The kinematics of origami structures are typically derived from zero-thickness models. However, in practical engineering applications where thick materials are required to ensure motion accuracy and structural robustness, the panel thickness can no longer be ignored, leading to deviations in the expected kinematic behavior. In general, the accumulation of material thickness during folding results in geometric interference, making folding or deployment difficult. To address this issue, numerous strategies have been proposed to enable the folding of origami structures with thick panels. For example, Faber et al. employed yielding hinges with a Young's modulus of 25 N/mm² and rigid panels with a Young's modulus of 2852 N/mm² to fold a Miura origami structure [36]. Chen et al. proposed a method that replaces traditional creases with rigid panels connected through offset folds to actuate single-vertex origami, and further established the relationship between the offset distance and the crease angle [37]. In addition, Gu et al. introduced an approach in which the creases are replaced by two auxiliary panels, allowing a thick-panel cube to be fully flat-folded [33]. Trautz et al. assigned an additional translational degree of freedom to the crease, which increases the foldability range of thick Miura origami [38]. Tachi using tapered or two-ply panels and hinges located at edges of thick panel structure [39].

However, these methods each suffer from certain limitations. The use of compliant hinges compromises the structural strength; offsetting panels results in non-uniform panel thickness; introducing auxiliary panels and Tachi's method leads to an unseamless flat-folded configuration; and adding translational hinges cannot achieve full flat-folding of the Miura origami. In addition, most strategies for thick-panel origami have been developed primarily for planar origami patterns. Since no single strategy can be universally applied to all origami geometries, it is crucial in practical origami applications to identify or develop the most suitable thick-panel folding method for each specific structure.

1.3 Actuation strategies for origami-based applications

Effectively actuating multi-unit origami structures poses a significant challenge, as it directly

influences their practicality, controllability, and integration into engineering systems. Various actuation strategies have been developed to drive origami-inspired designs, such as direct actuation by stepper motors at creases [40], utilizing stimulus-responsive materials [41-44], pneumatic actuation [16, 45-47], magnetic actuation [18, 48-50] and tendon-driven actuation and others. Among these, tendon-driven actuation stands out for its compact implementation, remote controllability, simple control strategy, and compatibility with both elastic and rigid origami structures. It enables complex folding motions with minimal mechanical interference, making it particularly suitable for lightweight and deployable robotic systems. For instance, Lee et al. proposed a series of variable-diameter wheel drive robots based on an origami structure inspired by magic-ball origami, which is capable of adapting to various terrains [14, 15, 51]. Similarly, Liu et al. introduced a variable-width origami wheel inspired by Miura-ori, demonstrating enhanced mobility on sandy surfaces [52]. Both origami wheels employ tendon-driven actuation to achieve their shape reconfiguration. A tendon-driven bistable origami flexible gripper was proposed by Liu et al., featuring high-speed adaptive grasping capabilities [53]. A tendon-driven crawling origami robot controlled by a single motor was proposed by Banerjee et al [54]. In addition to the aforementioned examples, tendon-driven actuation is also widely applied in origami robotic arms. Based on the twisted tower origami structure, Lee et al. developed a robotic gripper capable of adaptable grasping of objects with varying shapes, weights, sizes, and surface textures [19]. Utilizing the same origami structure, Liu et al. further proposed a multi-degree-of-freedom robotic arm actuated by four motors [20]. Similarly, multi-degree-of-freedom soft origami robotic arms based on other origami structures—such as origami spring structures [55], water-bomb origami [56], Miura-ori [12], Kresling origami [57, 58], and Yoshimura origami [59-61]—can also be actuated using tendon-driven mechanisms. These examples demonstrate that tendon-driven actuation is well-suited for cylindrical origami structures.

1.4 Goals

This thesis propose a novel origami structure that possesses rigid-foldability, flat-foldability, and a multi-prismatic configuration. Furthermore, a folding method is proposed that enables flat folding even when thick plates are used in the origami structure. In addition, a method for driving the proposed origami structure using a tendon-driven actuation system is proposed.

1.5 Thesis Organization

The thesis is composed of five chapters.

Chapter 1 introduces the application domains of origami structures, folding strategies for thick-panel origami, and various actuation methods used in origami-based systems. It also highlights the major limitations of existing origami structures, namely the lack of rigid-foldability, flat-foldability, and well-defined three-dimensional configurations. These three properties are essential prerequisites in the design of my origami structure.

Chapter 2 presents a method for constructing a rigid-foldable multi-prismatic structure, referred to as the Foldable Prism Origami (FP-ori). The kinematics during the folding process are analytically derived. Depending on the structural geometric parameters, FP-ori exhibits tunable mechanical

behaviors, including flat-foldability, monostability, and bistability. Through finite element method simulation, the minimum energy method, and experimental validation, the correlations between geometric parameters and the tunable mechanical properties are systematically identified.

Chapter 3 utilizes the FP-ori structure with a cubic configuration, referred to as the Foldable Cube Origami (FC-ori). This structure simultaneously exhibits rigid-foldability and flat-foldability, making it an ideal candidate for deployable systems. By assigning additional translational degrees of freedom (DOF) to selected creases, the thick-panel FC-ori possesses folding characteristics consistent with those of its zero-thickness model. Using the DH transformation matrices, the kinematics of the thick FC-ori are derived, including the relationship between translational displacement and panel thickness. Furthermore, by changing the number of magnets and springs, a method is proposed to impart programmable multistability to the FC-ori unit. Based on these multistable FC-ori units, an origami mobile robot capable of multiple transformation modes is developed. Through transformation, the robot demonstrates the ability to adapt to and traverse various terrains.

Chapter 4 addresses the folding difficulty of the FC-ori caused by its inherent self-locking behavior. The axial self-locking mechanism in a fully deployed, thick FC-ori is analyzed, demonstrating that external force applied to the side panels is required for folding. To achieve this and enable rapid folding and unfolding of the FC-ori structure, a method driven by tendons sequentially wired along the side panels is proposed. Optimization strategies are further proposed to reduce tendon friction and to enhance the load-carrying capability of the FC-ori. Finally, a multi-unit origami robotic arm was developed, demonstrating the advantages of single actuation and rapid folding and deployment motion.

Chapter 5 summarizes the conclusions in each chapter and states the further study.

Chapter 2

Rigid-Foldable Cylindrical Origami with Tunable Mechanical Behaviors

2.1 Introduction

Unlike 2D origami, cylindrical origami has some creases that must be glued together to form a 3D unfolded configuration, which is more suitable for deployable structures [62]. Various types of cylindrical origami exist, such as Kresling origami, twisted tower origami, Yoshimura origami, and water-bomb origami. These origami structures have been widely applied in reconfigurable antennas [63], crawling robots [64], origami grippers [19], origami robotic arms [58], energy absorption structures [65] and origami wheels [66, 67]. Moreover, adding creases, combining multiple origami units, and introducing incisions can be applied to conventional origami configurations to endow them with enhanced or additional functionalities. For instance, Zhang et al. proposed a structure exhibiting programmable multistability through the integration of origami and kirigami [32]. Filipov assembled various Miura origami tubes to create a metamaterial that can be deployed, stiffened, and tuned [3]. Overall, cylindrical origami demonstrates strong potential for advancing deployable structures, origami-inspired robotic systems, and mechanical metamaterials.

In the theory and application of origami, two crucial properties must be considered: rigid-foldability and flat-foldability. Rigid-foldability determines whether an origami structure can be constructed using rigid panels and hinges, while flat-foldability ensures its compactability. However, most cylindrical origami structures lack these two properties, limiting their application range to soft materials or elastic hinges. To address this issue, several origami configurations have been proposed, such as the Tachi–Miura origami [68], the Sarrus linkage [9], and the kirigami cuboid [32]. However, the Tachi–Miura origami does not possess a prismatic configuration, while the Sarrus linkage and kirigami cuboid have relatively large footprints.

Hence, inspired by the Kresling origami, I propose a new cylindrical origami, named the Foldable Prism Origami (FP-ori), which incorporates diagonal cuts on the side facets. FP-ori simultaneously exhibits rigid-foldability, flat-foldability, a prismatic configuration, and a small footprint, making it an ideal deployable structure.

2.2 Foldable prism origami

FP-ori drew inspiration from Kresling origami and the transformation process from it to FP-ori is illustrated in Fig. 2.1(a). A foldable cube with $n=4$, where n is the number of polygon sides, is used as an example to explain the transformation process. The peak creases are depicted as red dashed line, valley creases as blue dashed-dotted line, and cut lines as black dashed double-dotted line. The crease pattern of a Kresling origami prism consists of several right triangles, and I add cut lines along the diagonal without creases. Subsequently, the crease pattern is reassembled into a windmill-like shape. Figure 2.1(b) demonstrates the final step, how to transform the crease pattern into a 3D FP-ori structure.

During the fabrication process, it is necessary to fold along creases and connect the overlapping regions using glue. To provide a more intuitive demonstration of the transformation process of FP-ori, a method for directly converting a prism into FP-ori is proposed. Based on the final step, all edges of the cube can be considered as peak creases and add valley creases and cuts on the side facets. Taking one side facet as an example, if the valley crease goes from the lower-left vertex to the upper-right vertex, then the cut extends from the upper-left vertex to the lower-right vertex. The directions of valley creases and cuts are identical on all side facets. This transformation method is referred to as the FP-ori method. In addition to square prisms, the FP-ori method can be used to rigidly fold all the polygonal prisms. (Please refer to Section 2.8 Supplementary Material, subsection 1, for the crease patterns and flat configurations of three types of FP-ori: a triangular prism, a pentagonal prism, and a hexagonal prism).

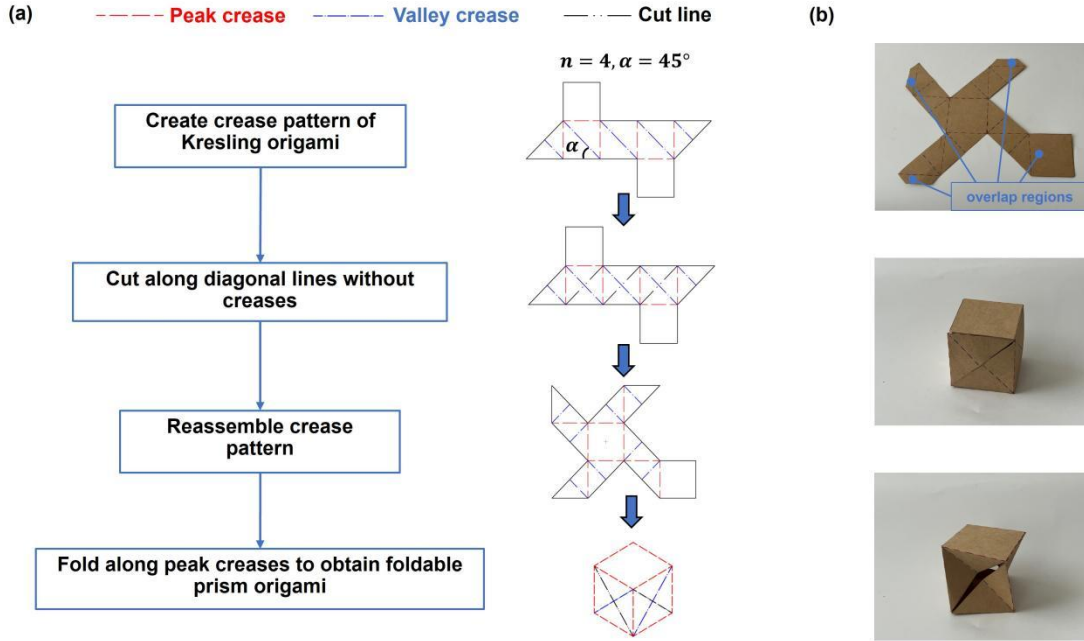


Figure 2.1 Transformation process of FP-ori. (a) Transformation from Kresling origami to FP-ori ($n=4$ and $\alpha=45^\circ$). (b) Fabrication process from crease pattern to 3D FP-ori structure.

2.3 Geometry model

This section focuses on constructing the geometric model of FP-ori. An FP-ori model (i.e., $n=4$) with eight vertices, denoted as A to H, is illustrated in Fig. 2.2(a) as an example. The bottom facet (i.e., ABCD) and the top facet (i.e., EFGH) are two identical regular polygons with the same side length l , interior angle β , and the number of polygon sides n . Points I and J represent two intersection points of the diagonals. A Cartesian coordinate system with its origin at the center point O of the bottom facet (O-xyz) is established. The x-axis runs parallel to the vector $\overrightarrow{DA}$ and the z-axis is perpendicular to the bottom facet ABCD.

According to origami theory, the facets were considered as rigid panels and creases as axial rotation hinges. For the sake of convenience, I assumed that the top and bottom facets remain parallel to each other during the entire folding process, ensuring geometric symmetry in the four limbs (ABEH, BCFE, CDGF, and DAHG). This assumption results in a single degree of freedom for the entire folding

process, establishing a one-to-one correspondence for all parameters. The coordinates of points A, B, E, I, and J are provided in Table 2.1. Here, α represents the angle between the diagonal BJ and the bottom side BA, where $0 < \alpha \ll \beta/2$, φ_i ($i=1, 2, 3, 4, 5$) are the dihedral angles from the top facet to the bottom facet, as depicted in Fig. 2.2(a), where $0 < \varphi_1, \varphi_3, \varphi_5 \leq \pi/2$ and $0 < \varphi_2, \varphi_4 \leq \pi$. Additionally, h is the height from the top facet to the bottom facet, and θ signifies the rotation angle between the top and bottom facets.

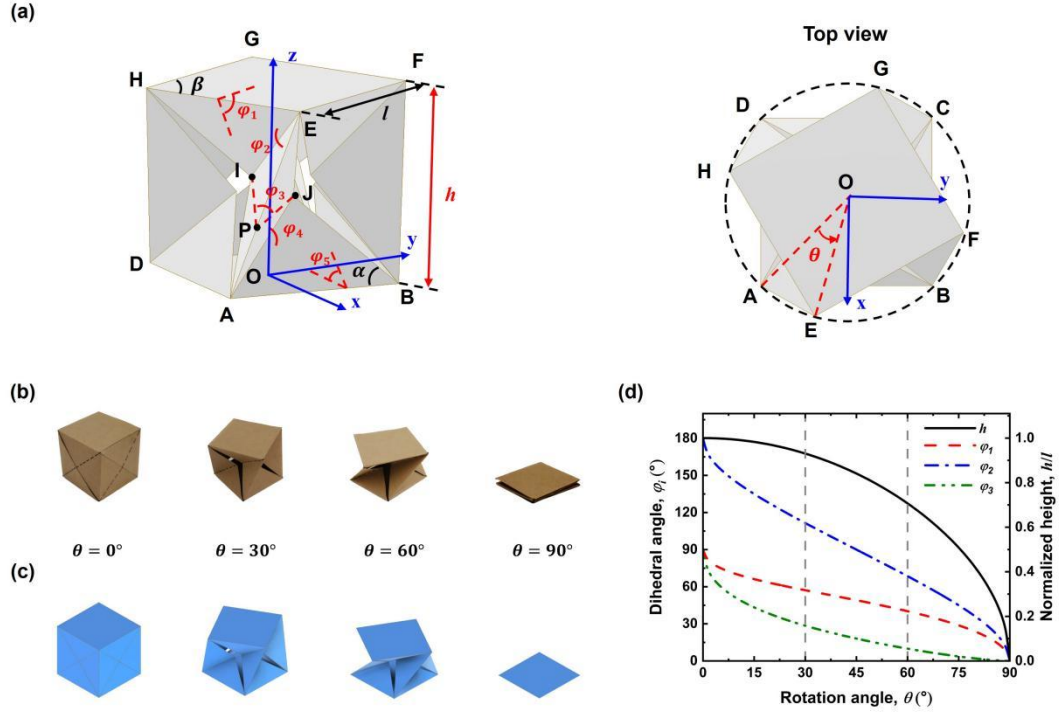


Figure 2.2 Geometric relationships of FP-ori. (a) Schematic diagram and top view of FP-ori with $n=4$ and $\alpha=45^\circ$. (b) Actual folding process and (c) simulation results. (d) Variation of φ_i and h during the folding process of FP-ori with $n=4$ and $\alpha=45^\circ$.

Table 2.1 Coordinates of points A, B, E, I, and J.

Poi nt	x-coordinate	y-coordinate	z-coordinate
A	$\tan(\beta/2) l/2$	$-l/2$	0
B	$\tan(\beta/2) l/2$	$l/2$	0
E	$[\tan(\beta/2) \cos \theta + \sin \theta] l/2$	$[\tan(\beta/2) \sin \theta - \cos \theta] l/2$	h
I	$[\tan(\beta/2) - \cos \varphi_1 \tan \alpha] \cos \theta l/2$	$[\tan(\beta/2) - \cos \varphi_1 \tan \alpha] \sin \theta l/2$	$h - \sin \varphi_1 \tan \alpha l/2$
J	$[\tan(\beta/2) - \cos \varphi_1 \tan \alpha] l/2$	0	$l \sin \varphi_1 \tan \alpha/2$

Because the deformation of the surface is not considered, the distance between points E and A and that between points E and J are calculated as follows:

$$|\overrightarrow{EA}| = l \tan \alpha \quad (2.1)$$

$$|\overrightarrow{EJ}| = l / (2 \cos \alpha) \quad (2.2)$$

From the definition of the dihedral angle, the following equation can be obtained:

$$\cos \varphi_4 = \vec{N}_{ABJ} \cdot \vec{N}_{AEJ} \quad (2.3)$$

where $\vec{N}_{ABJ}$ and $\vec{N}_{AEJ}$ are the unit normal vectors of facets ABJ and AEJ, respectively.

Point P is the midpoint of line AE. Therefore, line segments IP and JP are respectively perpendicular to line AE. In the triangle PIJ, according to the law of cosines, the following equation can be obtained:

$$|\overrightarrow{IJ}|^2 = |\overrightarrow{PI}|^2 + |\overrightarrow{PJ}|^2 - 2|\overrightarrow{PI}||\overrightarrow{PJ}|\cos \varphi_3 \quad (2.4)$$

Some parameters are identical throughout the folding process because of symmetry; they can be written as:

$$\begin{cases} \varphi_1 = \varphi_5 \\ \varphi_2 = \varphi_4 \end{cases} \quad (2.5)$$

Solving and arranging equations (1), (2), (3), and (4) yields the following equations:

$$h = l \cdot \sqrt{\tan^2 \alpha - \frac{1 - \cos \theta}{2 \cos^2 (\beta/2)}} \quad (2.6)$$

$$\left(\tan \frac{\beta}{2} (\cos \theta - 1) + \sin \theta + \tan \alpha \cos \varphi_1 \right)^2 + \left(\cos \theta - \sin \theta \tan^2 \frac{\beta}{2} + \left(\frac{2h}{l} - \tan \alpha \sin \varphi_1 \right)^2 \right) \cos^2 \alpha = 1 \quad (2.7)$$

$$\cos \varphi_2 = \frac{2 \sin^4 \alpha + 1 - 3 \sin^2 \alpha}{2 \sin^2 \alpha (1 - \sin^2 \alpha)} - \frac{\cos \theta + \cos (\theta + \beta)}{4(1 - \sin^2 \alpha) \cos^2 \beta/2 \tan^2 \alpha} \quad (2.8)$$

$$\cos \varphi_3 = 1 - \frac{4 \cdot \cos^2 (\beta/2) \cdot \tan^2 \alpha \cdot (h/l - \tan \alpha \sin \varphi_1)^2}{1 - \cos \theta} \quad (2.9)$$

Therefore, φ_i and h can be obtained from equations (2.6), (2.7), (2.8), and (2.9) for various values of α , β , and θ . β is determined from the number of polygon sides n as:

$$\beta = \frac{n-2}{n} \pi \quad (2.10)$$

Figure 2.2(b) illustrates the folding process of a paper-made cubic FP-ori in four stages corresponding to $\theta=0^\circ$, 30° , 60° , and 90° , and Fig. 2.2(c) displays the simulation results obtained using Autodesk Inventor Professional 2021. Based on the previously described geometry model, the variation of φ_i during the folding process of this FP-ori was calculated and the results are illustrated in Fig. 2.2(d). It is evident that there is a one-to-one correspondence between φ_i and θ , which verifies FP-ori as a type of rigid-foldable origami. In simpler terms, this FP-ori can be rigidly folded from a cube into a square resulting in a significant volume change, rendering it suitable for using in deployable structures.

2.4 Mechanical behaviors of FP-ori with different parameters

In the case of FP-ori, the origami configuration is completely determined by three main geometric parameters, namely l , n , and α , while l controls the structure proportionally scaled up and down. Consequently, an FP-ori configuration can be predominantly determined by n and α . This section mainly delves into the mechanical behaviors of FP-ori with different values of n and α .

2.4.1 Flat foldability

The preceding calculations and simulations demonstrated that FP-ori with $n=4$ and $\alpha=45^\circ$ can transform from a 3D prism to a 2D polygon plane after rigid folding, indicating its flat-foldability. The hexagonal prism ($n=6$), as shown in Fig. 2.3(a), is utilized to determine the condition for flat-foldability. The top and bottom facets are designated as $\Sigma 1$ and $\Sigma 6$, respectively, while the triangular facets are denoted as $\Sigma 2$, $\Sigma 3$, $\Sigma 4$, and $\Sigma 5$, as depicted in Fig. 2.3(a). The top view in Fig. 2.3(a) reveals that only one of the limbs becomes flat without considering the influence of facets $\Sigma 1$ and $\Sigma 6$. Rotation angle θ represents the rotation angle of point C around center point O of the bottom facet and the rotation angle θ' signifies the angle between line CD and line C'D', where C'D' indicated the position of line CD after folding. For this origami structure to be flat-foldable, the top facet should remain a hexagon and the center points of the top and bottom facets should coincide during the folding process. Consequently, the two rotation angles θ and θ' must be identical, yielding the following equations:

$$|\overrightarrow{C'B}|^2 = |\overrightarrow{C'O}|^2 + |\overrightarrow{BO}|^2 - 2|\overrightarrow{C'O}||\overrightarrow{BO}| \cos \theta \quad (2.11)$$

$$\theta' = 4\alpha - \beta \quad (2.12)$$

Substituting equation (2.11) into equation (2.12), the relationship equation can be rewritten as:

$$\left(\tan \alpha - \tan \left(\frac{\pi(n-2)}{2n} \right) \right) \cos 2\alpha = 0 \quad (2.13)$$

Solving equation (2.13) yields the following condition for the flat-foldability of FP-ori:

$$\alpha = \frac{\pi(n-2)}{2n} = \frac{\beta}{2} \text{ or } \alpha = \frac{\pi}{4} \quad (2.14)$$

FP-ori can be folded into a plane without facet or crease deformation only when $\alpha = \beta/2$ or $\alpha = \pi/4$.

2.4.2 Self-locking

Figure 2.3(b) displays three types of hexagonal FP-ori, with $\alpha = 30^\circ$, 45° , and 60° , respectively. The folding process is segmented into Stages A, B, and C, representing the initial configuration, intermediate configuration, and final configuration of FP-ori, respectively. When the hexagonal FP-ori with $\alpha = 30^\circ$ reaches the folding limit at Stage C, facets $\Sigma 1$ and $\Sigma 2$ as well as facets $\Sigma 5$ and $\Sigma 6$ interfere with each other and there remains a certain angle between facets $\Sigma 3$ and $\Sigma 4$. This configuration is referred to as $\Sigma 1$ - $\Sigma 2$ and $\Sigma 5$ - $\Sigma 6$ self-locking. When $\alpha = 45^\circ$, all facets align simultaneously within the same plane at Stage C, which demonstrates the aforementioned rigid and flat-foldability of FP-ori. For FP-ori with $\alpha = 60^\circ$, which also satisfies the flat-foldability condition, facets $\Sigma 3$ and $\Sigma 4$ yet interfere with each other, characterizing it as $\Sigma 3$ - $\Sigma 4$ self-locking.

To clarify the self-locking conditions of FP-ori, the variations of φ_1 , φ_2 , φ_3 , and h/l of FP-ori with n and α are illustrated in Fig. 2.3(c). The solid lines in the figure indicate that φ_i ($i=1, 2, 3$) and h/l become zero simultaneously at the end of the folding process only when $\alpha = 45^\circ$. For cases involving $n=5$ and $\alpha=54^\circ$ or $n=6$ and $\alpha=60^\circ$, represented by the dashed-dotted lines, φ_3 is zero while φ_1 and φ_2 are not zero at the end of the folding process, even though the flat-foldability condition is satisfied, which is attributed to $\Sigma 3$ - $\Sigma 4$ self-locking. When $\alpha = 30^\circ$, as indicated by the dashed lines, only φ_1 becomes zero at the end of the folding process, signifying $\Sigma 1$ - $\Sigma 2$ self-locking. Consequently, FP-ori can exhibit rigid and flat-foldable only when $\alpha = 45^\circ$; self-locking occurs when $\alpha \neq 45^\circ$. It is apparent that $\Sigma 1$ - $\Sigma 2$ and $\Sigma 5$ - $\Sigma 6$ self-locking arises when $\alpha < 45^\circ$ and $\Sigma 3$ - $\Sigma 4$ self-locking occurs when $\alpha > 45^\circ$. These conclusions are consistent with the results obtained from the aforementioned simulation.

2.4.3 Bistability

Kresling origami structures with specific parameters exhibit two unstrained configurations during the folding process. Building upon the calculations in the previous section, it has been observed that certain FP-ori structures cannot be folded flat even when they satisfy the flat-foldability condition. This implies that some FP-ori structures may also possess two unstrained configurations. As a result, it is speculated that after reaching the self-locking state, FP-ori under certain parameters may exhibit bistability, similar to that of Kresling origami.

For instance, self-locking structures with $\alpha = \beta/2$ (e.g., $n=5$ and $\alpha=54^\circ$ or $n=6$ and $\alpha=60^\circ$) satisfy the flat-foldability condition, as previously discussed. The structure should undergo no facet deformation in these two configurations (self-locking and flat-folded states). Put differently, no deformation energy is generated in these two states, whereas deformation energy exists between these states. To validate this, it is assumed that facets $\Sigma 3$ and $\Sigma 4$ can penetrate each other after self-locking, causing φ_3 to negative. The negative value is used to reflect the degree of deformation, with a larger absolute value of the angle φ_3 indicating a greater stored energy for the entire structure.

Figure 2.3(d) illustrates the variations of φ_1 and φ_3 during the folding process of hexagonal FP-ori ($n=6$) with $\alpha=30^\circ$, 45° , 54° , and 60° . The gray dotted line serves as the positive and negative dividing line for φ_3 . The figure shows that the structure is both rigid and flat-foldable when $\alpha=45^\circ$ because φ_1 and φ_3 simultaneously reach zero. Self-locking occurs at $\alpha=30^\circ$, 54° , and 60° . When $\alpha=30^\circ$, only φ_1 becomes zero, indicating that $\Sigma 1$ - $\Sigma 2$ self-locking occurs but $\Sigma 3$ and $\Sigma 4$ do not interfere with each other. For $\alpha=54^\circ$ and 60° , φ_3 becomes zero first, signifying $\Sigma 3$ - $\Sigma 4$ self-locking, while the trend of the curves in these two configurations is distinct thereafter. When $\alpha=54^\circ$, φ_3 does not return to zero with an increase in φ_1 , but when $\alpha=60^\circ$, φ_3 crosses the zero line and eventually returns to zero. Consequently, it is speculated that FP-ori with $\alpha=60^\circ$ possesses bistability because φ_3 has two zero points during the folding process, whereas FP-ori with $\alpha=54^\circ$ should be a monostable structure as φ_3 steadily decreases with only one zero point.

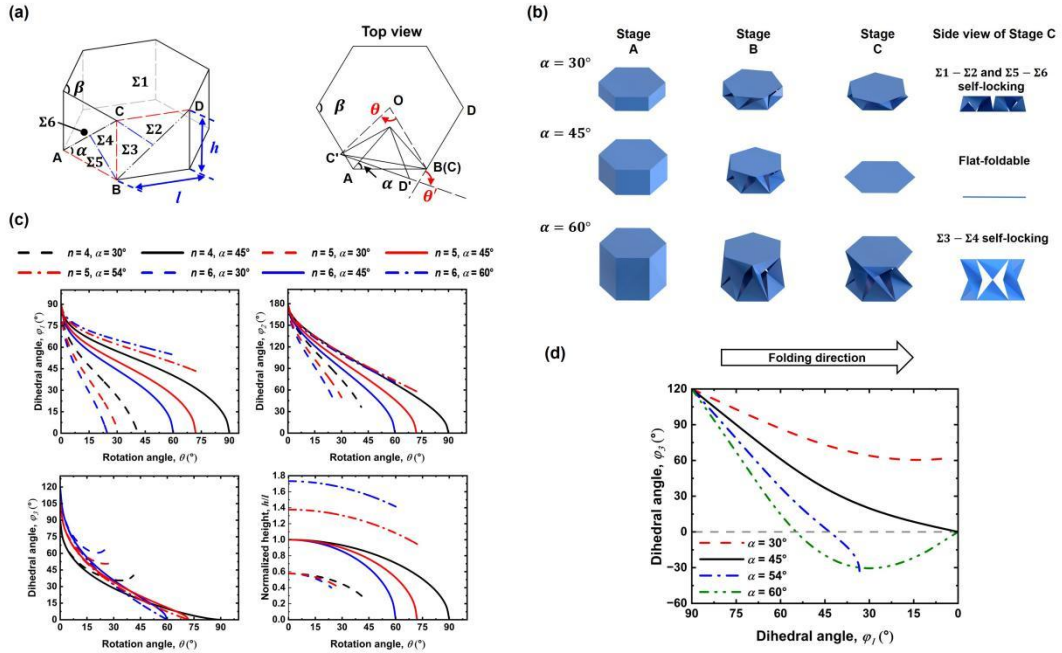


Figure 2.3 Mechanical behaviors of FP-ori with various parameter values. (a) Schematic diagram and top view of a single limb (ABCD) in hexagonal FP-ori (b) Folding process of FP-ori structure with various values of α ($\alpha=30^\circ$, 45° , 60°). (c) Variation of φ_1 , φ_2 , φ_3 , and h/l with n and α . (d) Variation of φ_1 and φ_3 with α ($\alpha=30^\circ$, 45° , 54° , 60°).

2.5 Verification through finite element method and experiment

To verify the properties of FP-ori as discussed in the previous section, finite element method (FEM) simulations were conducted using Abaqus 2021. To simplify the simulation of FP-ori, as shown in Fig. 2.4(a), a truss mode was established wherein all the creases were regarded as trusses capable of stretching and compressing without bending. The joints of the trusses were considered as hinges that could freely rotate in any direction. Young's modulus was set at 210 MPa and Poisson's ratio was 0.3. Each truss had a single element to prevent bending with the section area of 1 mm^2 and the length of each hexagon side was 5 mm. Simulations were conducted on four FP-ori truss models with $\alpha=30^\circ$, 45° , 54° , and 60° to verify the mechanical behaviors discussed in the previous section. The initial configuration of each FP-ori structure corresponds to the configuration where self-locking occurs when

$\alpha=30^\circ$, 54° , and 60° . Since no self-locking occurs when $\alpha=45^\circ$, the initial position represents the configuration where $\varphi_1=45^\circ$ (The analysis can be found in Supplementary Material, section 2).

The simulation results are presented in Fig. 2.4(b). The strain energy U represents the deformation energy in the folding process. The strain energy remains zero when $\alpha=45^\circ$, which verifies that FP-ori with $\alpha=45^\circ$ is a rigid and flat-foldable structure. When $\alpha=30^\circ$ or 54° , there is only one zero-energy point, namely in the initial configuration. The FP-ori structure with $\alpha=30^\circ$ can store significantly more strain energy than that with $\alpha=54^\circ$, indicating that FP-ori with $\alpha=30^\circ$ possesses a greater stiffness than that of FP-ori with $\alpha=54^\circ$. For $\alpha=60^\circ$, two zero-energy points are identified, consistent with bistability. Figure 2.4(c) illustrates the compression force-displacement curve, further confirming the validity of the previously drawn conclusions.

Furthermore, we established an energy model to elucidate the tunable mechanical behavior of FP-ori origami when $\alpha>45^\circ$ (Please refer to Supplementary Material, section 3, for calculation details). This model is also based on the origami truss model. The trusses composing the top and bottom facets are assumed to remain rigid throughout the entire process, while the axial trusses located between the top and bottom facets are considered to generate linear elastic deformation with the same Young's module and section as in FEM. By summing the strain energy produced by each elastic truss during the compression process, I obtained the deformation energy of the entire FP-ori structure. By employing the principle of minimum total potential energy approach and utilizing MATLAB to solve partial differential equations, I obtained the analysis results depicted in Fig. 2.4(b). It is evident that the results of the energy model are in good agreement with the FEM simulation results.

Therefore, I can summarize FP-ori's tunable mechanical behaviors as follows (illustrated in Fig. 2.4(d)): when the angle α is between 0° and 45° , it belongs to type 1, $\Sigma 1$ - $\Sigma 2$ and $\Sigma 5$ - $\Sigma 6$ self-locking. At 45° , it exhibits rigid foldability and flat-foldability, referred to as type 2. Between 45° and $\beta/2$, it belongs to $\Sigma 3$ - $\Sigma 4$ self-locking, and there exists a certain value that separates it into type 3, comprising a solely monostable state, and type 4, comprising a bistable state.

To further validate the previously obtained conclusions, I conducted two sets of comparative experiments involving monostable and bistable configurations. As shown in Fig. 2.4(e), four models using paper were crafted with a thickness of 0.35mm, including two hexagonal FP-oris ($n=6$) with the angle α of 54° and 60° , as well as two octagonal FP-oris ($n=8$) with the angle α of 54° and 67.5° , and all the polygons possess a side length of 40 mm. Notably, 60° ($n=6$) and 67.5° ($n=8$) are both equal to $\beta/2$. According to the previous conclusion, FP-ori should exhibit bistable behavior in these two cases. When I subjected these four structures to simple compression experiments, I found that for $n=6$ and $\alpha=54^\circ$, and $n=8$ and $\alpha=54^\circ$, only a unique stable state was observed. However, for $n=6$ and $\alpha=60^\circ$, and $n=8$ and $\alpha=67.5^\circ$, two clear bistable states were observed. Consequently, even when the paper thickness couldn't be negligibly small, I still obtained results consistent with FEM, confirming that FP-ori indeed possesses tunable mechanical behaviors under different parameters.

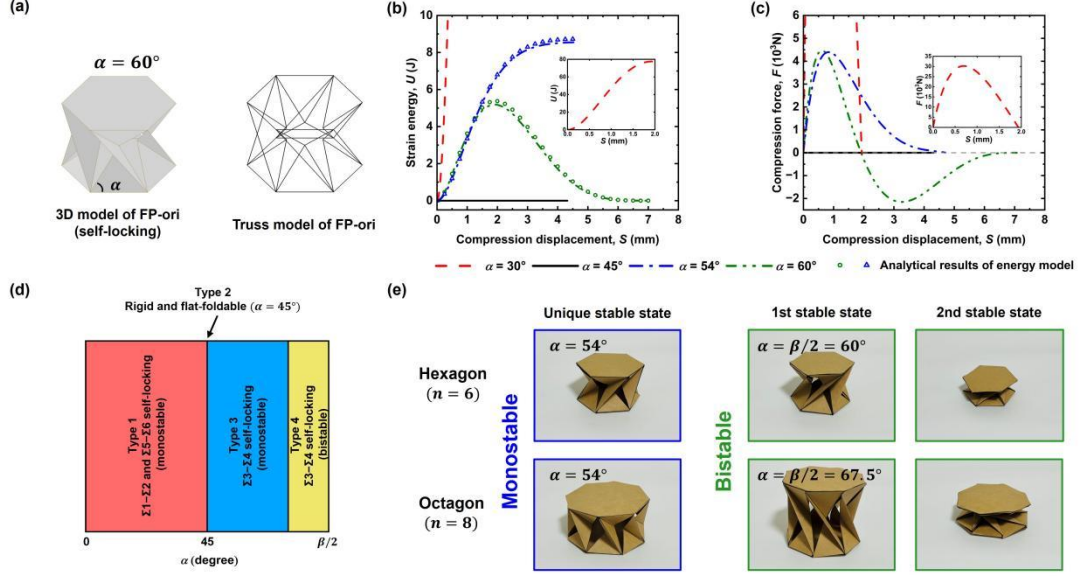


Figure 2.4 Results of FEM simulation and experiments using paper model. (a) Transformation from the cylindrical structure based on FP-ori with $\alpha=60^\circ$ to truss model. (b) Generated strain energy during the folding process for various α values. (c) Force-displacement curves for various α values. (d) Tunable mechanical behaviors with respect to the angle α . (e) Comparative experiments between paper-made bistable FP-ori ($n=6, \alpha=60^\circ$; $n=8, \alpha=67.5^\circ$) and monostable FP-ori ($n=6, \alpha=54^\circ$; $n=8, \alpha=54^\circ$)

2.6 Programmable multi-unit FP-ori structure

In the previous sections, I described the geometry, kinematics, and mechanical behaviors of an FP-ori unit. However, when multiple origami units are combined to form a complex structure, a wide range of properties can be achieved. Taking the Miura origami, the most widely recognized and extensively researched origami structure, as an example, when units with different parameters are combined, it exhibits the ability to design a ‘globally planar’ or ‘globally curved pattern’ [69-73]. It also demonstrates properties such as self-locking [26], graded stiffness [74], and other interesting geometric and mechanical characteristics. Therefore, researching how to combine multiple origami units into complex origami structures holds profound significance for future research. In this section, I introduce methods for the vertically and horizontally connecting multiple FP-ori units, which can be employed to control the rotation direction and construct 3D structures with a negative Poisson's ratio.

2.6.1 Vertically stacked structure

When all the parameters of two FP-ori units are the same but mirror-symmetrical under the given folding angle, the only difference between these two FP-ori units is the rotation direction between the top and bottom facets, which is referred to as chirality. Two symmetrical cubic FP-ori units are depicted in Fig. 2.5(a). The rotation direction of the left (red) one is counterclockwise and that of the right (blue) one is clockwise. By combining these two FP-ori units, three types of two-layer stacked FP-ori structure can be created, as shown in Fig. 2.5(b). If two FP-ori units with the same rotation direction are combined, the rotation direction of the stacked structure remains unchanged. When a clockwise FP-ori unit is combined with a counterclockwise one, the top and bottom facets can be

regarded as relatively static with only the middle part rotating, which is similar to Kresling origami. By stacking FP-ori units with different mechanical properties, complex mechanical properties, such as multi-stability, can be achieved (Please see Supplementary Material, section 4 for details). Therefore, the rotation directions and mechanical properties of vertically stacked FP-ori are both programmable, making them applicable in the design of deployable structures such as crawling robots [18] and robotic arms [9].

2.6.2 Planar tessellation configuration

FP-ori can also be combined into a planar tessellation configuration, drawing inspiration from square kirigami tessellation. In Fig. 2.5(c), compacted and deployed configuration of such kirigami with periodic square tiling is exhibited. The cuts along the edges of the squares are designed to allow for rotational in-plane deployment around a set of hinges [75]. A basic unit of the tessellation structure is formed by connecting four pairwise chiral FP-ori units, as shown in Fig. 2.5(d). The yellow and green dashed lines represent the contour of the top and bottom facets, respectively. The FP-ori tessellation structure can be regarded as composed of a square kirigami tessellation and another one rotated by 90° . Figure 2.5(e) illustrates the folding process of the tessellation structure when all bottom facets are fixed on the same plane. Using this method, the multi-unit FP-ori structure can be extended in three directions (x , y , and z), as shown in Fig. 2.5(f). Similar to kirigami tessellation, the FP-ori tessellation structure exhibits a negative in-plane Poisson's ratio. Additionally, owing to the properties of FP-ori itself, the structure also has a negative out-of-plane Poisson's ratio (Please see Supplementary Material, section 5 for details on the negative Poisson's ratio calculation). In comparison to planar kirigami tessellation, 3D FP-ori tessellation offers one additional designable dimension. Consequently, FP-ori tessellation is a novel structure with a negative Poisson's ratio that holds great potential for broad application in the field of functional metamaterials [76].

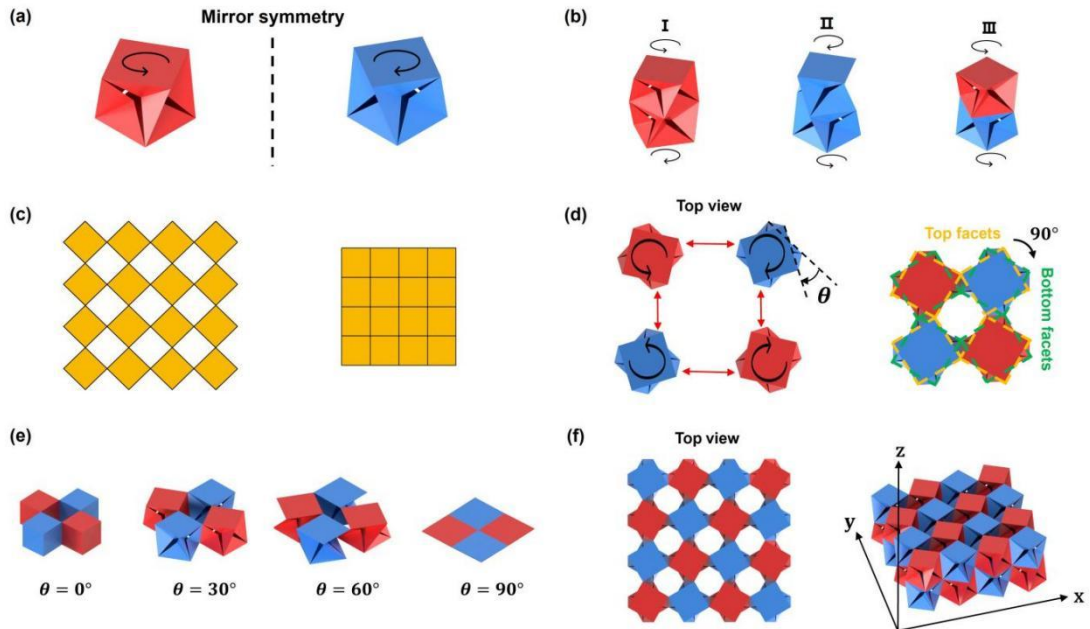


Figure 2.5 Multi-unit FP-ori structures. (a) Two basic chiral FP-ori units. (b) Two-layer stacked FP-ori structures. (c) Deployed and compacted configurations of square kirigami tessellation. (d) Basic unit of

FP-ori tessellation structure. (e) Folding process of a single basic unit. (f) Two-layer FP-ori tessellation structure.

2.7 Discussion

I proposed FP-ori, a rigid-foldable origami inspired by Kresling origami, and conducted a comprehensive analysis of its geometry and mechanical behaviors using the geometric method, FEM simulation, energy model and experiment. To achieve rigid-foldability, FP-ori incorporates several cut lines to Kresling origami. I calculated its geometric relationships between parameters and verified them using 3D modeling software. Different parameter values for FP-ori were found to yield various behaviors, including self-locking, flat-foldability, and bistability. The sole condition for achieving rigid and flat-foldability is $\alpha=45^\circ$, which also serves as the boundary between the two different self-locking types. In addition, for the second type of self-locking ($\Sigma 3$ - $\Sigma 4$ self-locking), the existence of bistability depends on the geometric parameter values of FP-ori. FEM simulation was applied to verify the tunable mechanical behaviors of FP-ori with different parameter values and the results aligned with energy model analytical result and experiment. Furthermore, I proposed two methods for constructing multi-unit FP-ori structures. The first method leverages chirality to control the rotation direction of the multi-unit stacked FP-ori structure. The second method was inspired from kirigami tessellation, combining multiple FP-ori units to create a multi-layer tessellation structure with a significantly negative Poisson's ratio.

In addition, I noticed that Yasuda proposed a truss structure inspired by Kresling origami [77], which possesses similar tunable mechanical behaviors with FP-ori. Compared with it, FP-ori exhibits several advantages: First, the FP-ori modified method is not limited to truss structures, but can be applied to origami structures, which has potential in deployable structures that prohibit removing facets. Secondly, FP-ori with $\alpha=45^\circ$ has both rigid-foldability and flat-foldability, while Yasuda's truss model can only fold a distance equivalent to 15% of its initial height in zero-stiffness mode. Thirdly, FP-ori units can be vertically and horizontally connected, providing additional designable dimensions than other modified Kresling origami structure.

In summary, FP-ori with $\alpha=45^\circ$ can achieve both rigid and flat-foldable, resulting in a considerable variation in volume, indicating this type of FP-ori is well-suited for deployable structures and origami robots. Moreover, FP-ori structures with other parameter values have potential as origami metamaterials because of their tunable mechanical behavior. However, the study presented in this chapter is based on a zero-thickness model of the origami structure. In practical applications, the finite thickness of origami sheets cannot be neglected, and this often alters the kinematics of the structure, leading to unexpected interference during folding. In chapter 3, this issue will be addressed in detail.

2.8 Supplementary Materials

2.8.1 Crease patterns of triangular, pentagonal, and hexagonal foldable prism origami

In Fig. 2.1, I showed that the FP-ori method can be applied to all regular prisms to achieve rigid folding. The crease patterns, deployed configurations, and flat-folded configurations of a triangular prism with $\alpha=30^\circ$, a pentagonal prism with $\alpha=54^\circ$, and a hexagonal prism with $\alpha=60^\circ$ are shown in Fig. S2.1 These three examples all satisfy the flat-foldability conditions obtained in the main article, so the flat-folded

configuration can be obtained without considering the intermediate process of the bistable state.

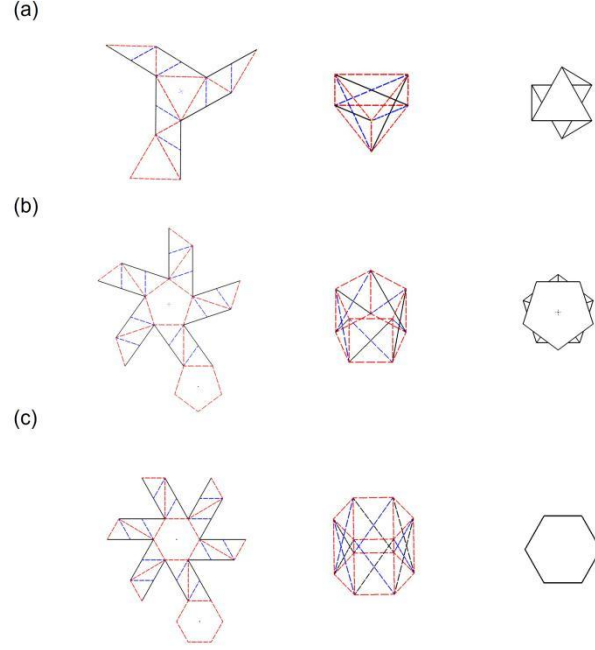


Figure S2.1 Crease patterns, deployed configurations and flat-folded configurations of various FP-ori structures. (a) Triangular FP-ori with $\alpha=30^\circ$. (b) Pentagonal FP-ori with $\alpha=54^\circ$. (c) Hexagonal FP-ori with $\alpha=60^\circ$.

2.8.2 Folding process by FEM simulation

Figure S2.2 illustrates the stress variation during the folding process, with colors indicating the magnitude of the axial stress. Consequently, changes in color reflect alterations in stress throughout the folding process. When $\alpha=30^\circ$ or 54° , the color of the trusses gradually becomes darker as the folding process advances and the stress does not become zero even when the structure is completely flattened. However, when $\alpha=45^\circ$, the stress remains nearly zero throughout the process, verifying the rigid foldability of FP-ori. For $\alpha=60^\circ$, the figure shows the stress at zero in both the initial and flattened configurations, with stress appearing in the intermediate states. The initial increase and subsequent decrease of the stress in the truss are consistent with bistability.

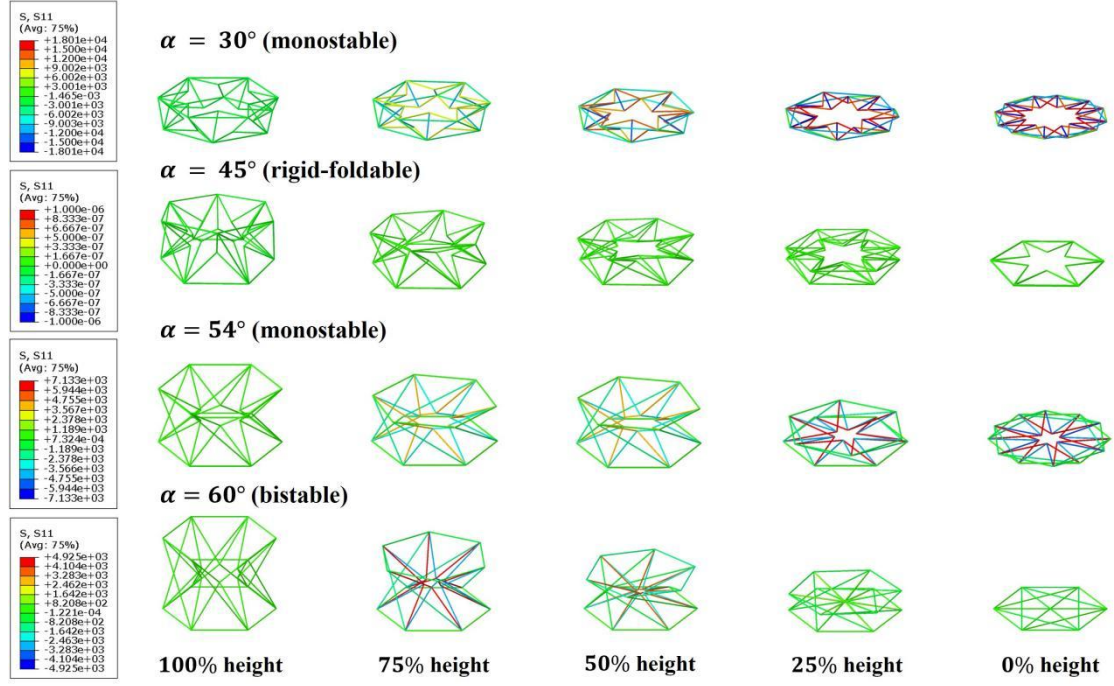


Figure S2.2 Stress variation during the folding process for various α values.

2.8.3 Energy Model of the FP-ori truss structure

To evaluate how the energy changes with the compression, I have developed an energy model for FP-ori based on a truss model. Because the boundary of monostable and bistable states are within the $\Sigma 3$ and $\Sigma 4$ self-locking, the configuration is still considered as the initial configuration, consistent with the FEM simulation. In this truss energy model, the trusses comprising the top and bottom facets are considered rigid, while the axial trusses between the top and bottom facets are treated as elastic trusses with a modulus of elasticity E . Figure S2.3 displays a schematic and a top view of the truss model, with red (CE and EB), blue (AE and ED), and green (CB) representing trusses with different deformations. Next, I calculated the elastic strain energy U of the FP-ori structure. I defined u as the compression distance, h_0 as the initial height of the FP-ori, with a_{10} , a_{20} , and b_0 representing the initial lengths of the three different kinds of axial trusses, θ_0 as the rotation angle of the top and bottom facets at self-locking, θ as the additional rotation angle generated during the compression process, R as the radius of the circumscribed circle of the top and bottom facets, and r as the radius of the inscribed circle composed of points E in each limb. Based on geometric relationships, I can derive the length changes of the three types of trusses during the compression process as follows:

$$a_1 = \sqrt{(h_0 - u)^2 / 4 + R^2 + r^2 - 2Rr \cos(\theta_0 / 2 + \theta / 2)} \quad (S2.1)$$

$$a_2 = \sqrt{(h_0 - u)^2 / 4 + R^2 + r^2 - 2Rr \cos(\theta_0 / 2 - \theta / 2)} \quad (S2.2)$$

$$b = \sqrt{(h_0 - u)^2 + 4R^2 (\sin(\theta_0 / 2 + \theta / 2))^2} \quad (S2.3)$$

Based on Eq. (S2.1), (S2.2), (S2.3), the total elastic energy can be expressed as

$$U(u, \theta, r) = nEA \left(b_0 \varepsilon_b^2 + 2a_{10} \varepsilon_{a_1}^2 + 2a_{20} \varepsilon_{a_2}^2 \right) / 2 \quad (\text{S2.4})$$

where ε_{a_1} , ε_{a_2} , ε_b are the strains of the trusses and n represents the number of sides of the polygon. Applying the principle of minimum potential energy to Eq. (S4), the following two partial differential equations can be obtained:

$$\partial U / \partial \theta = 0 \quad (\text{S2.5})$$

$$\partial U / \partial r = 0 \quad (\text{S2.6})$$

To obtain the solution to the system of equations, MATLAB is utilized to establish the relationship between the compression distance and the model's deformation energy. When incorporating the material parameters as well as the cross-sectional area of the trusses set in Abaqus, it becomes evident that the analytical results of the truss energy model closely match the results of FEM simulations shown in Fig. 2.4(b).

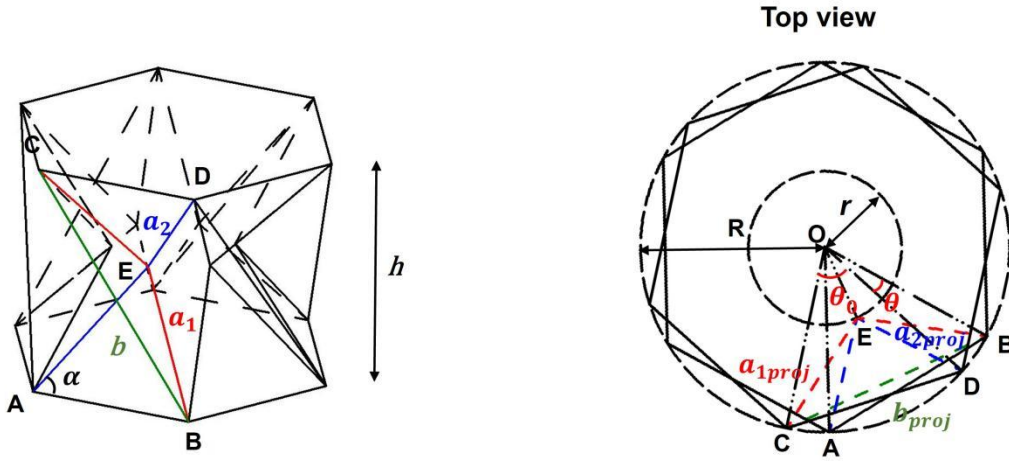


Figure S23 Schematic diagram and top view of FP-ori truss model with $n=6$ and $\alpha=60^\circ$.

2.8.4 Multi-stable structure

To show the properties of the stacked FP-ori structure, a simulation was conducted. Here, I focus on the type-II stacked FP-ori shown in Fig. 2.5(b), which is composed of two hexagonal FP-ori units with $\alpha=60^\circ$. The section areas of the truss were set to 1 and 0.5 mm^2 , respectively, in the simulation to distinguish the lower and upper FP-ori units. Other parameters were the same as those in the main article.

Figure S2.4 shows the variation of strain energy during the folding process. It shows five configurations of the folding process (A, B, C, D, and E). The strain energy in configurations A, C, and E is zero, where FP-ori is at a steady state. In configurations B and D, the strain energy takes maximum values. The stress variation corresponding to these five configurations is also shown in the figure. The stress in the initial state (configuration A) is zero. Then, the upper layer with a smaller section area is

flattened first (configuration C). The lower layer then begins to be compressed until the upper layer is flattened (configuration E). The variations of strain energy and stress verify that multi-stability can be obtained when FP-ori units are stacked. FP-ori with $n=6$ and $\alpha=60^\circ$ was shown to be bistable in the main article. Therefore, there may be three or more steady states if two or more such FP-ori units are combined.

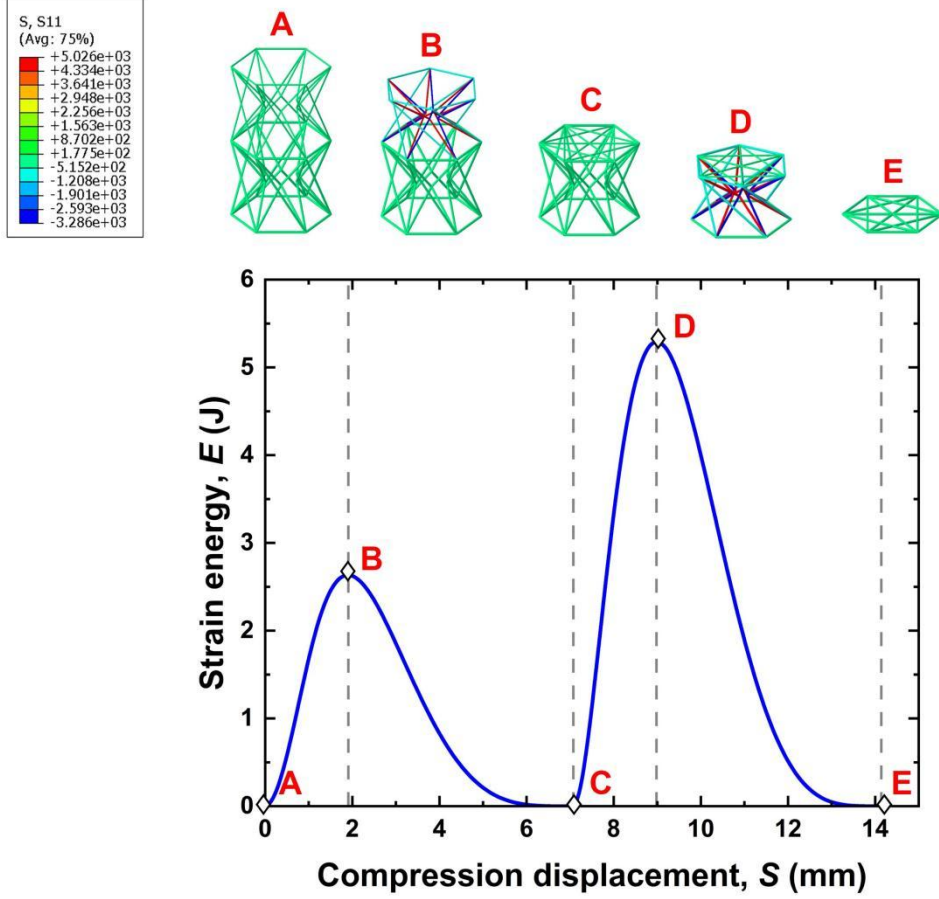


Figure S2.4 Strain energy and stress variation of stacked FP-ori structure composed of two FP-ori units with $n=6$ and $\alpha=60^\circ$.

2.8.5 Calculation of negative Poisson's ratio of tessellation structure

The FP-ori unit in the upper-left corner on the left side of Fig. S2.5 is used as an example to calculate the negative Poisson's ratio of the FP-ori tessellation structure. The vertices of the bottom and top facets are marked as ABCD and EFGH, respectively. From the top view, CG is parallel to AE, so for a unit, the width w can be considered to be the projection distance from point G to point A on the bottom facet ABCD. Point O is the center of the top facet, $\theta \in [0, \pi/2]$ is the rotation angle between the top and bottom facets, and l is the side length of the square. Therefore, the distance between A and G can be calculated as

$$w = \sqrt{2}l \cos \gamma = \sqrt{2}l \cos(\theta/2) \quad (S2.7)$$

Similarly, s can be calculated as

$$S=W \quad (S2.8)$$

Substituting $\alpha=45^\circ$ and $\beta=90^\circ$ into equation (6) (main article) yields

$$h=l\cdot\sqrt{\cos\theta} \quad (S2.9)$$

Therefore, the Poisson's ratios of one unit can be calculated as

$$\nu_{sw}=-\varepsilon_s/\varepsilon_w=-1 \quad (S2.10)$$

$$\nu_{hw}=\nu_{hs}=-\varepsilon_h/\varepsilon_w=-\frac{\sqrt{2}\cos(\theta/2)}{\sqrt{\cos\theta}} \quad (S2.11)$$

For the tessellation structure, m , n , and p represent the number of FP-ori units in the directions of x , y , and z , respectively. The following equations can be obtained:

$$S=ms \quad (S2.12)$$

$$W=nw \quad (S2.13)$$

$$H=ph \quad (S2.14)$$

Therefore,

$$\nu_{SW}=-\varepsilon_S/\varepsilon_W=-m/n \quad (S2.15)$$

$$\nu_{HW}=(p/n)\nu_{hw} \quad (S2.16)$$

$$\nu_{HS}=(p/m)\nu_{hs} \quad (S2.17)$$

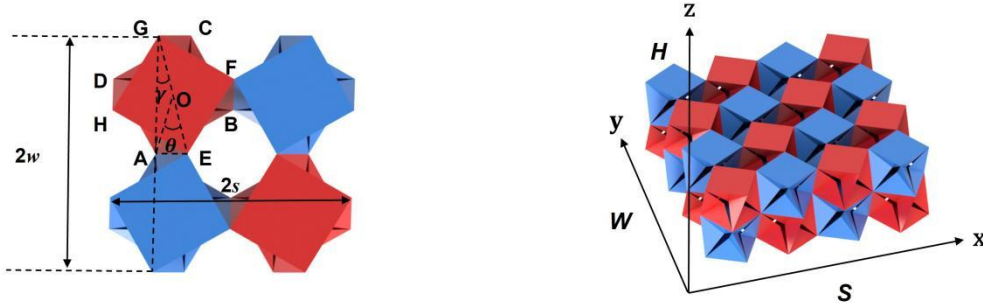


Figure S2.5 Schematic diagram of tessellation structure.

Chapter 3

Foldable Cube Origami with Thick Panel and its Applications to Deployable Structure

3.1 Introduction

In the previous chapter, I demonstrated that certain configurations of FP-ori possess both rigid-foldability and flat-foldability, depending on their geometric parameters. Building on these findings, the next stage of this research aims to develop a modular deployable structure that leverages the advantages of such origami mechanisms. Origami-based mechanisms inherently satisfy many of the desirable properties of deployable structures. An ideal deployable system should minimize its volume when folded, maintain stability and stiffness in designated configurations, and allow for rapid deployment [78]. These requirements align with the features of origami, which has recently gained widespread application in metamaterials [2–7], deployable structures [79–85], robotics [10,86–89], energy absorbers [65,90–93], and other engineering fields.

However, research on soft-material origami still dominates over that on rigid materials. Soft materials such as paper [94], elastomers [95], and hydrogels [96] typically exhibit significant hysteresis and residual strain, making them less suitable for precise mechanical applications. In order to overcome these limitations, possessing both rigid and flat-foldability is a key requirement for origami structures. Existing such rigid and flat-foldable origami structures include single-vertex origami that satisfies Kawasaki's theorem [29] (e.g., Miura origami), Tachi-Miura origami [31], Sarrus linkage [9], kirigami-inspired foldable cuboid [32], FP-ori and some rigid-foldable cubes [33–35]. Different from Miura origami and Tachi-Miura origami, the latter types all feature regular prismatic configurations, which means that they are more easily applicable in robotics. Especially for Sarrus linkage, kirigami-inspired foldable cuboid and FP-ori, due to the absence of creases on the top and bottom facets, they can be easily stacked into multi-unit structures with thick panels of uniform thickness. Figure 3.1(a)-(c) shows the zero-thickness models of the Sarrus linkage, a kirigami-inspired foldable cuboid, and Foldable Cube Origami (FC-ori, a special case of FP-ori with a cube configuration) with two units, respectively. All of these structures are initially configured as rectangular prisms with square bases, where the height h is twice the length of the base edge l . During the folding process, all three origami structures achieve rigid and flat foldability. Notably, FC-ori has a significant advantage in its flat-folded configuration. Unlike the plus shapes of the Sarrus linkage and kirigami-inspired foldable cuboid, the inward-folding side facets of FC-ori result in a square shape, occupying only 20% of the area compared to that of the other two examples.

Moreover, when the panels of an origami structure have finite thickness, its kinematics will deviate from the zero-thickness model, leading to interference between adjacent faces. To

address this issue, researchers have proposed several methods. Existing methods include setting reasonable offsets between creases [37], utilizing sliding hinges capable of generating axial translation [38], replacing some creases with two auxiliary thin panels [33], trimming by bisecting planes [39], and so on. These methods could mitigate the negative effects of thickness to varying degrees. Therefore, to apply FC-ori in practical scenarios, appropriate methods for folding it must be identified.

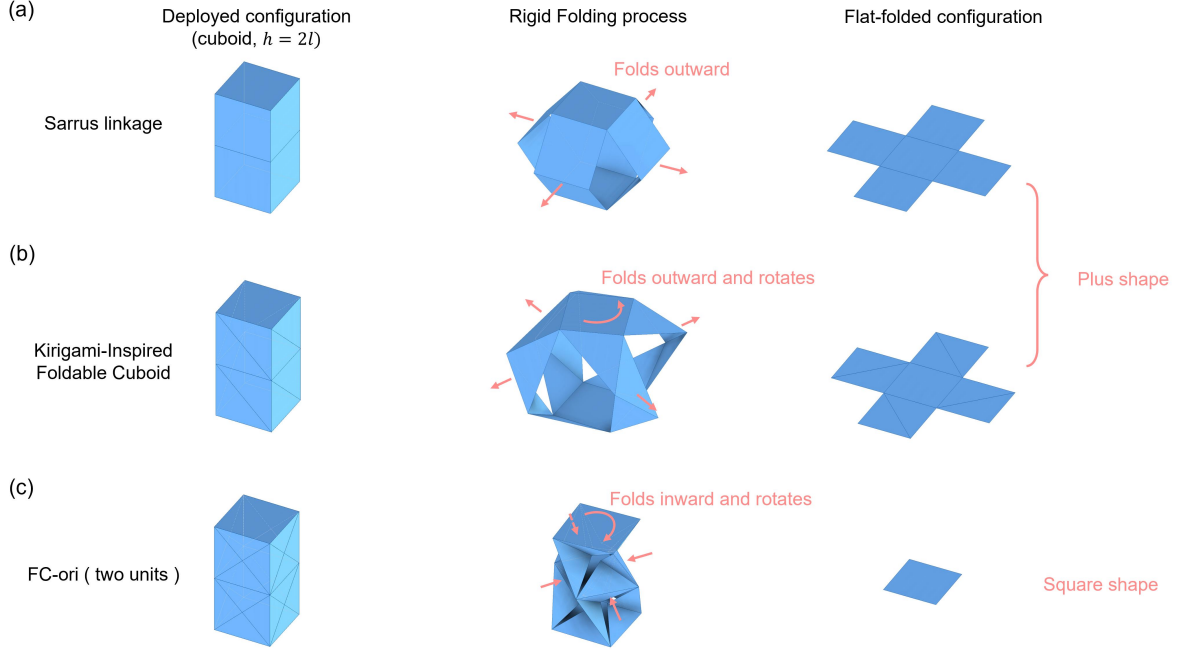


Figure 3.1 Comparison of folding processes for three types of rigid and flat-foldable rectangular origami. (a) Sarrus linkage, (b) kirigami-inspired foldable cuboid, and (c) FC-ori with two units. The initial configurations of the three origami are identical where the height h is twice the base edge's length l . The flat-folded configurations are as follows: (a) and (b) form a plus shape and (c) forms a square shape.

3.2 Rigid and flat foldable cubic origami

In Section 3.2, I propose a rigid and flat-foldable origami named FC-ori and introduce a method to preserve flat-foldability in corresponding thick structures by adding an additional translational degree of freedom to some creases. The folding processes of both the zero-thickness and thick FC-ori structures are simulated and compared using 3D software.

In Chapter 2, a Foldable Prism Origami (FP-ori) was proposed by introducing diagonal incisions into Kresling origami with a regular prism configuration. Depending on the geometric parameters, FP-ori exhibits tunable mechanical behavior such as flat-foldability, monostability, and bistability. Foldable Cube Origami (FC-ori) is a special case of FP-ori with a cube configuration, possessing both rigid and flat foldability as well as extreme compactness. To provide an intuitive understanding of how to

build it, I introduce a method of deriving an FC-ori from a closed cube directly. The method illuminated in Fig. 3.2(a) entails adding a valley crease and an incision along the two diagonals on one side facet and ensuring consistency across all sides. The crease pattern of FC-ori is shown in Fig. 3.2(b). The four side facets are composed of four identical isosceles triangles. When folded flat, these four side facets combine to form a cube identical to the base facet. This means that in the flat-folded configuration, there is no remaining space inside the structure. This extreme compactness makes FC-ori an ideal deployable structure.

Figure 3.2(c) shows the folding process of a zero-thickness FC-ori structure. It is assumed that during the folding process, the top and bottom facets rotate around the normal axis passing through their center points, thereby constraining the folding motion to a single degree of freedom. As shown in the figure, an FC-ori structure can be transformed from a cube to a square by rotating its top and bottom facets and contracting, without any deformation of the facets.

However, in engineering applications, the material thickness cannot be ignored and it is desirable for thick origami structures to exhibit flat-foldability similar to zero-thickness origami structures. Figure 3.2(d) shows the folding process of a thick FC-ori structure under the same assumption as that for the zero-thickness structure to constrain its degrees of freedom. Based on the incisions, the sides of an FC-ori structure can be divided into four identical limbs. The four panels on a limb are defined as P_n ($n=1, 2, 3, 4$, from top to bottom). The top and bottom panels are defined as P_{top} and P_{bottom} , respectively. The folding process of a thick FC-ori structure can be divided into two stages according to foldability. In the first stage, all creases are considered as ideal hinges without any translation along rotation axes. When folded to a certain degree, the FC-ori structure becomes self-locking due to the interference between P_2 and P_3 . This configuration represents a critical point in the two-stage folding process. In the second stage, both the self-locking and flat-folded configurations meet the conditions for rigid origami. However, their intermediate configurations require panel deformation. To enable rigid folding between these two configurations, I introduced a translational degree of freedom along the rotational axis at certain creases. For convenience, I refer to this approach as the sliding crease method. This method was proposed by Trautz et al. to address the flat folding problem for thick Miura origami [38]. Unfortunately, applying the sliding crease method to Miura origami can only expand the range of rigid-foldability but cannot achieve flat folding, as the four creases of a uniformly thick Miura origami can never be parallel to the same plane. However, this method perfectly resolves the issues associated with thick FC-ori and represents the first successful application of this approach to achieving flat-foldability in thick origami structures, as shown in Fig. 3.2(d). I assumed that sliding only occurs on the creases between P_{top} and P_1 , as well as between P_{bottom} and P_4 , and that the distances are always equal to maintain the symmetry between the red and blue sections. In the second stage, starting from the self-locking configuration, the sliding distance of the creases increases from 0, reaches its maximum value, and then gradually decreases back to 0, ultimately achieving complete flat-folding.

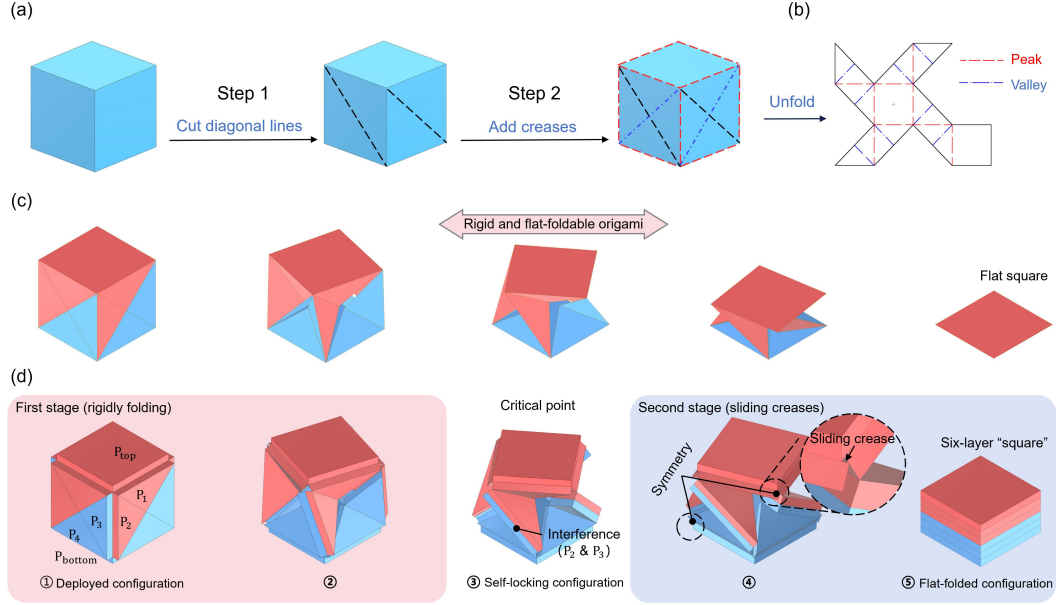


Figure 3.2 Folding process of FC-ori. (a) Transformation method from cube into FC-ori structure. (b) Crease pattern of FC-ori structure. The red dashed lines represent mountain creases and the blue dash-dotted lines represent valley creases. (c) Rigid folding process of zero-thickness FC-ori structure. (d) Rigid folding process of thick FC-ori structure utilizing sliding crease method.

3.3 Kinematics of thick FC-ori structures

In Section 3.3, I convert thick FC-ori into a linkage model to calculate its kinematics utilizing the D-H transformation matrix and numerical solution method. To derive explicit equations between the geometric parameters in the second stage, the coordinate system method is applied due to the complexity of matrix simplification in the linkage modeling method. Finally, I experimentally validated the feasibility of flat folding a thick FC-ori using the sliding crease method.

3.3.1 Linkage modeling method

To facilitate the calculation of the kinematics of FC-ori, the following hypothesis is proposed: the top and bottom panels rotate around the same axis during the entire folding process. Due to rotational symmetry, all geometric parameters for the four limbs are identical, so it is sufficient to analyze the motion of just one limb. Figure 3.3(a) shows a schematic diagram of a limb of the thick FC-ori and a coordinate system $O-xyz$ is established with the center of the upper surface of the bottom panel as the origin O . The z -axis is aligned with the rotational axis of the top and bottom panels, the x -axis is perpendicular to the crease between the bottom panel and the side panel, and the y -axis is parallel to this crease. l represents the length of the square panel, t denotes the thickness of the side panels, h represents the height, which is the shortest distance between the top and bottom panels, φ_i denotes the dihedral angle between adjacent panels with i ranging from 1 to 5, θ is the rotation angle between the top and bottom panels and s is the sliding distance on the creases connecting the side panels with the top and bottom panels required to achieve rigid-foldability. Since the origami structure is kinematically equivalent to a spatial linkage, four side panels on one limb as well as the top and bottom panels can form a closed-loop spatial 7-bar linkage mechanism, as

shown in Fig. 3.3(b). From bottom to top, the joints are numbered as i ($i=0, 1, 2, 3, 4, 5$, and 6). The specific steps to convert a limb of the FC-ori into a linkage are as follows: The top and bottom panels can rotate relative to each other, and the distance between them varies along the axial direction. Therefore, a rotation pair (joint 6) and a prismatic pair (joint 0) are required. The remaining five creases can be treated as rotation pairs, with their rotational axes aligned with the direction of the creases. To facilitate subsequent calculations, the shape of the links connecting two joints is made to conform to the boundaries of the panels. It is worth noting that, to satisfy the conditions of the sliding crease method, joint 1 and joint 5 also have an additional axial translational degree of freedom. Therefore, in the second stage, these two joints should be classified as cylindrical pairs. According to the modified Grübler–Kutzbach formula [97–99], the number of degrees of freedom of this linkage mechanism can be calculated as

$$M = d(n - g - 1) + \sum_{i=1}^g f_i + v \quad (3.1)$$

where M is the mobility of a mechanism, d is the order of a mechanism, n is the number of links, g is the number of kinematic pairs, and f_i is the freedom of the i -th kinematic pair. v is the parallel constraint, which is also called virtual constraint, for a single-loop mechanism $v=0$. According to screw theory, the order of the FC-ori mechanism is 6 (The detailed calculation process can be found in the SI). In the first stage, since no sliding occurs, the 7-linkage mechanism is classified as a 6R1P linkage. According to equation (1), $6(7-7-1)+7+0=1$, the degree of freedom of this linkage model is one.

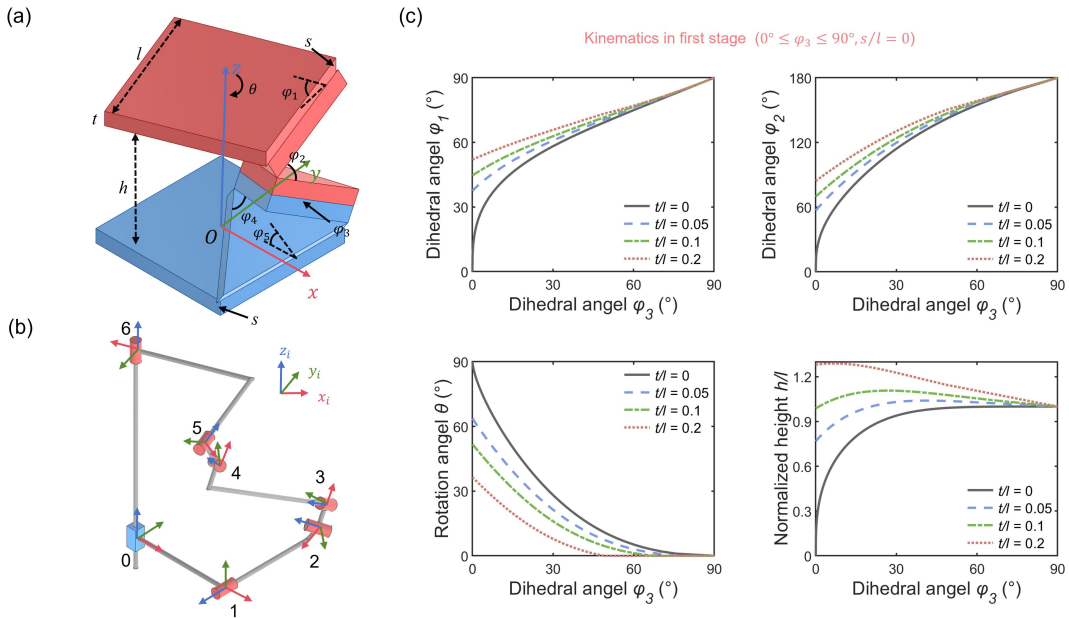


Figure 3.3 Linkage modeling method. (a) Schematic diagram of one limb of FC-ori with a coordinate system $O-xyz$. (b) Corresponding 7-linkage model. (c) Kinematics of FC-ori in the first stage, where $0^\circ \leq \varphi_3 \leq 90^\circ$, $s/l=0$.

In Fig. 3.3(b), the coordinate systems for each joint are labeled. The z_i axis is parallel to the

rotation axis of joint i , the x_i axis is perpendicular to both the z_{i-1} and z_i axes, and the y_i axis is determined by the right-hand rule. The coordinate system of joint 0 coincides exactly with the global coordinate system $O-xyz$. The Denavit–Hartenberg (D-H) parameters can be defined as follows [100]:

d_i^j : distance along the axis z_j from the origin of frame j , located between joint j and joint i , to the intersection with the x_i axis.

β_i^j : angle around the z_j axis from x_j to x_i .

r_i^j : distance along the x_i axis from the intersection with the z_j axis to the origin of frame i .

α_i^j : angle around the x_i axis from z_j to z_i .

T_i^j is the D-H transformation matrix between the coordinate systems of joint j and joint i (joint i and joint j are adjacent joints). It can be represented as

$$T_i^j = \begin{bmatrix} \cos \beta_i^j & -\sin \beta_i^j \cdot \cos \alpha_i^j & \sin \beta_i^j \cdot \sin \alpha_i^j & r_i^j \cdot \cos \beta_i^j \\ \sin \beta_i^j & \cos \beta_i^j \cdot \cos \alpha_i^j & -\cos \beta_i^j \cdot \sin \alpha_i^j & r_i^j \cdot \sin \beta_i^j \\ 0 & \sin \alpha_i^j & \cos \alpha_i^j & d_i^j \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.2)$$

For a closed-loop spatial linkage [101], the product of its transformation matrices equals the identity matrix I_4 , expressed as

$$T_1^0 T_2^1 \dots T_i^{i-1} T_0^i = I_4 \quad (3.3)$$

From this equation, I can conclude that

$$T_1^0 T_2^1 \dots T_6^5 = T_6^0 \quad (3.4)$$

Based on the coordinate systems corresponding to each joint, I can determine the D-H parameters between joint $i-1$ and joint i as follows:

$$\begin{aligned} d_1^0 &= 0, \beta_1^0 = 0, r_1^0 = l/2, \alpha_1^0 = \pi/2; \\ d_2^1 &= -l/2 + s, \beta_2^1 = -\pi/2 - \varphi_5, r_2^1 = -t, \alpha_2^1 = \pi/4; \\ d_3^2 &= 0, \beta_3^2 = \varphi_4 - \pi, r_3^2 = t, \alpha_3^2 = \pi/4; \\ d_4^3 &= l, \beta_4^3 = -\varphi_3, r_4^3 = t, \alpha_4^3 = -3\pi/4; \\ d_5^4 &= 0, \beta_5^4 = \pi - \varphi_2, r_5^4 = -t, \alpha_5^4 = \pi/4; \\ d_6^5 &= l/2 - s, \beta_6^5 = \pi/2 + \varphi_1, r_6^5 = l/2, \alpha_6^5 = -\pi/2. \end{aligned} \quad (3.5)$$

Similarly, joint 0 can also directly transform into joint 6. Moreover, since the rotation axes of the two joints are completely aligned, only the d_6^0 and β_6^0 parameters are relevant. These parameters can be determined as

$$d_6^0 = h, \beta_6^0 = -\theta - \pi/2, r_6^0 = 0, \alpha_6^0 = 0$$

(3.6)

Due to symmetry, I can easily obtain that

$$\begin{aligned}\varphi_1 &= \varphi_5 \\ \varphi_2 &= \varphi_4\end{aligned}\tag{3.7}$$

In the first stage, according to the assumption, none of the creases undergo sliding, and hence $s=0$. By substituting the obtained D-H parameters into the closed-loop linkage condition, I can obtain the following:

$$T_{06}=T_1^0 T_2^1 \cdots T_6^5=T_6^0=\begin{bmatrix} -\sin \theta & \cos \theta & 0 & 0 \\ -\cos \theta & -\sin \theta & 0 & 0 \\ 0 & 0 & 1 & h \\ 0 & 0 & 0 & 1 \end{bmatrix}\tag{3.8}$$

Therefore, I can observe that the product of T_1^0 to T_6^5 yields a new transformation matrix, T_{06} , where the elements $T_{06}(1,3)$, $T_{06}(1,4)$, $T_{06}(2,3)$, $T_{06}(2,4)$, and $T_{06}(3,2)$ should equal zero. By selecting any two of these elements (e.g., $T_{06}(1,3)$ and $T_{06}(2,4)$), I can establish the relationship among t , φ_1 , φ_2 , and φ_3 . Therefore, given a specific thickness t and utilizing an interpolation method (e.g., the `fsolve` function in MATLAB) with suitable initial values, I can calculate the corresponding φ_1 and φ_2 under various values of φ_3 ($0 \leq \varphi_3 \leq \pi/2$). Because angle changes are continuous, the values of φ_1 and φ_2 obtained from the previous iteration can be used as the initial values for the current iteration. For example, a φ_3 value of 90° , a φ_1 value of 90° , and a φ_2 value of 180° is the determined initial state for FC-ori. If I want to find the values of φ_1 and φ_2 when φ_3 is 89° , these values obtained with $\varphi_3=90^\circ$ can be used as the initial values for interpolation. Similarly, when φ_3 is 88° , I can use the values obtained with $\varphi_3 = 89^\circ$. Additionally, utilizing $T_{06}(1,1)$ and $T_{06}(3,4)$, the corresponding rotation angle θ and height h can be easily obtained. Using this method, I obtained the relationship curves between various parameters. Figure 3.3(c) shows the relationship curves of φ_1 , φ_2 , θ , and h/l with respect to the variation of φ_3 for various values of normalized thickness t/l . When t is equal to zero, representing a zero-thickness FC-ori structure, it is observed that when FC-ori is completely folded, all geometric parameters simultaneously become zero. This characteristic aligns with the concept of flat-foldability. However, when t is not zero, representing a thick FC-ori structure, φ_3 being zero does not imply that other parameters are also zero. This proves that in situations where thickness cannot be neglected, an FC-ori structure undergoes self-locking because of the interference between P_2 and P_3 . Additionally, due to the effect of thickness, height h initially increases and then decreases, which differs from the behavior for the zero-thickness structure, where it consistently decreases.

The same method can also be used to calculate the geometric relationships in the second stage by setting $\varphi_3=0^\circ$. In the second stage, joint 1 and joint 5 can be regarded as cylinder pairs, while joint 3 is completely fixed. Therefore, the linkage mechanism is classified as a 3R2C1P linkage. According to equation (1), this structure has two degrees of freedom. Due to the assumption of symmetry, the sliding distances of joint 1 and joint 5 are equal, making these two pairs linearly dependent, thus reducing the structure to a single degree of freedom. Using MATLAB, the geometric relationships in the second stage can be easily derived.

3.3.2 Coordinate system method

Although the linkage modeling method can be used to solve the kinematics in the second stage, the resulting matrix from multiplying six D-H transformation matrices is quite complex, making it difficult to simplify its elements. Therefore, in the second stage, I use the coordinate method to drive the explicit expression between parameters. Since P_2 and P_3 interfere with each other, only one variable—the dihedral angle φ_2 is needed to determine the configuration of the FC-ori. Figure 3.4(a) shows a schematic diagram of the second stage of FP-ori. As shown, I established a new coordinate system within the intersecting plane between P_2 and P_3 . The origin O was located at the vertex of the right angle, with the x and y axes aligned with the two edges, and the z axis was perpendicular to the intersecting plane. Hence, I can easily determine the coordinates of all points on one limb. Taking P_1 and P_2 (red section) as an example, let O, A_1 , B_1 , C_1 represent the vertices on P_2 , and A_1 , B_1 , D_1 , E_1 , D_1 represent the vertices on P_1 . Here, $\overrightarrow{A_1B_1}$ denotes the crease between P_1 and P_2 , and $\overrightarrow{E_1F_1}$ represents that between P_{top} and P_1 . Similarly, the points on P_3 and P_4 (blue section) are denoted accordingly, sharing a symmetric relationship with P_1 and P_2 . For instance, the coordinates of E_1 correspond to those of E_2 , as $x_{E_1}=y_{E_2}$, $y_{E_1}=x_{E_2}$, and $z_{E_1}=-z_{E_2}$. According to geometric relationships, the coordinates of points E_1 , E_2 , F_1 , F_2 , A_1 , and G_1 can be written as

$$\begin{aligned} E_1 &= [\sqrt{2}l/2 \quad -t \cdot \sin \varphi_2 \quad t(1 + \cos \varphi_2)]; \\ E_2 &= [-t \cdot \sin \varphi_2 \quad \sqrt{2}l/2 \quad -t(1 + \cos \varphi_2)]; \\ F_1 &= [0 \quad \sqrt{2}l/2 \cdot \cos \varphi_2 - t \cdot \sin \varphi_2 \quad \sqrt{2}l/2 \cdot \sin \varphi_2 + t \cdot \cos \varphi_2]; \\ F_2 &= [\sqrt{2}l/2 \cdot \cos \varphi_2 - t \cdot \sin \varphi_2 \quad 0 \quad -\sqrt{2}l/2 \cdot \sin \varphi_2 - t \cdot \cos \varphi_2]; \\ A_1 &= [0 \quad 0 \quad t]; \\ G_1 &= [\sqrt{2}l/4 \quad \sqrt{2}l/4 \cdot \cos \varphi_2 \quad \sqrt{2}l/4 \cdot \sin \varphi_2 + t]. \end{aligned} \quad (3.9)$$

Hence, the rotation angle θ can be obtained by calculating the included angle ψ between $\overrightarrow{E_1F_1}$ and $\overrightarrow{E_2F_2}$ as

$$\psi = \arccos\left(\frac{\overrightarrow{E_1F_1} \cdot \overrightarrow{E_2F_2}}{\|\overrightarrow{E_1F_1}\| \cdot \|\overrightarrow{E_2F_2}\|}\right) = \arccos\left(\frac{-2\cos\varphi_2 - \sin^2\varphi_2}{2}\right) \quad (3.10)$$

$$\theta = \psi - \pi/2 \quad (3.11)$$

The height h is the shortest distance between $\overrightarrow{E_1F_1}$ and $\overrightarrow{E_2F_2}$; it is calculated as

$$h = \frac{|(E_1 - E_2) \cdot \vec{n}|}{\|\vec{n}\|} = \left(\frac{\sqrt{2}l - \sqrt{2}l \cos \varphi_2 + 4t \sin \varphi_2}{\sqrt{3 + \cos^2 \varphi_2 - 4\cos \varphi_2}} \right) \quad (3.12)$$

where $\vec{n}$ is the normal vector to $\overrightarrow{E_1F_1}$ and $\overrightarrow{E_2F_2}$. The dihedral angle φ_1 can be calculated from the angle between vectors $\overrightarrow{G_1A_1}$ and $\vec{n}$ as

$$\varphi_1 = \arcsin\left(\frac{\overrightarrow{G_1A_1} \cdot \vec{n}}{\|\overrightarrow{G_1A_1}\| \cdot \|\vec{n}\|}\right) = \arcsin\left(\frac{\sqrt{2}(1 - \cos \varphi_2)}{\sqrt{3 + \cos^2 \varphi_2 - 4\cos \varphi_2}}\right) \quad (3.13)$$

Utilizing the projection method, I can deduce the sliding distance s based on geometry. Figure 3.4(a) also shows a top view of the FC-ori structure. M_1 , N_1 , P_1 , and Q_1 and M_2 , N_2 , P_2 , and Q_2 are the projection points of P_{top} and P_{bottom} on the top-view plane, respectively. R is the rotation axis, K is the intersection point between M_1N_1 and M_2N_2 , and H is the midpoint of M_1N_1 . E_1 and E_2 correspond to the projection points of the respective points. According to the law of cosines, we can deduce the following:

$$|E_1K| = \sqrt{\frac{|E_1E_2|^2}{2(1-\cos\psi)}} = \sqrt{\frac{d^2-h^2}{2(1-\cos\psi)}} \quad (3.14)$$

d is the real distance between points E_1 and E_2 , which is obtained based on the coordinates:

$$d = \sqrt{2(\sqrt{2}l/2 + t\sin\varphi_2)^2 - 4t^2(\cos\varphi_2 + 1)^2} \quad (3.15)$$

According to the geometric relationships in the figure, sliding distance s can be determined as

$$s = |M_1E_1| = |M_1H| - |E_1K| - |KH| = \frac{l}{2} - \sqrt{\frac{d^2-h^2}{2(1-\cos\psi)}} - \frac{l}{2} \sqrt{\frac{1+\cos\psi}{1-\cos\psi}} \quad (3.16)$$

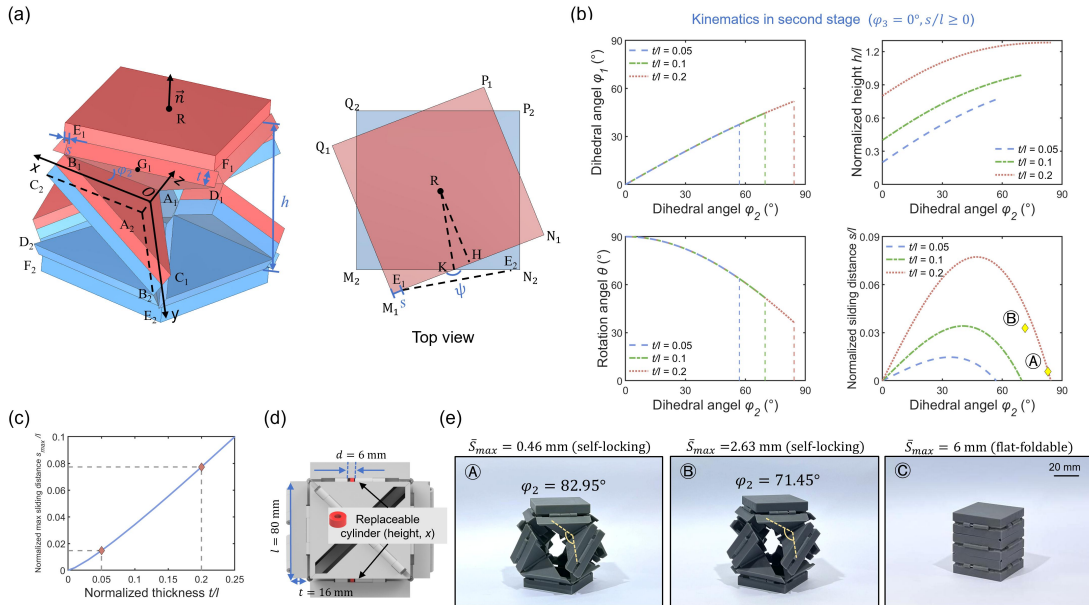


Figure 3.4 Coordinate system method. (a) Schematic diagram of FC-ori structure under sliding distance s with new coordinate system $O-xyz$ and the top view of FC-ori structure with projection points shown on top-view plane. (b) Kinematics of FC-ori in the second stage, where $\varphi_3=0^\circ$, $s/l \geq 0$. (c) Relationship curve between normalized thickness t/l and normalized max sliding distance $s_{\max}/l$. (d) Schematic diagram of the experimental setup used for validating the feasibility of the sliding crease method. The red replaceable cylinders are used to adjust $s_{\max}$. (e) Maximum folding position of FC-ori

structure for various values of $\bar{s}_{\max}$. Compared with (b), the sliding distance required to fold to the same angle is less than the theoretical value in the ideal case.

Figure 3.4(b) shows the relationship curves of φ_1 , θ , h/l , and s/l with respect to the variation of φ_2 for various values of normalized thickness t/l . It can be observed that s initially increases to a maximum value and then decreases back to zero during the folding process. The maximum sliding distance $s_{\max}$ is a necessary parameter for designing a thick FC-ori structure as it indicates the required gap to be set in hinges. From the relationship curve between s/l and φ_2 , I know that the maximum of a function corresponds to points where the derivative is zero. Hence, the value of φ_2 when s/l is at its maximum can be determined by solving the following equation in MATLAB:

$$\frac{ds}{d\varphi_2}=0 \quad (3.17)$$

By substituting this value into Eq. (3.16), I can calculate the maximum translation required for the FC-ori structure to achieve rigid and flat foldability at a specified thickness. Figure 3.4(c) shows the relationship between $s_{\max}/l$ and t/l . These two parameters are roughly positively correlated. Figure 3.4(d) shows the experimental setup used to verify the effectiveness of the sliding crease method. For this structure, the length l was 80 mm, thickness t was 16 mm ($t/l=0.2$), and maximum reserved sliding distance d was 6 mm (the theoretical value is 6.184 mm, calculated from the point (0.05, 0.0773) in Fig. 3.4(c)). Small cylinders (red part) with height x , which can be easily replaced, are used to control the maximum sliding distance. Figure 3.4(e) shows the maximum foldable configurations for various values of $\bar{s}_{\max}$ (measured average value) and the measured value of φ_2 . When $\bar{s}_{\max}$ is 0.64 or 2.63 mm, the FC-ori structure exhibits self-locking. A comparison of φ_2 in these two cases indicates that the range of rigid folding increases with $\bar{s}_{\max}$, which is consistent with theory and calculation. When $\bar{s}_{\max}$ is 6 mm, this structure can be completely flat-folded, confirming the feasibility of the sliding crease method for maintaining rigid and flat foldability for thick FC-ori structures. A comparison of experimental results with the calculated curves indicates that the sliding distance is smaller than the theoretical value for a given value of φ_2 . This discrepancy is due to the interference fits introduced at all creases to ensure smooth rotation.

3.4 3D-printed thick FC-ori module

In Section 3.4, I present thick FC-ori modules fabricated using a 3D printer with programmable multistability, achieved by configuring different numbers of magnets and springs. A naming method is proposed to distinguish these units. Additionally, the units can be quickly assembled by magnetic force.

For the fabrication of FC-ori modules, stereolithography 3D printing was used to produce panel components. The length of square panels was 80 mm and the thickness of each panel was 4 mm. According to theoretical calculations, the maximum sliding distance should be 1.176 mm. However, a sliding distance of approximately 0.2 mm around all hinges to ensure smooth rotation is sufficient for smooth folding according to my test result. Figure 3.5(a) shows a schematic diagram of two chiral FC-ori modules. An FC-ori module consists of top and bottom panels and four side panels (A, B, C, and D; specific dimensions of the panels are given in SI,

Section 2). By simply changing the arrangement of the side panels from ABCD to CDAB, the rotation direction of the FC-ori unit will shift from clockwise to counterclockwise. Adjacent panels are connected by metal shafts with a diameter of 2 mm and a length of 40 mm. To endow the rigid-foldable thick FC-ori modules with multistability (the details of the testing of multistability are shown in Section 5), torsion springs with an initial angle of 90° are attached at the right-angle edges, and magnets are installed on panels using super glue. The two modules are easily connected by magnetic force and the square mortise-tenon structure restricts their rotational freedom. Additionally, by connecting two FC-ori units with opposite rotation directions, a structure can be created where the two ends remain relatively static, as indicated by the dashed frame in Fig. 3.5(c). This type of combination is commonly applied in Kresling origami applications, such as crawling robots [18].

Each FC-ori module has 24 magnet installation positions and 24 spring installation positions. To distinguish them, I propose a naming method (described below) based on the positions and quantities of installed magnets and springs. Figure 3.5(b) shows one limb of an FC-ori module. The magnets on the top and bottom panels are used for connecting different units, so the available magnet installation positions are only on the side panels P_i , where $i=1,2,3,4$. The spring can be configured on the creases C_j , where $j=1,2,3$, with an initial dihedral angle of 90° . To maintain structural symmetry, the distribution of magnets and springs among the four limbs should be identical. Therefore, I can use the distribution on one limb to represent the entire structure. In the naming method, m_i represents the number of magnets on corresponding panels; similarly, s_j represents the number of springs installed at corresponding hinges. Therefore, an FC-ori structure can be named as $Mm_1m_2m_3m_4Ss_1s_2s_3$.

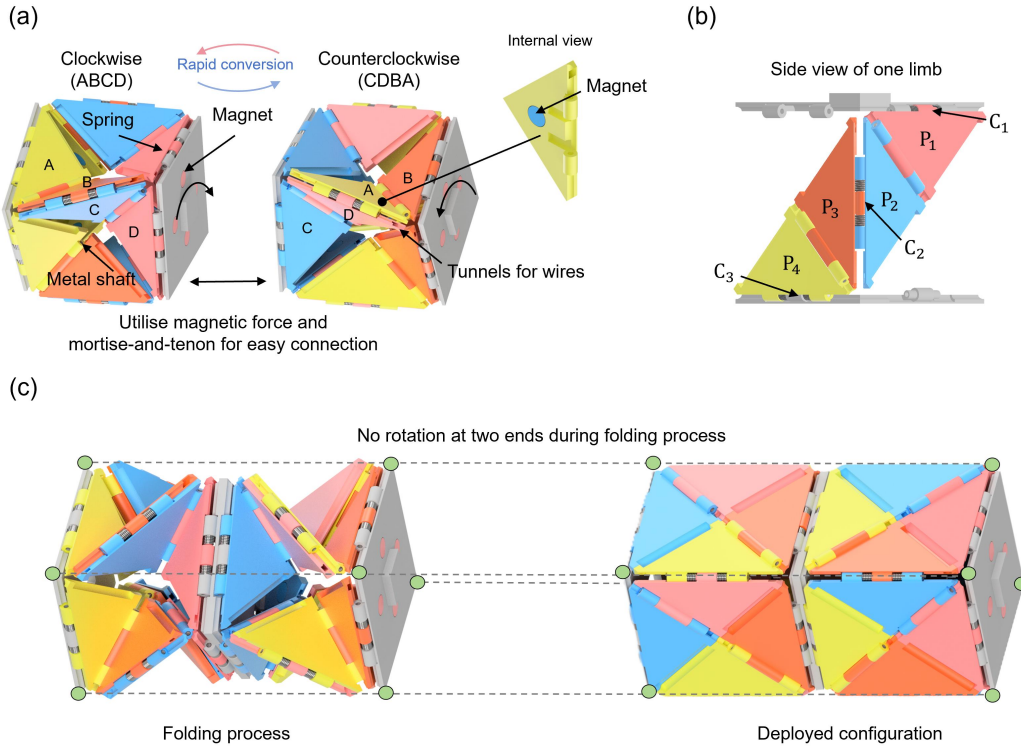


Figure 3.5 3D-printed thick FC-ori module. (a) Two chiral FC-ori modules. Changing the order

of the side panels (e.g. from ABCD to CDAB) can alter the rotation direction. (b) Naming method for FC-ori based on the numbers of magnets (installed at P_i) and springs (installed at C_j) on a limb. (c) Non-rotating structure at two ends composed of two chiral FC-ori modules.

3.5 Modular FC-ori module with programmable multistability

In Section 3.5, I conduct mechanical testing on the deploying process of FC-ori units with programmable multistability and establish a spring-magnet energy model to theoretically explain it. Furthermore, I discover that the thick FC-ori modules exhibit self-locking property in the deployed configuration.

An FC-ori unit has programmable multistability, including zero-force folding, monostability, bistability, and tristability, depending on the positions and quantities of the installed magnets and springs. The corresponding configurations are M0000S000, M0000S202, M1001S202, and M1111S222, respectively. Among these, the bistable unit M1001S202 and the tristable unit M1111S222 most closely meet the requirements for my modular deployable robot. Their stable states are shown in Fig. 3.6(a). The yellow dashed lines indicate the panels of M1001S202 without magnets. These stable states correspond to the special nodes in the folding process of a thick FC-ori structure: ① represents the deployed configuration, ③ represents the self-locking configuration, and ⑤ represents the flat-folded configuration. Configurations ① and ⑤ are ideal for the robot's deployment and storage. Therefore, the two types of FC-ori modules can be used as modular robot units.

To further clarify the programmable multistability of an FC-ori structure, mechanical tests were conducted using the apparatus shown in Fig. 3.6(b). This apparatus primarily consists of a force tester, a fixture (red part), and a rotatable base (blue part) (a schematic diagram of the rotatable base is shown in SI, Section 3). In the experiment, the specimen was first stretched by 66 mm and then compressed by 10 mm because the theoretical height of a thick FC-ori structure does not continuously increase. Figure 3.6(c) shows the force-displacement curves for FC-ori units with four different mechanical properties. In these figures, the solid lines represent the tensile process, the dash-dotted lines represent the compression process, diamonds indicate the stable states of the structure, and stars represent the separation nodes between the magnets on the two panels. The curve for M0000S000 indicates that the force remains close to zero throughout the stretching process. However, the side panels of an FC-ori structure struggle to completely reach the deployable configuration, as shown in the figure. Therefore, springs were introduced to ensure complete deployment. M0000S202, which is an FC-ori module with only springs, consistently experiences force in the negative direction during stretching. This indicates that the structure is monostable. M1001S202 is a typical bistable structure. The first stable state corresponds to the initial position. The sudden drop in force indicates the separation of P_{top} and P_1 , as well as P_4 and P_{bottom} , causing all the magnets to lose their effect. As a result, the latter part of the curve is similar to that of M0000S202. The second stable state is reached during compression. M1111S222 has two segments where the force suddenly decreases, which results in an additional magnet separation node, P_2 and P_3 , compared to those of M1001S202, which accounts for its extra stable state. The fluctuations in force observed before magnet separation are primarily due to the magnets on different limbs not separating at the same time. Figure 3.6(d)

shows the special configurations of M1111S222. The first three configurations correspond to three stable states and the last configuration corresponds to the self-locking state. Apart from M0000S000 (because of incomplete deployment), the other three configurations experienced self-locking during the compression process. The self-locking behavior of the FC-ori structure can be attributed to two main factors. The first factor is the configuration of the zero-thickness FC-ori structure itself. As mentioned in a study by Zhai [4], Kresling origami with obtuse-angled sides is easily compressible, whereas that with acute-angled sides is more resistant to compression. Hence, the right-angled triangle can be regarded as the critical point between these two characteristics. Because FC-ori is derived from Kresling origami with right-angled triangular sides, it exhibits similar properties. The second factor is thickness. A simple analysis of the compression force on P_1 in the deployed configuration was used to determine the direction of torque generated at the crease between P_1 and P_2 (a detailed analysis is given in SI, Section 4). It was found that the thickness causes the hinge to rotate in only one direction, and in the deployed configuration, the direction of the torque generated by compressing the top and bottom panels at the hinge between P_1 and P_2 is opposite to the direction in which the hinge can rotate. This is another key reason for the self-locking behavior. Self-locking is advantageous for deployable structures as it helps maintain the deployed configuration.

To further demonstrate the multistability of the FC-ori modules, I established a spring-magnet energy model (Section 5 of the SI provides the details of the calculation process). I assume that the friction forces from hinge rotation and sliding are negligible and that all panels remain rigid during the folding process, adhering to the kinematics described in Section 3.3. According to the principle of energy conservation, the energy relationship of the entire system during the deploying process is:

$$E_{\text{spring}} + E_{\text{magnet}} + E_{\text{gravity}} = W_{\text{force}} \quad (3.18)$$

Here, the spring energy can be expressed using Hooke's law:

$$E_{\text{spring}} = 2s_1 k (\varphi_1 - \varphi_1^0)^2 + 2s_2 k (\varphi_3 - \varphi_3^0)^2 + 2s_3 k (\varphi_5 - \varphi_5^0)^2 \quad (3.19)$$

where k is the spring constant, φ_i is the dihedral angle, φ_i^0 is the natural angle of the spring, then $\varphi_i^0 = \pi/2$ and s_i is the number of springs.

The magnetic force between the two pairs of magnets and their distance is given by an empirical formula [102]:

$$F_{\text{magnet}} = \frac{C}{r^n} \quad (3.20)$$

where C is the empirical constant, r is the distance between the magnets, and n is the empirical exponent. From experiments, I determined the following parameters: $C=34 \text{ N/mm}^{1.5}$ and $n=1.5$ (The comparison between the experimental curve and the fitted curve is presented in Section 5 of the SI). Disregarding the effect of the angle between the dipoles, the energy of the magnets can be calculated as:

$$E_{\text{magnet}} = \int \frac{C}{r^n} dr \quad (3.21)$$

In Fig. 3.6(c), the blue solid line represents the theoretical results based on the energy method, which shows the same steady-state characteristics as the experimental results. However, due to the fact that in the experiment, the separation of magnets may not occur simultaneously and there is slack in the hinges, the point at which the magnets fully separate and fail in the experimental curve occurs later than predicted by the theory.

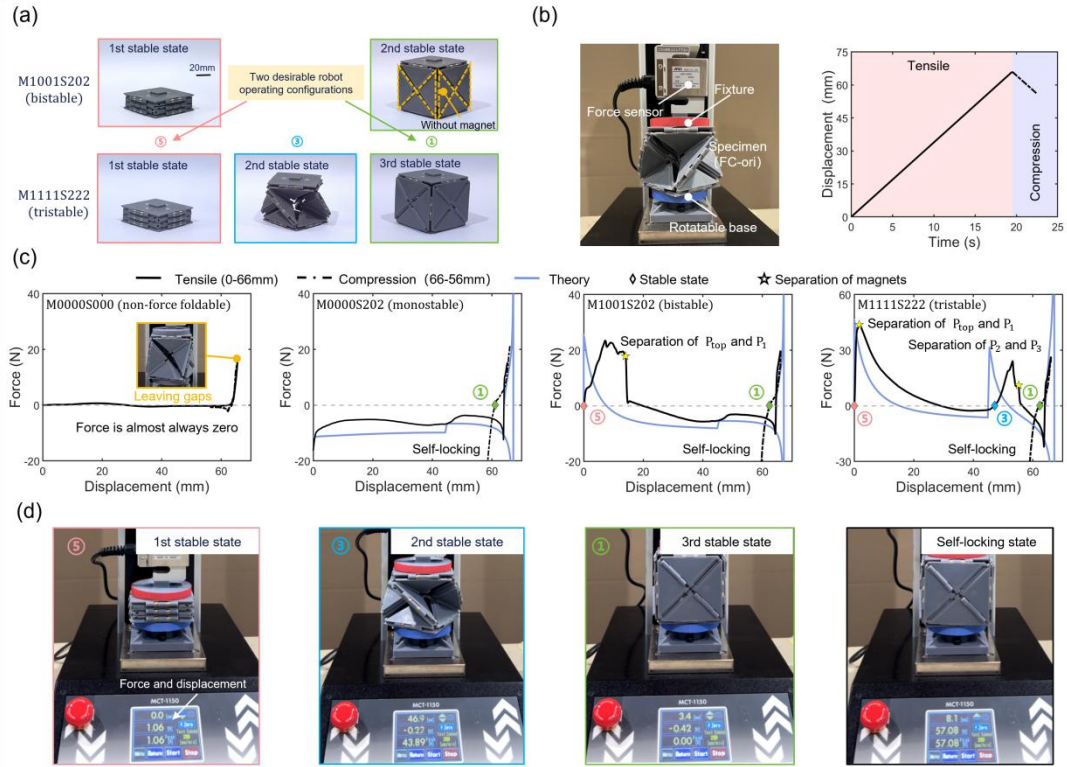


Figure 3.6 Thick FC-ori structure with tunable mechanical behavior. (a) Stable configurations of bistable FC-ori M1001S202 and tristable FC-ori M1111S222. The panels marked with yellow dashed lines indicate panels where magnets are not installed. (b) Apparatus used for mechanical testing, which includes tensile testing machine, fixture, specimen, and rotatable base, and obtained force-displacement curve. (c) Force-displacement curves for four thick FC-ori units with different mechanical properties: M0000S000, M0000S202, M1001S202, and M1111S222. The solid line represents the tensile stage and the dash-dotted line represents the compression stage. The blue solid line represents the theoretical results obtained through the energy method. Diamonds indicate the nodes where stable states occur and stars represent the separation of two panels with magnets. The positive direction of force is vertically downward. (d) Special configurations of M1111S222 during experiment including three stable states and a self-locking state.

3.6 Modular deployable mobile robot

In Section 3.6, I developed a modular deployable mobile robot that can adapt to various terrains

and tasks through transformation. I demonstrated its load-carrying capacity through mechanical experiments and demonstrated various functionalities such as an adjustable-height camera, passing through narrow gaps, and traversing ditches in different modes. Additionally, I used a 3D model to explore the potential applications of FC-ori in other deployable structures.

3.6.1 Various configuration modes of OriFlex

In the previous section, a thick FC-ori module with both multistability and self-locking properties was proposed. In this section, by utilizing FC-ori modules along with non-foldable modules with electronic components, a modular deployable mobile robot named the origami-inspired flexible robot (OriFlex) with multiple morphing capabilities is designed. Figure 3.7(a) shows the structure of OriFlex. It is composed of 12 chiral FC-ori modules (red and blue), four driving wheel modules, two driven wheel modules, a core module, and an additional functional module (Section 6 in SI illuminates more details about OriFlex). The twelve FC-ori modules used in OriFlex consist of both M1111S222 and M1001S202. Four M1001S202 are placed next to the driving modules, while the rest are M1111S222. The key difference is that M1111S222 has magnetic force between all the panels, providing greater stability in the flat-folded configuration, making them ideal for main structural modules. M1001S202, lacking magnetic force between some panels, allows slight movement in the flat-folded configuration, ensuring all six wheels of OriFlex stay in contact with the ground. The core unit houses a battery and a microcontroller board and is equipped with omnidirectional support wheels for stability. The additional functional module can be equipped with components such as cameras and sensors as needed. Since each FC-ori transformation is independent, OriFlex can operate in multiple modes (denoted A to F), as shown in Fig. 3.7(b). In cases where part of the FC-ori module is suspended, noticeable bending deformation can occur due to manufacturing errors and the weight of electronic components. To address this issue, the self-locking of FC-ori was utilized by threading transparent lines through small holes, pulling the four vertices of the FC-ori modules tight. Figure 3.7(c) shows a zoom-in view of a transparent line. A comparison of the bending degree before and after the application of this method indicates that the transparent lines significantly improve the bending strength of the FC-ori structure and that the lines do not affect the transformation of OriFlex.

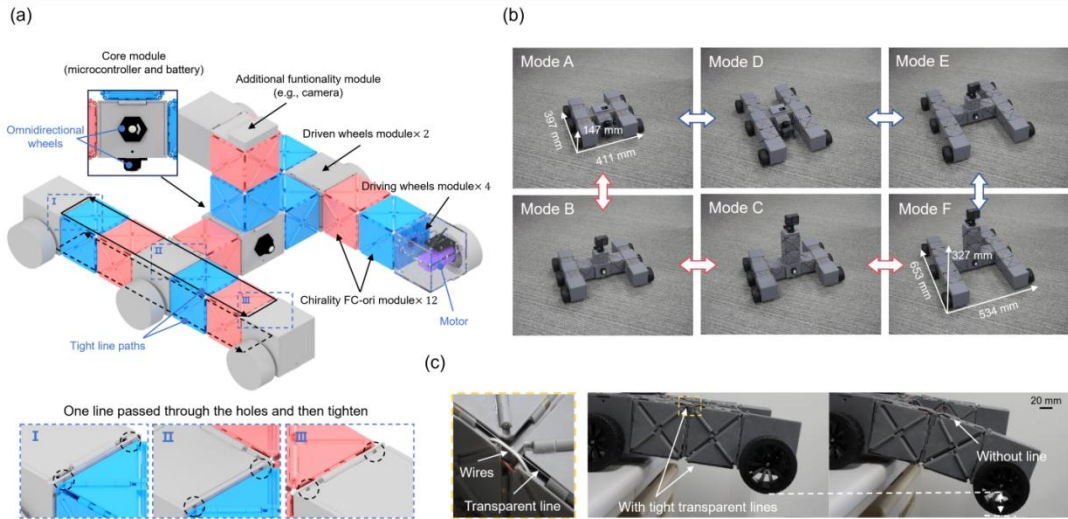


Figure 3.7 Origami-inspired flexible robot (OriFlex). (a) Schematic diagram of components of OriFlex. (b) Six modes (A to F) of OriFlex. There are three transformation routes from mode A to mode F. (c) Comparison of OriFlex's bending degree before and after application of the tight line method.

Generally, thick origami can achieve much higher strength and stiffness when compared to their non-thick origami counterparts [80]. I tested the bending strength and stiffness of a cantilever beam structure composed of two FC-ori units to demonstrate the load-carrying capability of OriFlex. Figure 3.8(a) shows the experimental setup for the bending test, where one end of the FC-ori structure is fixed and the other end is free. Additionally, a taut transparent line is used to reinforce the structure. By applying pressure to the free end with a plunger connected to a force sensor, the force-displacement curve of the structure is obtained. Figure 3.8(b) compares the bending strength of the original structure with that of the reinforced structure. Due to slack in the 3D-printed hinges, the cantilever beam bends under its own weight, causing the intersection point of the curve with the x-axis to be greater than zero. Although the FC-ori structure, as a rigid origami, exhibits strong load-carrying capability, adding a taut line can improve the bending strength of the structure and compensate for manufacturing errors.

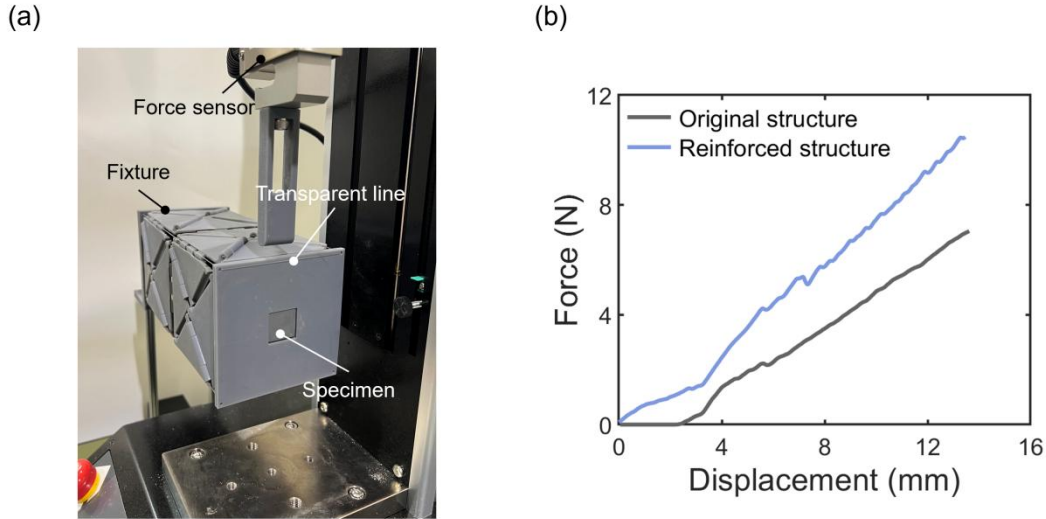


Figure 3.8 Load-carrying capability of OriFlex. (a) Experimental setup for the bending test of a cantilever beam composed of two FC-ori units. (b) Force-displacement curve of the bending test, comparing the reinforced structure and the original structure.

3.6.2 Functionalities of OriFlex under various modes

OriFlex possesses various functionalities in its different modes. For instance, Fig. 3.9(a) shows two photographs taken at the same position in modes A and C, respectively. The higher camera in mode C provides a better field of view and can be extended into narrow spaces, such as chimneys. OriFlex can also adapt to different terrains via adjustments in the wheelbase and track width. Figure 3.9(b) shows OriFlex navigating through a low gap in mode A. Figure 3.9(c) and (d) shows OriFlex in mode E traversing a 310-mm-wide double-sided bridge and a 150-mm-wide ditch, respectively. It is worth noting that to achieve the functionality shown in Fig. 3.9(d), a metal frame needs to be installed at the bottom of OriFlex to enhance its structural strength and

prevent the wheels from getting stuck in the ditch. OriFlex, which has multi-terrain crossing capabilities and the option to attach various functional modules, is suitable for space exploration. It can be compactly folded into a very small volume, saving transportation space and costs, and its form can be adapted according to different tasks or terrains. In addition, similar to LEGO blocks, FC-ori modules can be assembled in various ways to create other interesting deployable structures. In Fig. 3.9(e), 3D models of three applications are shown: a deployable robotic arm, a deployable quadcopter, and a deployable habitable shelter.

Compared to existing origami robots and deployable structures, OriFlex offers distinct advantages. Unlike pneumatic- or magnetic-driven soft origami crawlers [17, 18, 105], OriFlex's rigid foldability ensures both load-bearing capabilities and suitability for larger-scale applications. When compared to mobile robots equipped with origami wheels [15, 52], OriFlex demonstrates greater versatility in configuration transformations and achieves a higher folding ratio. Additionally, unlike self-locking origami arms [9], OriFlex's folding units can extend in multiple directions rather than being restricted to axial extension.

Despite these advantages, a critical challenge for OriFlex and the FC-ori structure is the reliance on external forces for deployment. To avoid using soft materials, it is not feasible to apply responsive materials working with heat [104, 105], light [106], electronics [41] or shape memory polymers (SMPs) [107] as creases, which are commonly used in self-folding origami structures. The self-locking prevents the structure from being folded by simply applying pressure between the top and bottom panels. The multi-stability also conflicts with the functionality of repeated folding and deploying. Additionally, since the origami units are independent modules that can be freely assembled and disassembled, it is not feasible to drive the entire structure with just a few motors. my future research will focus on enabling rigidly self-folding and deploying functionality. To achieve this, the magnets should be removed to eliminate the multi-stability, leaving only the springs at the creases to enable self-deploying. For self-folding, I believe that cable-driven methods, commonly employed in controlling the motion of origami structures [108, 109], are a promising solution. Since folding the FC-ori requires force to be applied simultaneously on all four sides, threading cables through each side of limbs and applying tension using a motor-driven spool should be an effective folding strategy. If active folding can be achieved, it would further enhance the practicality and potential of FC-ori in deployable structures.

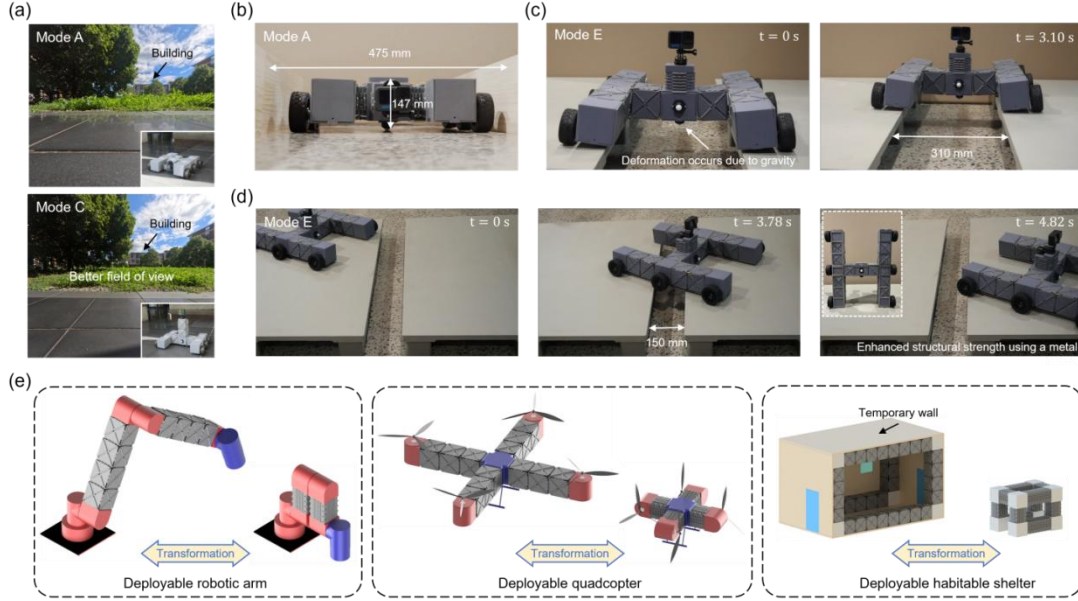


Figure 3.9 Various functionalities of OriFlex. (a) Comparison of photographs taken by a camera with adjustable height. (b) OriFlex navigating through a low gap in mode A. (c) OriFlex traversing double-sided bridge in mode E. (d) OriFlex traversing ditch in mode E. (e) Other potential applications of FC-ori, namely deployable robotic arm, deployable quadcopter, and deployable habitable shelter.

3.7 Discussion

In this chapter, a cubic origami inspired by Kresling origami, named FC-ori, was proposed for assembling modular deployable structures. Some existing Kresling origami structures reduce the force required for folding by replacing certain creases with incisions [43,46,110,111], but they still exhibit multistability and cannot prevent facet deformation. In contrast, the FC-ori structures possess both rigid and flat-foldability. Thus, I believe that FC-ori has greater potential for various rigid origami applications than other modified Kresling origami structures. The structural advantages of FC-ori include its regular geometric shape, high folding efficiency, and uniform thickness of all components. Hinged origami connections with uniform thickness have superior load-carrying performance compared to those with non-uniform thickness [112]. This work applied the sliding crease method, allowing a thick FC-ori structure to maintain its rigid and flat foldability. The kinematics during its folding process were calculated using both the linkage model and coordinate methods. Stereolithography 3D printing was used to create prototypes of a thick FC-ori structure. Tunable mechanical properties were achieved by incorporating magnets and springs. FC-ori units can be easily and rapidly connected and disconnected, a feature used here to design a modular, foldable mobile robot called OriFlex. This robot can change its configuration to perform various functions based on different tasks. The LEGO-like assembly of FC-ori units allows other deployable structures, such as robotic arms, quadcopters, and temporary shelters, to be constructed.

In summary, OriFlex, constructed from FC-ori modules, demonstrates clear advantages in fabrication simplicity, structural robustness, reconfigurability, and modular assembly. The

prototype confirms the capability of FC-ori to form complex deployable structures. At the current stage, however, the system still relies on manual folding for configuration changes. This limitation will be addressed in the next chapter through the development of actuation and self-folding strategies.

3.8 Supplementary Materials

3.8.1 Calculation of the order of the FC-ori mechanism

In Section 3.3, I used the modified Grübler–Kutzbach equation to calculate the degrees of freedom of the FC-ori structure in the 7-bar linkage model. A key parameter, d , represents the order of the mechanism, which is equal to the rank of the screw matrix. To clarify it, I constructed a 7-bar linkage model (6R1P) in Fig. S3.1, consisting of 6 revolute pairs and 1 prismatic pair, based on the non-thickness FC-ori. Fig S1 labels all the vertices on a limb of an FC-ori sequentially as A to F, and a coordinate system $O\text{-}xyz$ with the bottom surface coordinates as the origin is established. The x -axis is perpendicular to AB, the y -axis is parallel to AB, and the z -axis coincides with the rotation axis of the top and bottom facets. For convenience in calculating the coordinates, I assume that the edge length of the square bottom facet is 2. Using the dihedral angle φ_1 , the rotation angle θ , and the height h , I can obtain the coordinates of all the vertices:

$$\begin{aligned} O &= (0 \ 0 \ 0); A = (1 \ -1 \ 0); B = (1 \ 1 \ 0); C = (1 - \cos \varphi_1 \ 0 \ \sin \varphi_1); \\ D &= (\cos \theta + \sin \theta \ \cos \theta - \sin \theta \ h); \\ E &= ((1 - \cos \varphi_1) \sin \theta \ (1 - \cos \varphi_1) \cos \theta \ h - \sin \varphi_1); \\ F &= (\sin \theta - \cos \theta \ \cos \theta + \sin \theta \ h). \end{aligned} \quad (S3.1)$$

The direction vectors of the five creases are as follows:

$$\begin{aligned} \overrightarrow{AB} &= B - A = (0 \ 2 \ 0); \\ \overrightarrow{CB} &= B - C = (\cos \varphi_1 \ 1 \ -\sin \varphi_1); \\ \overrightarrow{DB} &= B - D = (1 - \cos \theta - \sin \theta \ 1 - \cos \theta + \sin \theta \ -h); \\ \overrightarrow{ED} &= D - E = (\cos \theta + \cos \varphi_1 \sin \theta \ \cos \varphi_1 \cos \theta - \sin \theta \ \sin \varphi_1); \\ \overrightarrow{FD} &= D - F = (2 \cos \theta \ -2 \sin \theta \ 0). \end{aligned} \quad (S3.2)$$

Next, the six motions of revolute pairs and one prismatic pair are expressed as screws, $\$_i = (S_i; \ r_i \times S_i)$ and $\$_i = (0; \ S_i)$, respectively, where S_i denotes the unit vector in the direction of the joint axis and r_i denotes the position vector. I can write the seven screws, as follows:

$$\begin{aligned} \$_0 &= (0 \ 0 \ 0; \ 0 \ 0 \ 1); \\ \$_6 &= (0 \ 0 \ 1; \ 0 \ 0 \ 0); \\ \$_1 &= \frac{1}{|\overrightarrow{AB}|} (\overrightarrow{AB}; \ \overrightarrow{OA} \times \overrightarrow{AB}) = (0 \ 1 \ 0; \ 0 \ 0 \ 1); \\ \$_2 &= \frac{1}{|\overrightarrow{CB}|} (\overrightarrow{CB}; \ \overrightarrow{OB} \times \overrightarrow{CB}) = \frac{1}{\sqrt{2}} (\cos \varphi_1 \ 1 \ -\sin \varphi_1; \ -\sin \varphi_1 \ \sin \varphi_1 \ 1 - \cos \varphi_1); \end{aligned}$$

$$\begin{aligned} \mathcal{S}_3 &= \frac{1}{|\overrightarrow{DB}|} (\overrightarrow{DB}; \overrightarrow{OB} \times \overrightarrow{DB}) = \frac{1}{\sqrt{4(1-\cos\theta)+h^2}} (1-\cos\theta-\sin\theta \quad 1-\cos\theta+\sin\theta \quad -h; \quad -h \quad h \quad 2\sin\theta); \\ \mathcal{S}_4 &= \frac{1}{|\overrightarrow{ED}|} (\overrightarrow{ED}; \overrightarrow{OD} \times \overrightarrow{ED}) = \end{aligned} \quad (S3.3)$$

$$\begin{aligned} & \left(\frac{1}{2} (\cos\theta + \cos\varphi_1 \sin\theta \quad \cos\varphi_1 \cos\theta - \sin\theta \quad \sin\varphi_1; \quad \sin\varphi_1 (\cos\theta - \sin\theta) - h(\cos\varphi_1 \cos\theta - \sin\theta) \right. \\ & \quad \left. h(\cos\theta + \cos\varphi_1 \sin\theta) - \sin\varphi_1 (\cos\theta + \sin\theta) \right. \\ & \quad \left. (\cos\theta + \sin\theta)(\cos\varphi_1 \cos\theta - \sin\theta) - (\cos\theta - \sin\theta)(\cos\theta + \cos\varphi_1 \sin\theta) \right); \end{aligned}$$

$$\mathcal{S}_5 = \frac{1}{|\overrightarrow{FD}|} (\overrightarrow{FD}; \overrightarrow{OD} \times \overrightarrow{FD}) = (\cos\theta \quad -\sin\theta \quad 0; \quad h\sin\theta \quad h\cos\theta \quad -1)$$

Combine all the screws $\mathcal{S}_4$ except into a matrix J and eliminating the denominators, which is:

$$J = \begin{pmatrix} \mathcal{S}_0 \\ \mathcal{S}_6 \\ \mathcal{S}_1 \\ \mathcal{S}_2 \\ \mathcal{S}_3 \\ \mathcal{S}_5 \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ \cos\varphi_1 & 1 & -\sin\varphi_1 & -\sin\varphi_1 & \sin\varphi_1 & 1-\cos\varphi_1 \\ 1-\cos\theta-\sin\theta & 1-\cos\theta+\sin\theta & -h & -h & h & 2\sin\theta \\ \cos\theta & -\sin\theta & 0 & h\sin\theta & h\cos\theta & -1 \end{pmatrix} \quad (S3.4)$$

Using Gaussian elimination, eliminate the second, third, and sixth columns of the last three rows with the first three rows to obtain:

$$J \rightarrow \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ \cos\varphi_1 & 0 & 0 & -\sin\varphi_1 & \sin\varphi_1 & 0 \\ 1-\cos\theta-\sin\theta & 0 & 0 & -h & h & 0 \\ \cos\theta & 0 & 0 & h\sin\theta & h\cos\theta & 0 \end{pmatrix} \quad (S3.5)$$

Subtract the fifth row multiplied by $\sin\varphi_1/h$ from the fourth row. I have

$$J \rightarrow \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ \cos\varphi_1 - \sin\varphi_1 (1-\cos\theta-\sin\theta)/h & 0 & 0 & 0 & 0 & 0 \\ 1-\cos\theta-\sin\theta & 0 & 0 & -h & h & 0 \\ \cos\theta & 0 & 0 & h\sin\theta & h\cos\theta & 0 \end{pmatrix} \quad (S3.6)$$

Use the fourth row to eliminate the first column of the fifth and sixth rows. I have

$$J \rightarrow \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & \tan \theta & 1 & 0 \end{pmatrix} \quad (S3.7)$$

It can be concluded that at least 6 of the 7 screws are linearly independent. Therefore, the order, d of the non-thickness FC-ori 7-linkage model is 6. When considering thickness, $\$0$, $\$1$, $\$2$, and $\$6$ remain unchanged, while $\$3$, $\$4$, and $\$5$ are affected by the thickness. The thickness causes these screws to translate a distance t along the normal vector of the corresponding panels. By performing a coordinate transformation, I can obtain the new position vectors of these screws. After performing the numerical calculation by MATLAB, $\det J$ is still not zero. Thus, the order of the 7-linkage model with thickness should be also 6.

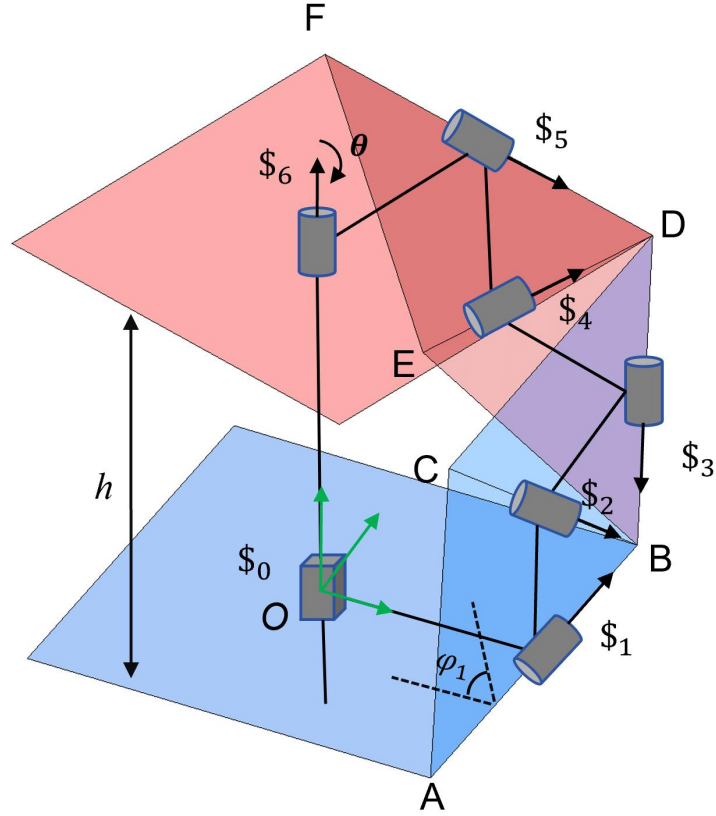


Figure S3.1 Schematic diagram of 6R1P linkage model

3.8.2 Engineering drawings of components of FC-ori unit

Figure S3.2 shows the components of an FC-ori unit, namely the bottom panel, top panel, and side panels A and D. The side panel B, which is not shown, is a mirror image of side panel A (the same applies to panels C and D). The dimensions marked in the figure are the ideal dimensions in the design; however, in production, there are slight differences between the actual and theoretical dimensions due to the inherent inaccuracies of stereolithography 3D printing and the unevenness

of polishing. From the engineering drawings, it can be seen that the reserved hinge movement range along the axis is ± 0.1 mm, with hole diameters of 2.2 mm (tight fit) and 2.5 mm (loose fit). The components are connected by a 2-mm-diameter metal shaft. Some hinge areas leave space for the installation of torsion springs. Inside the side panels, there is a tunnel with a width of 3 mm and a height of 2.5 mm for passing wires. Additionally, the cut lines of all side panels include a 1/4 circle notch with a length of 42 mm and a radius of 3.25 mm to accommodate the hinges of adjacent limbs when folded flat. An FC-ori unit can be obtained by assembling the printed components according to the steps.

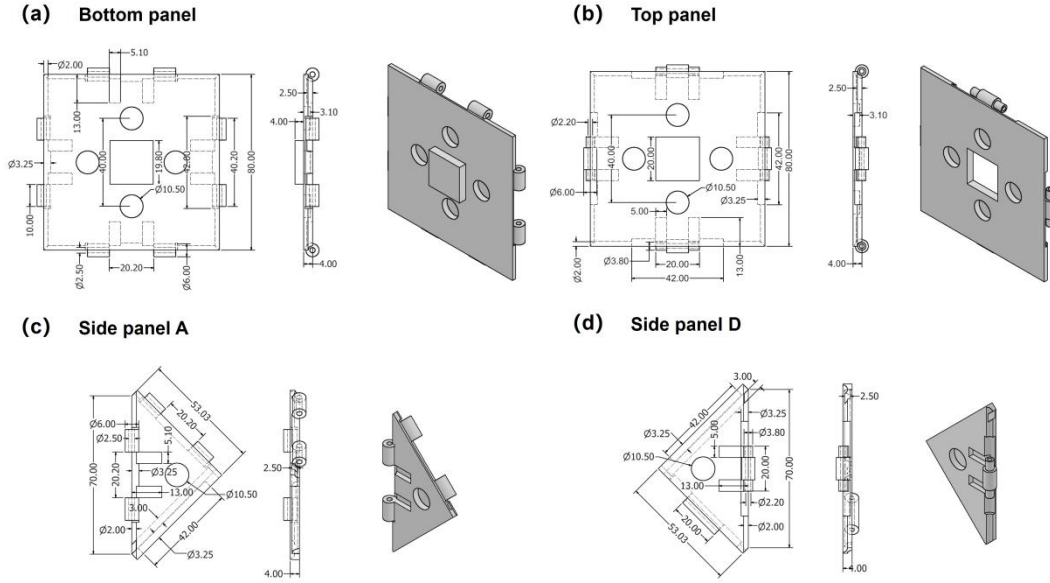


Figure S3.2 Schematic diagrams of components of FC-ori unit (top view, side view, and 3D model). (a) Bottom panel, (b) top panel, (c) side panel A, and (d) side panel D.

3.8.3 Design of rotatable base used in mechanical testing

During the deployment and folding process of the FC-ori structure, the top and bottom panels rotate. Therefore, it is necessary to design a base with only rotational degrees of freedom and minimal friction during rotation for the tensile test. As shown in Fig. S3, the rotatable base mainly consists of six parts. Except for the magnet and the bearing, the other components (labeled I, II, III, and IV) are all made using stereolithography 3D printing. Components II and IV are used to fix the bearing position and component III serves as the rotating axis, which is fixed to component I using a 2-mm-diameter metal shaft. The rotatable base is fixed to the tensile testing machine using M6 screws.

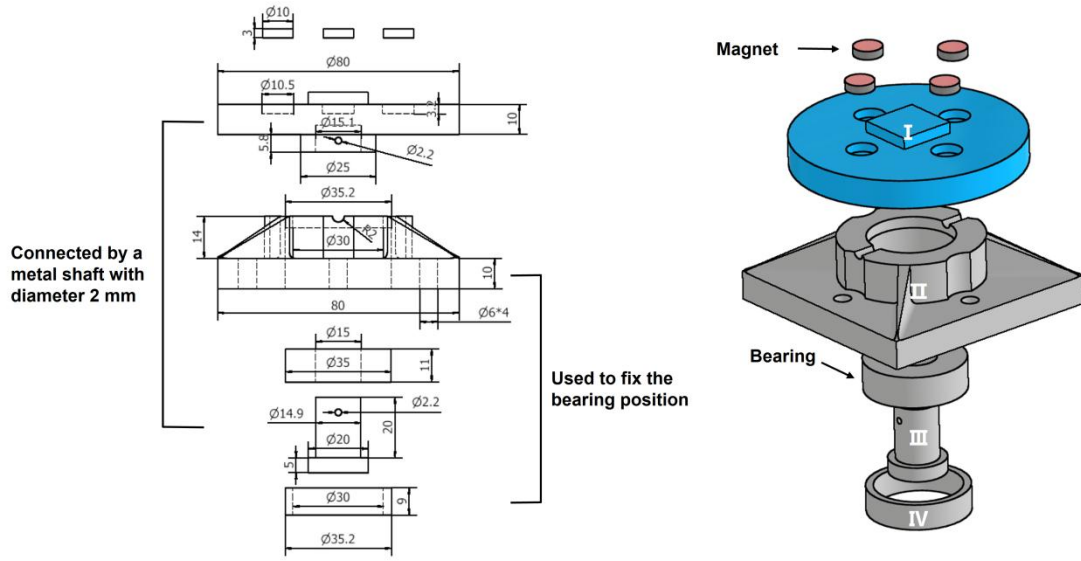


Figure S3.3 Schematic diagram of rotatable base (side view and 3D view).

3.8.4 Self-locking capability of FC-ori

In the above, I proposed that the self-locking capability of thick FC-ori is primarily due to two factors. First, Kresling origami with a prismatic configuration exhibits similar properties. Second, the thickness means that the self-locking property is not limited to the moment when the structure is in the deployed configuration; it persists during the initial phase of folding. The FC-ori structure exhibits high symmetry, not only with the four limbs being perfectly symmetric but also with each limb having symmetric upper and lower parts. This symmetry means that the geometric parameters during the folding process are identical and that if a force is applied to the central axis of the FC-ori structure, the force distribution on these parts will also be identical.

Therefore, I analyzed the self-locking by examining the forces on the panels P_1 and P_2 within one limb. Here, the positive direction of the moment is defined as being aligned with the folding direction. When the moment is positive, it means that the hinge can rotate normally. I found that the moment at the crease between P_2 and P_3 , under pressure F , is zero only in the deployed configuration (when the force aligns with the crease direction) and positive in all other configurations. This indicates that the self-locking of the FC-ori structure is not due to this crease. However, the situation is different at the crease between P_1 and P_2 .

Thus, I hypothesized that by fixing P_2 , I can analyze the relative motion between P_1 and P_2 under pressure F . Figure S3 shows the force analysis for P_1 . Assuming that a concentrated force F acts at the midpoint of the right-angle edge of P_1 , the distance between F and the crease is the moment arm L . The force F can be decomposed into two components: one perpendicular to the hinge and the other parallel to the hinge, denoted as $F_{\perp}$ and $F_{\parallel}$, respectively. According to the definition, the moment M is:

$$\vec{M} = \vec{L} \times \vec{F}_{\perp} \quad (\text{S3.8})$$

From the directions of the moment in the configurations shown in Figs. S4(a)–(c), I can draw the conclusions described below.

Figure S3.4(a) shows the deployed configuration, where the moment arm equals the thickness t and is negative. Due to the presence of thickness, P_1 cannot rotate at all along the direction of the moment. Figure S3.4(b) shows the critical configuration, where the shortest distance between F and the crease is zero, putting the P_1 at a delicate equilibrium point. Figure S3.4(c) shows the foldable configuration, where the moment direction becomes positive, allowing P_1 to fold normally.

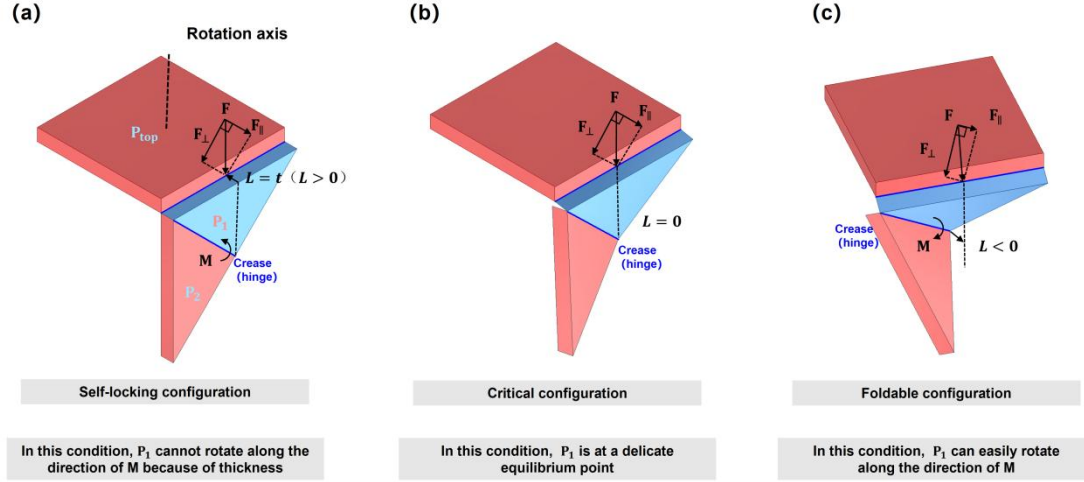


Figure S3.4 Analysis of self-locking capability of FC-ori. (a) Self-locking configuration, (b) critical configuration, and (c) foldable configuration of P_1 under pressure F .

A comprehensive analysis of one limb of an FC-ori structure involves considering many factors, making it quite challenging. Although my analysis ignores the effect of the crease between P_2 and P_3 , which means that the actual critical configuration would occur earlier than the configuration shown in Fig. S3.4(b) (since in this configuration, the moment between P_1 and P_2 is zero, but that between P_2 and P_3 it is positive; hence, overall, it can be folded), it still helps my understanding of why an increase in thickness leads to a larger self-locking range compared to that for the zero-thickness case. For zero thickness, the configurations shown in Fig. S4(a) and (b) overlap, so even a slight external disturbance can cause the structure to shift from a self-locking state to a foldable state. However, according to this theory, when the thick FC-ori structure is between the configurations shown in Fig. S3.4(a) and (b), a negative moment will cause P_1 to fold in the direction that increases the dihedral angle, thereby returning the entire structure to the deployed configuration shown in Fig. S3.4(a). This is why an FC-ori unit could return to the deployed configuration and then self-lock during compression experiments. This also provides a theoretical basis for the proposed folding method: by folding the sides beyond the critical state shown in Fig. S3.4(b), the entire structure loses its self-locking capability, enabling easy folding through compression. For forces in other directions, the same method can be used to analyze the state of P_1 .

3.8.5 Spring-Magnet energy model theory

In Section 3.5, I established a spring-magnet energy model to validate multistability of various FC-ori modules. To simplify the calculation, I assume that the friction forces from hinge rotation and sliding are negligible and that all panels remain rigid during the folding process, adhering to

the kinematics. According to the principle of energy conservation, the energy relationship of the entire system during the deploying process is:

$$E_{\text{spring}} + E_{\text{magnet}} + E_{\text{gravity}} = W_{\text{force}} \quad (\text{S3.9})$$

The work done by the force, W_{force} and gravitational potential energy E_{gravity} can be easily calculated, as

$$W_{\text{force}} = \int_{h_0}^h F dh = \int_{\varphi_1^0}^{\varphi_1} F d\varphi_1 \frac{dh}{d\varphi_1} \quad (\text{S3.10})$$

$$E_{\text{gravity}} = \int_{h_0}^h mg dh = \int_{\varphi_1^0}^{\varphi_1} F d\varphi_1 \frac{dh}{d\varphi_1} \quad (\text{S3.11})$$

Here, the spring energy can be expressed using Hooke's law:

$$E_{\text{spring}} = 2s_1 k(\varphi_1 - \varphi_1^0)^2 + 2s_2 k(\varphi_3 - \varphi_3^0)^2 + 2s_3 k(\varphi_5 - \varphi_5^0)^2 \quad (\text{S3.12})$$

where k is the spring constant which is 0.682 N·mm/deg according to the manufacturer, φ_i is the dihedral angle, φ_i^0 is the initial angle of the spring, then $\varphi_i^0 = \pi/2$ and s_i is the number of the spring.

The magnetic force between the two pairs of magnets and their distance can be calculated by an empirical formula, as

$$F_{\text{magnet}} = \frac{C}{r^n} \quad (\text{S3.13})$$

where C is the empirical constant, r is the distance between the magnets, and n is the empirical exponent. Vokoun et al. introduced a more precise analytical expression for calculating the attraction force between two cylindrical permanent magnets under the assumption of uniform magnetization. However, due to its complexity, I decide to use the empirical formula (S3.12) fitted with experimental results to calculate the attraction force between the two magnets. I used the experimental setup shown in Fig. S3.5(a) to test the force-displacement relationship of four magnets. The displacement is the distance traveled by the force tester, which may have a slight discrepancy with the actual distance between the magnets. Utilizing MATLAB, I determined the following parameters: $C=34 \text{ N/mm}^{1.5}$ and $n=1.5$. Figure S3.5(b) illuminates a comparison between the experimental and fitted curves of a single magnet, showing good agreement. The energy of the magnets can be calculated as:

$$E_{\text{magnet}} = \int \frac{C}{r^n} dr = \int \frac{C}{r^n} d\varphi_1 \frac{dr}{d\varphi_1} \quad (\text{S3.14})$$

The initial distances between the magnets correspond to the distances from the magnet to the top

and bottom surfaces of a side panel. According to the tests, the actual thickness of the magnet is approximately 2.9 mm; therefore, the distances are 0.9 mm and 0.2 mm, respectively. However, a key issue when using the empirical curve to calculate magnetic forces is that the force approaches infinity as the distance between the magnets approaches zero. Thus, I assume that when the two magnets are in full contact, the distance between them is not zero. I set this minimum distance to 0.4 mm. Slightly increasing the initial distances reduces only the force peak but does not affect the multi-stable characteristics of the theoretical curve. I can determine that in the flat-folded state, the initial distance between the magnets at P_{bottom} and P_1 is 1.5 mm, the distance between P_1 and P_2 is 2.6 mm, and the distance between P_2 and P_3 is 0.8 mm. Similarly, to simplify the calculation of the distance between the magnets, I approximate it as the sum of the initial distance and the distance between the projections of the magnet centers onto the panel surfaces. The latter can be determined using the dihedral angle between the two panels and the law of cosines. Moreover, considering the angle between the magnetic dipoles would make the formula very complex. Since the distance from the magnet's center to the creases is relatively large, the angle between the dipoles is nearly 90° when the interaction of the magnet is strong. Therefore, when calculating the magnetic energy, I do not account for the effect of the angle between dipoles. Furthermore, since the magnetic force decreases rapidly with distance, I also ignore the influence between magnets on non-adjacent panels.

Take the partial derivative of both sides of equation (S9) with respect to φ_1 , and I have

$$\left(\sum \frac{c}{r^n} \frac{dr}{d\varphi_1} + \frac{1}{2} mg \frac{dh}{d\varphi_1} - 8s_1 k \left(\frac{\pi}{2} - \varphi_1 \right) - 4s_2 \left(\frac{\pi}{2} - \varphi_3 \right) \frac{d\varphi_3}{d\varphi_1} \right) \frac{d\varphi_1}{dh} = F \quad (\text{S3.15})$$

Using equation (S3.15) and the kinematics of the FC-ori, the theoretical Force-Distance curve in Fig. 3.6(c) is plotted. The comparison in Fig. 3.6(c) illuminates that by configuring the magnets and springs, the FC-ori structure exhibits programmable multistability. Due to the various simplifications made to the magnetic force model, the theoretic result can only serve as a qualitative analysis of the multistable states.

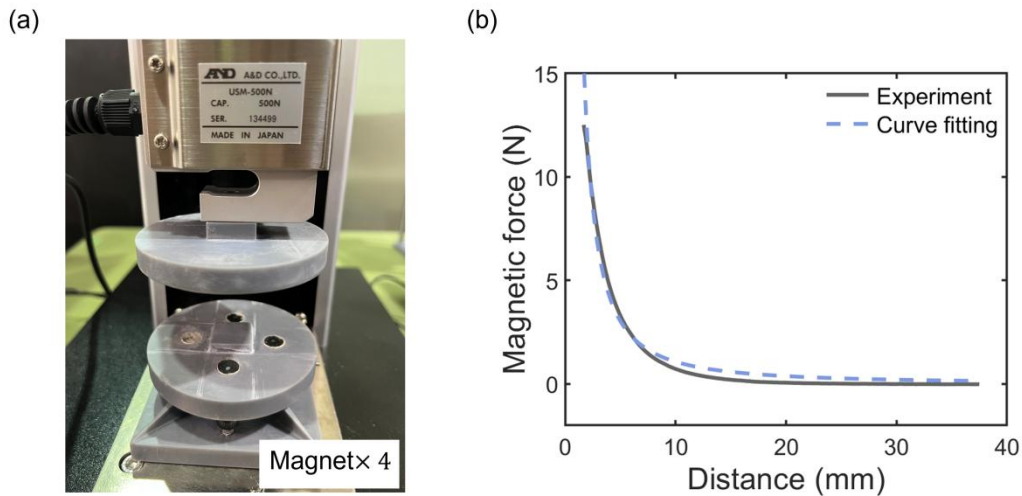


Figure S3.5 (a) Experimental setup for testing the relationship between magnetic force and distance. (b) Comparison between experimental curves and fitted curves (one magnet).

3.8.6 Modular, deployable mobile robot (OriFlex)

FC-ori modules, when equipped with springs and magnets, exhibit multistable properties, which provide a foundational structure for modular robots. However, essential electronic components for a robot, such as motors and power supplies, occupy a certain volume. Therefore, non-foldable modules are needed to house these components. The OriFlex robot mainly consists of FC-ori frames, along with non-foldable units that serve different functions. Figure S3.6 shows the basic structure of OriFlex. The red and blue units are FC-ori modules that rotate clockwise and counterclockwise, respectively. Using such a pair of chiral units between the wheels ensures that the robot maintains basic mobility before and after folding. Additionally, the numbers of springs and magnets used in the pair of FC-ori units connecting the driving and driven wheels differ. In the central part of OriFlex, a pair of chiral FC-ori units is positioned on both sides of the core module. This design allows the camera to flip as these FC-ori units fold, ensuring that the robot's overall height remains low after folding. The camera, a GoPro 12, records videos and takes photographs as the robot moves. To support the core module, two omnidirectional wheels are installed on its sides, ensuring that regardless of OriFlex's configuration, there is always an omnidirectional wheel in contact with the ground. Inside the core module, a 12-V rechargeable battery, an STM32 control board, an electronic display for motor information, and a signal receiver are housed. Furthermore, one FC-ori unit is designed with four tunnels along its diagonal sides for wires to pass through. The length of these tunnels remains nearly identical before and after folding. These tunnels allow the motors in the four driving modules located at the corners of OriFlex to connect to the control board in the central core module, enabling basic functions such as control and movement of the robot. The kinematics of OriFlex are relatively simple since it uses a four-wheel driving system. The robot's movement and steering are controlled by adjusting the speed and rotation direction of the wheels on both sides. This is not described in further detail here.

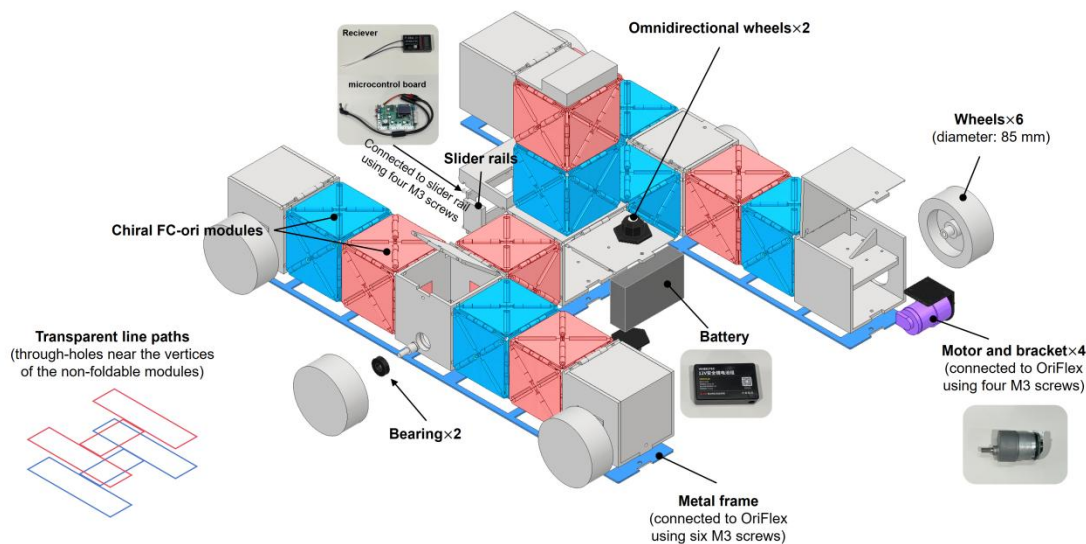


Figure S3.6 Schematic diagram of OriFlex.

Although the FC-ori modules in OriFlex do not experience significant deflection under the weight

of components such as motors in the flat-folded configuration, considerable deflection can occur in the deployed configuration, as shown in Fig. 3.7(c) in Section 3.6. This issue is mainly due to two reasons. First, 3D printing introduces some precision errors. To ensure that the hinges can rotate freely, the holes were designed to be slightly larger than the diameter of the metal shafts. This allows the hinges not only to rotate but also to have a small amount of play, which can cause slight wobbling. Since each FC-ori unit contains 20 hinges, the cumulative error leads to noticeable overall deflection. The other reason is the presence of four incisions in the FC-ori structure, which reduce the constraints between the four limbs. Under external forces, the gap between two limbs will expand. If the incisions were fixed together, the bending strength of the FC-ori would increase significantly. However, this would be inconvenient to install due to the number of incisions in OriFlex and the fixation needing to be removed during folding. Therefore, I chose an alternative solution, which I call the tight line method. This method involves tightening the four corners of the FC-ori unit's base panels with transparent lines. The line paths are shown in Fig. S3.4. This approach takes advantage of the self-locking of the FC-ori units. Regardless of the pressure on the base panels, the structure does not collapse but instead becomes more tightly connected, reducing the play in the hinges. This method does not affect the folding functionality of the FC-ori structure and is quite effective. However, for the experiment in which OriFlex traversed a ditch (Fig. 3.9(d) in the main text), the stiffness achieved by the tight line method alone was insufficient to allow the wheels to pass smoothly over the ditch due to the low height of the chassis. Therefore, I combined the tight line method with another method, called the metal frame method, to enhance structural strength. The metal frame method uses a 2-mm-thick steel frame shaped like the OriFlex chassis, secured with six M3 screws. The installation and removal of this frame are relatively simple and can be completed in about 2 minutes. By combining these two methods, the deflection under OriFlex's own weight is minimized, allowing successful completion of the ditch-crossing experiment. However, these methods are not optimal solutions. Improving hinge precision might fundamentally resolve this issue.

Chapter 4

A Self-Locking Tendon-Driven Robotic Arm Inspired by Cubic Origami

4.1 Introduction

In the previous chapter, the structural characteristics and practical potential of FC-ori were explored in detail. A thick-panel FC-ori structure was developed using the sliding-crease method, enabling a rigid-and flat-foldable configuration while maintaining uniform thickness. Its modular nature further allowed the construction of a foldable mobile robot, OriFlex, demonstrating that FC-ori can serve as a versatile building block for complex deployable systems. However, a major limitation identified was that FC-ori modules still required manual folding for configuration changes. This constraint restricts the scalability, environmental adaptability, and deployment speed of FC-ori based robots. Therefore, developing an actuation strategy that enables remote and rapid folding becomes essential for advancing FC-ori from manually reconfigurable prototypes toward practical robotic systems.

Enabling a deployable structure to switch between load-carrying and foldable states as required remains a key challenge for practical engineering applications [9]. To ensure adequate structural stiffness without compromising the inherent advantages of simplicity and lightweight design, several strategies have been explored, including shape memory polymer stiffening [113], layer jamming [114], pneumatic pressure [115], and the installation of additional locking mechanisms [9, 116]. However, if the deployable structure itself can provide sufficient stiffness by structure design, such as self-locking configurations exemplified by stacked Miura origami [26, 117], coupled Miura-ori tubes [118], and Kresling origami with acute-angled facets [4], it would greatly simplify the system. Furthermore, if both the panels and hinges are fabricated from rigid materials, the structural stiffness can be significantly enhanced relative to soft-material counterparts. For example, Zhu et al. proposed a rigid origami structure using mid-density fiberboard panels and metal hinges with a stiffness of 1875 kN/m in a columnar configuration [112]. Therefore, the FC-ori structure with self-locking capability is expected to exhibit good load-carrying performance.

However, due to self-locking, the FC-ori structure shared the same limitation as that of Zhu et al. [112], requiring manual folding. Manual folding imposes constraints on the size of the origami structure, limits its applicable environments, and reduces the speed of deployment. Therefore, for origami robots, the ability to be remotely controlled and to achieve rapid deployment and folding is of great importance. Various actuation strategies have been developed to drive origami-inspired designs, such as direct actuation by stepper motors at creases [40], utilizing stimulus-responsive materials [41-44], pneumatic actuation [16, 45-46], magnetic actuation [18, 48-50], tendon-driven actuation [51-61], and others. Among these, tendon-driven actuation stands out for its compact implementation, remote controllability, simple control strategy, and compatibility with both elastic and rigid origami structures. It enables complex folding motions with minimal mechanical interference, making it particularly suitable for lightweight and deployable robotic systems. Chapter 4 proposes employing a tendon-driven drive strategy to overcome challenges related to driving the FC-ori unit, and based on this, develops a

deployable robotic arm.

4.2 Rigid foldable structure with self-locking capability

For a deployable robotic arm, flat-foldability, rigid-foldability, sufficient stiffness, and a minimal footprint are essential requirements. For many cylindrical origami structures, while they can be easily folded and applied to soft robotic arms or crawling robots, they lack sufficient stiffness to ensure structural strength [18, 20]. To address this limitation, Suk-Jun Kim proposed combining the Sarrus Linkage structure with a locking mechanism to improve structural stiffness [9]. Unlike designs that rely on additional external locking components, Foldable Cube Origami (FC-ori), which can rigidly fold from a cube into a square, possesses self-locking properties in deployed configuration

4.2.1 Rigid-foldable thick origami

The crease pattern of FC-ori, shown in Fig. 4.1(a), was introduced in Section 3.2. The limitation of rigid folding in the thick FC-ori was addressed in Section 3.3, and Fig. 4.2(b) illustrates the sliding-crease method used to overcome this issue. Compared with the ideal hinge model, the sliding-crease model introduces an additional translational degree of freedom. The flat-folding process of the thick FC-ori enabled by this method is shown in Fig. 4.2(c).

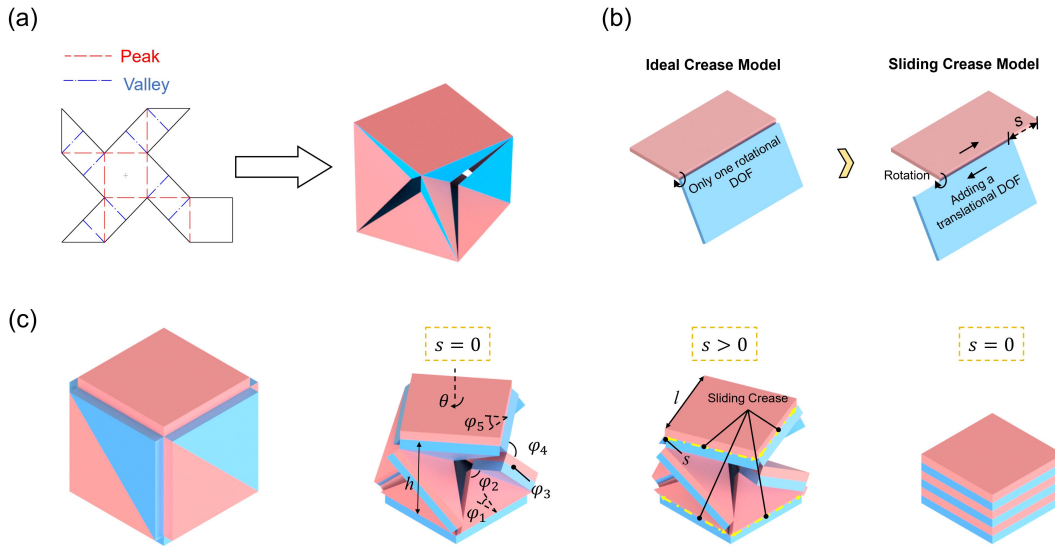


Figure 4.1 A rigid and flat-foldable cubic origami (a) Folding pattern of the Foldable cube origami (FC-ori) and the three-dimensional model without thickness. (b) Schematic diagram of the sliding crease method, where an additional degree of freedom along the axis is introduced to ideal creases. (c) Folding process of the thick FC-ori, where the sliding crease method is applied to achieve flat folding of the structure. The yellow dash-dot lines indicate the creases where axial sliding is allowed.

4.2.2 Self-locking property of FC-ori

Through the experiment shown in Fig. 4.2(a), it can be clearly observed that the FC-ori possesses self-locking properties in its cubic configuration (the deployed configuration). No matter how much force or torque is applied to the top panel, it cannot cause the structure to fold. To explain this

phenomenon, I analyze the geometric relationships of the FC-ori. The method for solving the geometric relationships of thick FC-ori has been previously detailed in Chapter 3, and here I will provide a brief overview. By transforming one limb of the FC-ori into a set of closed linkages, the product of its Denavit-Hartenberg (DH) transformation matrices T_i^j should equal the identity matrix I_4 [102, 103], which is expressed as:

$$T_1^0 T_2^1 \dots T_i^{i-1} T_0^i = I_4 \quad (4.1)$$

Next, utilizing the `fsolve` function in MATLAB (The Mathworks, Inc., MA) to solve the system of equations composed of elements of the DH matrix, I can determine the relationships between the various geometric parameters as illustrated in Fig. 4.2(b). The rhombus symbols on the curve represent the boundary point where sliding hinges occur or do not. It can also be observed that the dihedral angles φ_1 , φ_2 and φ_3 are positively correlated. By observing the $\varphi_1 - h/l$ curve, I can conclude that when the FC-ori starts folding from the cubic configuration, the normalized height first increases and then decreases. Therefore, no matter how large a vertical downward force is applied to the top panel in the cubic configuration, it cannot cause the structure to fold because of this geometric constraint.

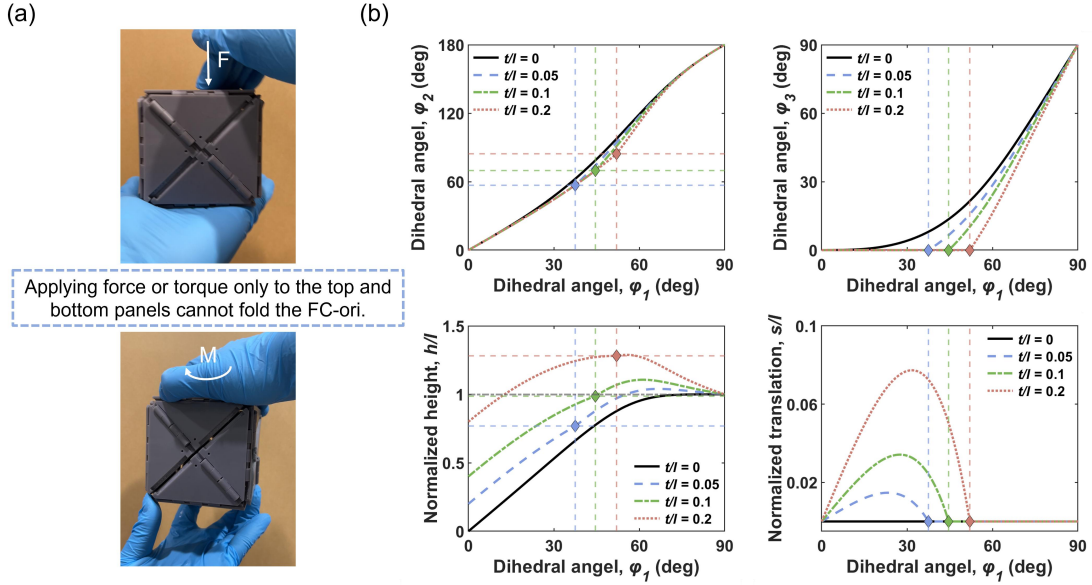


Figure 4.2 Self-locking behavior of the FC-ori in the deployed configuration. (a) Applying force or torque to the top and bottom panels cannot cause the structure to fold. (b) The relationship between the geometric parameters of the thick FC-ori, including the dihedral angles φ_2 , φ_3 , normalized height h/l , normalized sliding distance s/l , and the dihedral angle φ_1 , shown in the curves. The rhombus represents the boundary between whether the crease undergoes sliding. From the curves, it can be observed that the change in normalized height h/l does not monotonically decrease with the dihedral angle φ_1 . Therefore, in this deployed configuration, applying a downward force to the top panel does not cause it to fold.

The inability to fold through twisting can also be explained using geometric relationships. Based on the

relationship curve between the dihedral angle φ_1 and the twisting angle θ shown in Fig. 4.3(a), and the locally enlarged view of the curve presented in Fig. 4.3(b), it can be observed that, for a clockwise-rotating FC-ori, except for the non-thickness case, near $\varphi_1 = 90^\circ$, the top panel will first rotate counterclockwise by a small angle, then rotate clockwise. For better understanding, Fig. 4.3(c) shows a top view of the top and bottom panels with $t/l = 0.1$ simulated in Inventor 2024 (Autodesk, Inc., CA). It can be seen from schematic diagram ② that the maximum counterclockwise rotation angle of the top panel is approximately 0.56° , and there are two positions, ① and ③, where the rotation angle equals zero. ④ exhibits the relative relationship between the top and bottom panels when interference occurs on the side panels ($\varphi_3 = 0^\circ$). The data obtained from the simulation are marked with circles on the curve in Fig. 4.3(a) and (b). The data obtained from the 3D model built in Inventor 2024 closely aligns with the results of the numerical calculations. This indicates that, during the folding process of the thick FC-ori, the rotation angle is not monotonically increasing. Therefore, due to the non-monotonicity, no matter how large a clockwise torque is applied in the cubic configuration of a clockwise-rotating FC-ori, it is impossible to induce folding.

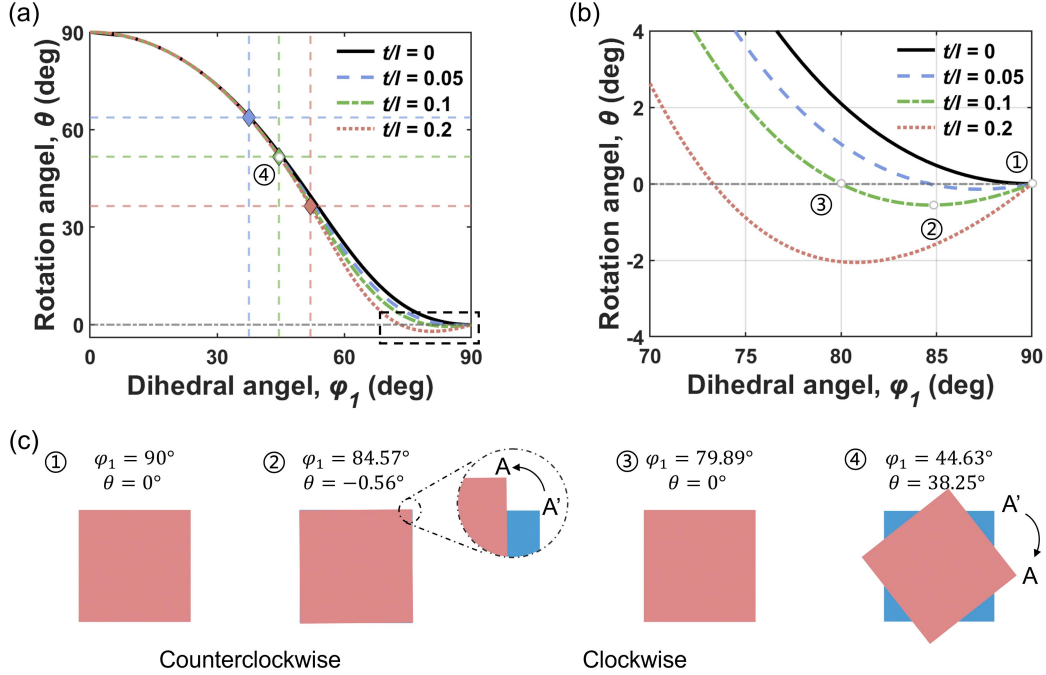


Figure 4.3 Self-locking of the top panel under clockwise torque. (a) The relationship between the rotation angles θ and the dihedral angles φ_1 . (b) The locally enlarged view of (a). (c) Top view of the 3D model with a relative thickness of $t/l = 0.1$, showing only the top and bottom panels. It is observable that for a clockwise-folding FC-ori, as φ_1 gradually decreases, the top panel first rotates counterclockwise by a small angle before rotating clockwise. The angular results from the 3D model are marked at the corresponding positions on the curves in (a) and (b).

4.2.3 Force and moment transmission between the top panel and creases

The previous section analyzed the self-locking mechanism of the FC-ori in the cubic configuration through geometric constraints. That explains why a downward force and clockwise torque cannot cause folding. However, it does not explain why upward force and counterclockwise torque also fail to

effectively transfer to the creases. To further understand this phenomenon, it is important to analyze how efficiently the force or torque on the top panel is transmitted to the hinge. Based on the symmetry assumption from earlier, the single-DOF motion is considered, and the dihedral angles on one limb satisfy $\varphi_1 = \varphi_5$ and $\varphi_2 = \varphi_4$. Therefore, it is only necessary to analyze the relationship between the torque T_1 , T_2 , or T_3 at the crease C_1 , C_2 , or C_3 and the force F or torque M applied to the top panel, as shown in Fig. 4.4(a).

If I only consider a single crease C_i as the input and the top panel as the sole output, while the other creases remain freely rotating. The force and torque transmission ratios between output and input can be calculated as the inverse of the velocity ratio. Due to the analytical difficulty of expressing the geometric relationships of the thick FC-ori, interpolation methods are used to solve the relationship between the velocities. Based on the principle of virtual work, the force and torque transmission ratios can be calculated as follows:

$$\frac{F}{T_i/l} = \frac{\omega_i \cdot l}{v} = \frac{\Delta\varphi_i \cdot l}{\Delta h} = \frac{(\varphi_i(\varphi_3) - \varphi_i(\varphi_3 - \delta)) \cdot l}{h(\varphi_3) - h(\varphi_3 - \delta)} \quad (4.2)$$

$$\frac{M}{T_i} = \frac{\omega_i}{\omega_{top}} = \frac{\Delta\varphi_i}{\Delta\theta} = \frac{\varphi_i(\varphi_3) - \varphi_i(\varphi_3 - \delta)}{\theta(\varphi_3) - \theta(\varphi_3 - \delta)} \quad (4.3)$$

where ω_i represents the angular velocity at the crease, ω_{top} is the angular velocity of the top panel along the axis of rotation, v denotes the velocity of the top panel in the vertical direction, and δ is a small angle. Figure 4.4(b) shows the curves of φ_3 versus moment ratio, M/T_i and φ_3 versus force ratio, $F/(T_i/l)$. When the ratio approaches infinity, it represents the singularity of the structure, where a large force applied to the top panel results in negligible force transfer to the corresponding crease. For the moment transfer, the singularities occur at φ_3 values of 67.5° , 78° , 83.5° , and 90° for different thicknesses of FC-ori ($t/l = 0.2$; 0.1 ; 0.05 ; 0). For force transfer, the singularities occur at values of 6.5° , 26.5° , 41° , and 90° . It is observable that as the thickness increases, the φ_3 of the singularity gradually decreases. Moreover, the singularity in force transfer occurs at a smaller φ_3 than in torque transfer. Additionally, it is worth noting that when $\varphi_3 = 90^\circ$, which corresponds to the cubic configuration, the smaller the thickness, the closer the force and torque transmission ratios are to infinity. Therefore, when the thickness is small, it is difficult to transmit the applied force on the top and bottom panels to the creases in the cubic configuration. This explains why the FC-ori with $t/l = 0.05$ can maintain the cubic structure even when a massive upward force or counterclockwise moment is applied to the top panel. However, as the thickness continues to increase, and the force ratio gradually decreases, it is possible to fold a thick FC-ori by stretching the top panel first and then rotating it. Interestingly, the self-locking behavior of FC-ori in the cubic configuration resembles a local self-locking mechanism. Although applying a compressive load directly to both ends of the origami structure cannot cause it to fold, the creases are not geometrically constrained, and thus the structure still retains its foldability. This is unlike stacked structures composed of different Miura sheets, which completely lose their foldability once folded into the self-locking configuration [26, 117]. Therefore, the combination of self-locking capacity and rigid foldability in FC-ori motivates its application in deployable robotic arm designs.

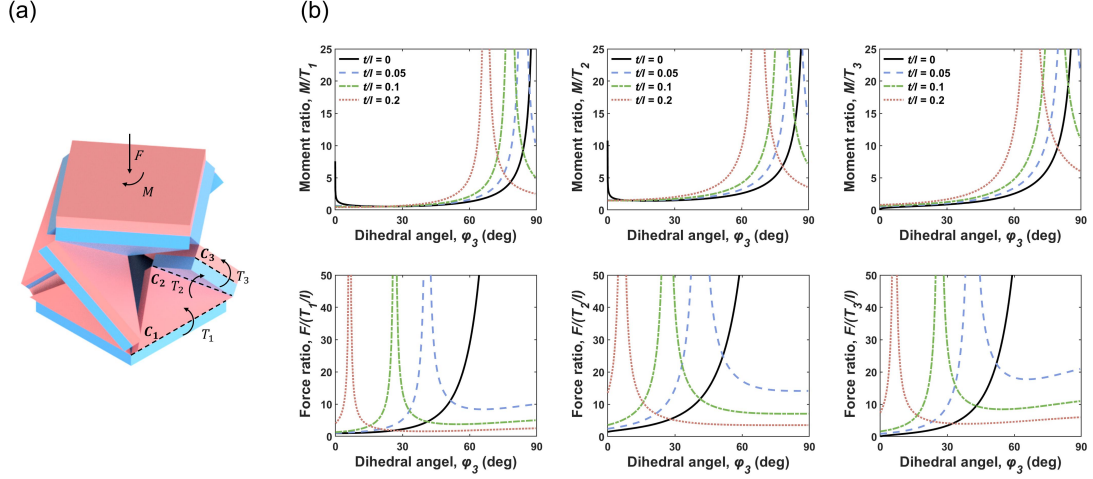


Figure 4.4 The force and moment transmission between the top panel and each crease (a) Schematic diagram of the forces and moment acting on the FC-ori. T_1 , T_2 , and T_3 represent the torques at the creases C_1 , C_2 , and C_3 , respectively. F and M represent the force and torque acting on the top panel. (b) The curve of the moment ratio M/T_i and force ratio $F/(T_i/l)$ versus the dihedral angles φ_3 . By observing the curves, it can be concluded that as the thickness approaches zero, the dihedral angle φ_3 at the location of the singularity point moves closer to 90° , and the transmission ratio in the deployed configuration deteriorates.

4.3 Tendon-driven FC-ori unit

Based on the previously calculated geometric and force and moment transmission ratios of FC-ori, it is clear that applying force or torque only to the top or bottom panels does not easily cause the structure to fold. To fold FC-ori, it is necessary to apply force to the side panels directly. Therefore, I apply a common actuation method used in origami mechanisms, namely, tendon-driven, to solve this problem.

4.3.1 Kinematic relationship and mechanical testing

Unlike the common tendon-driven origami mechanism [20, 51-61], the tendons of the FC-ori traverse not only the top and bottom panels but also the side panels. The green line in Fig. 4.5(a) illustrates the tendon path along one limb. In the flat-folded configuration, all the centers of the holes lie on a single straight axis, which greatly simplifies the installation of the tendon. The tendon can be easily threaded through all the holes in the flat-folded configuration, and the installation is completed once the structure is deployed. I denote l_i ($i = 1, 2, 3, 4, 5$) as the length of each part of the tendon between two adjacent panels, and γ_k ($k = 1, 2, 3, 4, 5, 6$) as the angle between two consecutive tendon segments. These are critical parameters for tendon-driven mechanisms, used both for kinematic analysis and friction estimation. To simplify the model, I assume that all the tendons always pass through the center of the holes. Thus, the relationship between l_i and γ_i can be derived using the law of cosines, using distance x_i between holes and creases, as

$$l_i = x_i \sqrt{2 - 2\cos\varphi_i} \quad (4.4)$$

To investigate the influence of hole placement on the tendon-driven process, an experimental setup was

designed as shown in Fig. 4.5(b). A local schematic illustrates the distribution of holes on one of the side panels. The square panel has a side length of 80 mm, and the adjacent triangular panel has a height of 40 mm. The thickness of each panel is 4 mm, corresponding to the actual dimensions of the experimental prototype. Starting from the right-angled vertex, holes are arranged in horizontal rows with a vertical spacing of 10 mm, labeled as R_n ($n = 1,2,3$). The first row contains only one hole. The second row has three holes, with 10 mm spacing between them. The third row also contains three holes, but with 20 mm spacing between adjacent holes. I use the notation $R_n C_m$ ($n = 1,2,3$; $m = 1,2,3$) to represent the hole at the n -th row in the m -th column. The relationship between the total tendon length and the dihedral angle φ_1 can be expressed as:

$$L(\varphi_1) = \sum_{i=1}^5 l_i(\varphi_1) + 6t \quad (4.5)$$

where t is the thickness of panels. Due to symmetry and geometric considerations, the positions of the holes within the same row do not affect the total length of the tendon. I define L_0 as the total tendon length in the fully deployed configuration, where $\varphi_1 = \varphi_3 = \varphi_5 = 90^\circ$; $\varphi_2 = \varphi_4 = 180^\circ$. The change in tendon length as a function of the folding state of the FC-ori structure can be expressed as:

$$\Delta L(\varphi_1) = L_0 - L(\varphi_1) \quad (4.6)$$

Additionally, to enable smooth self-deployment of the structure, I installed two torsion springs with an initial angle of 135° at each right-angle hinge. The 135° preloading ensures that even when the structure is fully deployed, at which point the hinge angle reaches 90° , the creases still retain sufficient restoring torque to overcome the frictional resistance generated by the tendons.

Figure 4.5(c) shows the relationship between the change in tendon length, ΔL , and the normalization height of the structure, h/l , when tendons are routed through holes at different positions. It is observable that the closer the hole is to the right-angled vertex of the triangular panel, the greater the tendon displacement required during folding. Assuming negligible friction, the same amount of elastic energy is stored in the springs during the folding process of the FC-ori, implying that a larger tendon displacement results in a lower average pulling force.

Additionally, to investigate the influence of hole position on the required driving force, I tested the tendon tension during the folding process using a tensile testing machine. Figure 4.5(d) shows the folding process at the $R_1 C_1$ position. As seen, the force increases from zero to a peak value of approximately 6.13 N, then decreases to around 4.1 N until the structure is flat folded. The peak force occurs when the dihedral angle φ_2 begins to change from 180° . Figure 4.5(e) presents the Force-displacement curves for tendons routed through holes at different positions. Different colors represent holes from different rows. It can be observed that the Force-displacement curves for holes within the same row are quite similar, while the primary difference between holes in different rows lies in the peak force. The required pulling force for stable folding is nearly the same after reaching equilibrium. Holes closer to the right-angled vertex of the triangular panel result in smaller peak forces. This is due to the influence of the torque arm between the tendon and the spring hinge. Therefore, I can obtain such conclusion that when selecting the tendon path, the holes should be positioned as close as

possible to the right-angled vertex of the triangular panel.

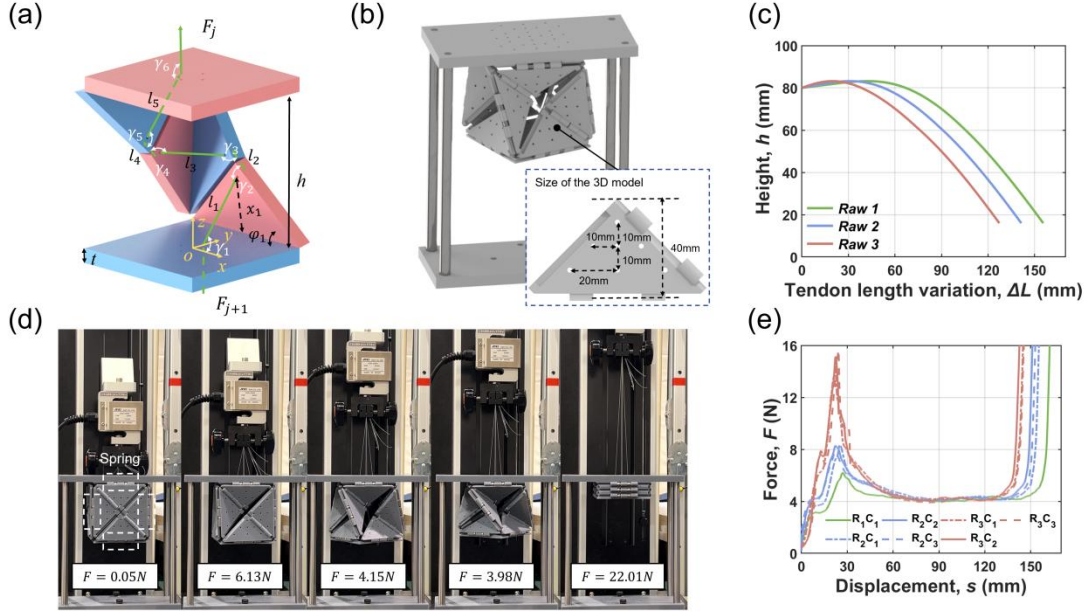


Figure 4.5 FC-ori unit capable of folding through tendon-driven actuation. (a) The schematic diagram of a tendon routing along a single limb. In the flat folded configuration, the holes through which the tendon passes are aligned along a straight line. (b) The experimental setup for testing the influence of hole positions on the tensile force required during folding. (c) Curves showing the relationship between tendon length variation ΔL and normalization height h/l at different positions. (d) Tensile test procedure through the hole at the first row and first column (R_1C_1). (e) Force-displacement curves during tensile test through holes at different positions. The curves exhibit an initial peak in tensile force, followed by a relatively stable reduction phase. The position of the hole influences the magnitude of the peak force.

4.3.2 Optimization methods to reduce friction between the tendon and panel

For tendon-driven robotic arms, minimizing friction is crucial. High friction increases actuator load and energy consumption. Moreover, FC-ori deployment relies on spring restoring torque, which cannot be infinitely increased. Therefore, in addition to standard approaches like using smoother tendons, rounded holes, and lubricants, optimizing the tendon path is essential.

To calculate the friction of the tendon passing through the hole, I could simplify the hole-tendon model into a capstan-tendon model because of the thin thickness [9]. According to the Euler-Eytelwein formula:

$$F_{out} = F_{in}e^{\mu\alpha} \quad (4.7)$$

the relationship between the tension before the tendon passes through the hole, F_{out} , and the tension after the tendon passes through the hole, F_{in} , can be calculated. α_k denotes the bending angle of the tendon, which is the supplement of the tendon's included angle γ_k , and μ is the friction coefficient

between the tendon and the hole. The angle between two tendons can be determined by the angle between their respective direction vectors, which in turn can be obtained from the coordinates of the centers of the holes through which the tendons pass. The coordinates of the holes located on adjacent panels can be derived using the coordinate rotation method for an arbitrary point around an arbitrary axis (details in Appendix A). The friction, f_k , equals the difference in tension at both ends of the k -th hole, which is

$$f_k = F_{in} - F_{out} = F_{in}(1 - e^{\mu\alpha_k}) \quad (4.8)$$

The total frictional force f_{total} of a limb in the j -th unit can be obtained as

$$f_{total} = F_j - F_{j+1} = F_j(1 - e^{\mu\sum_{k=1}^6\alpha_k}) = F_j(1 - e^{\mu\alpha_{sum}}) \quad (4.9)$$

F_j denotes the input tensile force applied to the tendon of the j -th unit, and F_{j+1} represents the output force transmitted to the $(j+1)$ -th unit. It is evident that the friction is positively correlated with the bending angle of the tendon. Therefore, optimizing the structure design to reduce the total tendon angle α_{sum} can effectively reduce the frictional force of the rope. The first optimization method is shown in Fig. 4.6(a). I transform the holes on the common square panel between the j -th and $(j+1)$ -th units into sliding slots, so that the position of the tendon on this panel is no longer fixed but moves during the folding process. As a result, the friction at the sliding slot is always zero. Assuming that the tendons between two adjacent units remain vertical, I can calculate the total bending angle of the tendon after optimization. As shown in Fig. 4.6(b), the black solid line represents the path before optimization, and the blue dashed line represents the path after optimization. It is evident that this method significantly reduces the total bending angle, thereby achieving the goal of reducing friction.

In addition to directly reducing the bending angle of the tendon, a second optimization method was employed to decrease the friction within a unit. In the previous design, the tendon on a single limb passed sequentially through four side panels. In the optimization design, a small portion of two intermediate panels was removed, allowing the tendon to bypass them and only pass through the upper and lower side panels. Although this modification does not significantly reduce the overall bending angle, it effectively decreases the contact area between the tendon and the panels. To verify the effectiveness of this method in reducing friction, I designed the experimental setup shown in Fig. 4.6(c). According to previous calculations, the tendon experiences the highest friction when the FC-ori is fully deployed, making this configuration evident for evaluating frictional differences. A 50-g weight was suspended from the lower end of the tendon, while the upper end was connected to a tensile testing machine. Figure 4.6(d) shows the Force-displacement curves for the two tendon paths under identical loading conditions. The friction force was estimated by subtracting the gravitational force of the weight from the measured tension. The results show that the average friction force before and after the optimization was approximately 1.29 N and 1.03 N, respectively, indicating a reduction of about 20%.

The deployed configuration of an optimized tendon-driven FC-ori unit is exhibited in Fig. 4.6(e). The hypotenuse of the triangular panel is 80 mm long; its thickness is 4 mm; the side length of the square panels is 80 mm; and its thickness is 8 mm, double that of the triangular panel (The schematic diagrams of panels can be found in Appendix B). For the FC-ori structure, a smaller thickness leads to

a shorter sliding distance required at the creases and enables a higher folding ratio. However, due to the limitations of 3D printing materials, if the panel thickness is too small, its structural strength may not meet the required performance. In addition, the dimensions of the torsion spring and metal shaft must be compatible with the panel. Considering these three factors, I selected a suitable panel thickness of 4 mm. Based on the aforementioned optimization methods, two square panels were modified to include central cutouts, which not only help reduce friction but also lower the overall weight of the unit and reduce 3D printing resin consumption. Additionally, a small portion near the right-angled vertices of several triangular side panels was removed. Torsion springs with an initial angle of 135° and a stiffness of $0.112 \text{ N}\cdot\text{mm}/\text{deg}$ were installed at all 90° creases to ensure deployment. These modifications result in smoother, lower-resistance folding and deployment. Figure 4.6(f) shows the connection method between two FC-ori units. Adjacent 3D-printed modules are connected via metal shafts and share a common square base panel with integrated male and female hinge connectors on its top and bottom surfaces. The triangular panels are attached by aligning these hinge parts, similar to LEGO assembly. The male connectors are designed with a transition fit, and the female connectors with an interference fit, ensuring a secure and stable joint. This design allows for easy shaft removal and quick panel replacement. To implement the sliding crease behavior, the male hinge components are intentionally made slightly shorter than their corresponding female counterparts. To implement the sliding crease behavior, the male hinge components are intentionally designed to be approximately 0.5 mm shorter than their corresponding female counterparts. This clearance allows a small range of axial movement along the crease direction, enabling the hinge to function as a sliding joint during folding. The sliding hinges are specifically located at the four creases that connect the square base panel to the side triangular panels. This design guarantees that the thick-panel FC-ori structure remains flat-foldable.

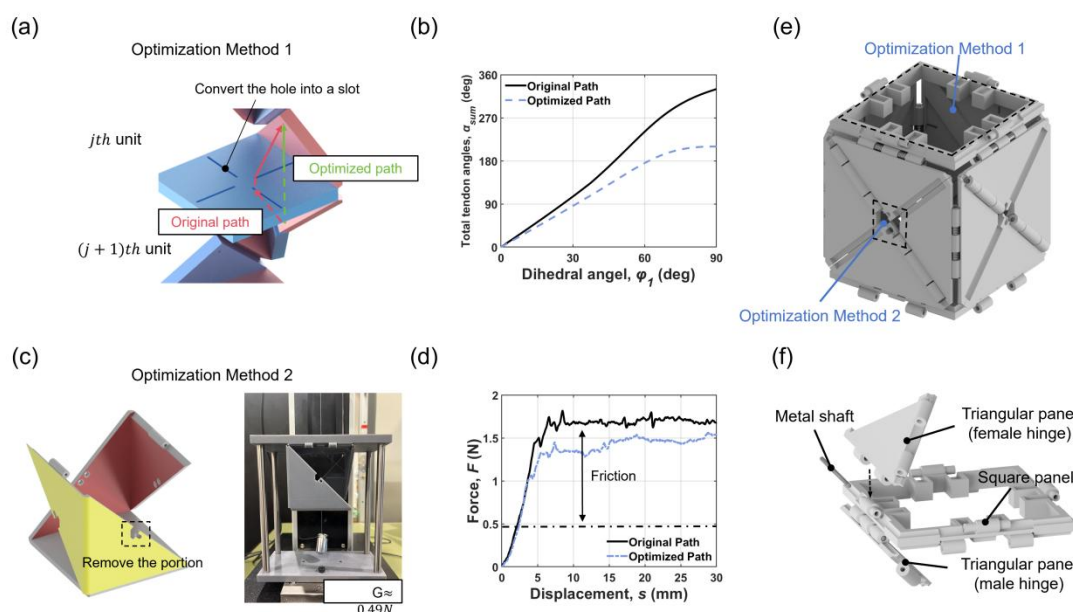


Figure 4.6 Two methods to reduce tendon friction. (a) Schematic diagram of the first optimization, where the hole through which the tendon passes between two connected FC-ori panels is replaced by a sliding slot. As the folding process occurs, the tendon moves accordingly within the slot. (b) The curve of the total bending angle α_{sum} and displacement s along the path of a limb before and after optimization. (c) Schematic diagram of the second optimization, where a small portion of two

intermediate side panels was removed to reduce the number of holes through which the tendon passes. And the tensile force required to lift a 50-g weight along the tendon path, before and after optimization, was tested using a tensile testing machine. (d) Force-displacement curves corresponding to the two different tendon paths. (e) Schematic diagram of the FC-ori model incorporating both optimization methods. (f) The connection method between units.

4.3.3 Effect of Load on Tendon Tension and Structural Load-carrying Capacity

To investigate the effect of external loads on the FC-ori unit as an origami-inspired robotic arm module, two experiments were conducted to evaluate the required tendon tension under suspended loads and the load-carrying capacity of the unit in its self-locking configuration.

As shown in Fig. 3.7(a), a tensile testing machine was used to measure the variation in tendon force with respect to displacement while suspending loads of different masses from the lower end of the FC-ori unit. The pulling speed of the testing machine was set to 300 mm/min. And the masses used in the experiment were 50 g, 100 g, 200 g, and 500 g. Figure 3.7(b) presents the relationship between tendon tension and displacement under different loading conditions. It can be observed that in the initial phase of folding, the influence of the suspended loads on the tendon force is negligible. However, as the folding progresses, the difference in required tendon tension between the loaded and unloaded conditions increases gradually. Taking the 500 g weight as an example, the maximum additional tendon force required to lift this load reaches approximately 5.3 N. According to the law of conservation of energy, the work done by the tendon force, W_{tension} , equals the sum of the energy stored in the spring, E_{spring} , the work done against gravity, G , and energy loss due to friction, W_{friction} :

$$W_{\text{tension}} = E_{\text{spring}} + G + W_{\text{friction}} \quad (4.10)$$

Specifically, the work done by the tendon force can be expressed as $W_{\text{tension}} = T \times \Delta L$, where T is the tendon tension and ΔL is the displacement at the tendon's driving end. The work done against gravity is given by $G = mg\Delta h$, where m is the mass of the payload and Δh is the vertical displacement of the load. Since the folding height is kept constant and both the elastic energy stored in the spring and the energy loss due to friction remain the same regardless of the suspended weight, the difference in required tendon force between the loaded and unloaded cases can be attributed solely to the gravitational work. Therefore, the additional tendon force required to lift the payload can be approximated by $\Delta T = mg \times (\Delta h / \Delta L)$. $\Delta h / \Delta L$ can be calculated by derivation of the kinematic relationship curve between tendon length and structure height presented in Section 3.1. According to the theoretical calculation, the maximum difference in tendon force occurs when the FC-ori unit is completely folded, with a peak value approximately equal to mg , which is similar to the experimental result. This relationship offers a practical estimation of the extra tendon force required for lifting tasks and provides design insight for actuator selection and power consumption analysis in tendon-driven origami robotic arms.

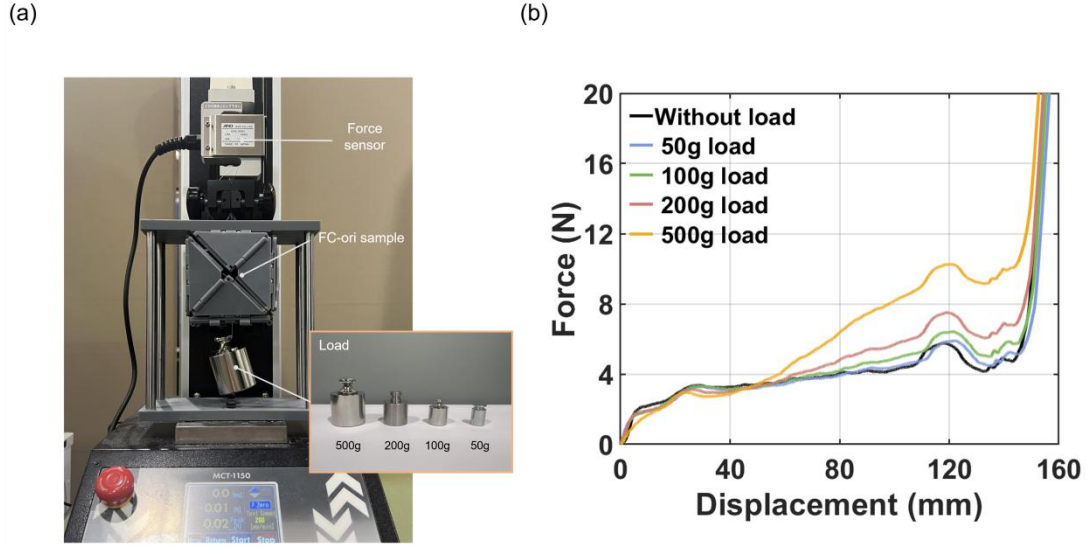


Figure 4.7 Behavior of the FC-ori structure with varying suspended payloads (a) Experimental setup for measuring tendon tension during FC-ori folding with varying payloads and a set of loads used in the experiment, with masses of 500 g, 200 g, 100 g, and 50 g. (b) Force-displacement curves under different suspended payloads.

Figure 3.8(a) illustrates the failure mode of the FC-ori unit under axial compressive loading. Cracks are observed to initiate near the hinge region, indicating that this area is the primary structural weak point and is particularly susceptible to failure under compressive forces. In addition, the diagonals of the FC-ori unit are designed with incisions, which lead to misalignment between panels during axial compression. This geometric instability reduces the overall structural stiffness. Figure 3.8(b) shows the damaged region near the hinge after compression. This area has a structural thickness of approximately 2 mm and is additionally subjected to the restoring force from the spring. Thus, it experiences higher stress, making it more susceptible to material failure. Figure 3.8(c) presents the Force-displacement curve of the FC-ori structure during axial compression. According to the experimental results, the structure composed of three serially connected FC-ori units exhibits a stiffness of approximately 6.23 kN/m and can withstand a maximum compressive load of about 101.17 N. To improve the structural stiffness of the FC-ori, a protrusion was introduced at the vertices of the pink triangular panels, functioning as a stopper, as illustrated in Fig. 3.8(d). The effectiveness of this design is confirmed in Fig. 3.8(e), which shows that the stopper successfully prevents diagonal panel misalignment in the FC-ori unit subjected to axial compression. This design significantly reduces the compressive displacement, thereby enhancing the overall stiffness. For clarity, the stiffness of an FC-ori unit with and without the stopper was compared under compression, with the maximum applied load set to 80 N. Figure 3.8(f) presents the comparison of Force-displacement curves between them. Based on the experimental data, the stiffness of the modified FC-ori unit was calculated to be 81.97 kN/m, which is considerably higher than that of the original unit without stoppers, 18.70 kN/m. These results demonstrate that the proposed method effectively enhances the structural stiffness of the FC-ori. Furthermore, the load-carrying capacity could be further improved by increasing the panel thickness or by employing materials with higher mechanical strength than the UV-cured resin with a Young's modulus of 2.8 GPa used in this study.

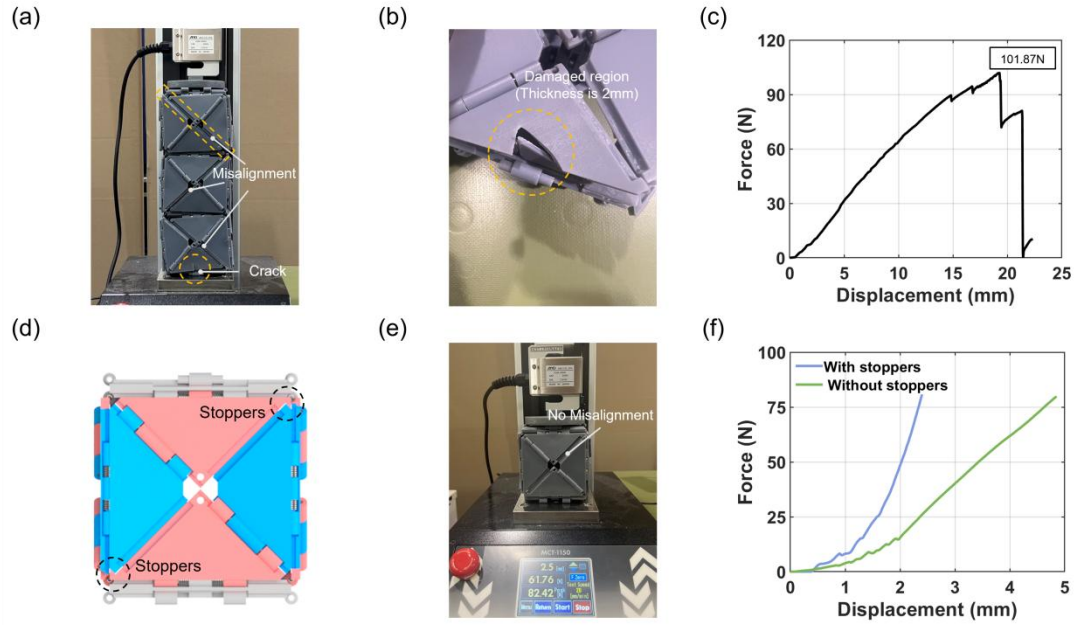


Figure 4.8 Load-carrying capacity and stiffness optimization method of FC-ori (a) Compression test of the three-unit FC-ori structure in the self-locking configuration. (b) Damaged region of FC-ori structure near the hinge after compression. (c) Force-displacement curve obtained from the axial compression test of the three-unit FC-ori structure. (d) Schematic diagram of stoppers. (e) Behavior of an FC-ori unit with stoppers under compression. (f) Comparison of Force-displacement curves of FC-ori units with and without stoppers under compression.

4.4 Origami robotic arm actuated by a single motor

In this section, I introduce two tendon-driven connection strategies for FC-ori units. In the first method, multiple units are actuated simultaneously by shared tendons, which I refer to as the serial configuration. In the second method, each unit is actuated by an independent tendon, but all tendons are wound around a common spool, which I call the parallel configuration. Regardless of configuration, both strategies require only a single motor to drive the entire system, greatly simplifying both actuator and control design.

4.4.1 Multi-unit serially connected robotic arm

A serially connected multi-unit FC-ori robotic arm mainly consists of three components: the actuation and control module, the origami module, and the function module, as illustrated in Fig. 4.9(a). Since only a single motor is required for actuation, the driving mechanism is remarkably simple. It includes a Hall-effect motor, a 3D-printed spool, a bearing, and a 3D-printed frame. Space is reserved above the motor for installing a battery, microcontroller, and signal receiver. The middle section consists of modular FC-ori units (Detail of 3D printing can be found in Appendix B: Materials and Methods), and the number of units can be flexibly adjusted based on specific application requirements. In my demonstration, three units were used. The bottom part is the function module. For example, a GoPro camera (GoPro, Inc., CA) can be installed here. According to measurements, the GoPro weighs

approximately 154 g. Based on the previous payload-force analysis, this additional mass increases the required actuation force by approximately 1.5 N, which remains well within the torque capacity of the motor. Figure 4.9(b) shows the folding process of the robotic arm composed of three FC-ori units. The transition from fully deployed to flat folded takes only 3 seconds (depending on the motor speed). During this folding process, the arm length reduces from approximately 272 mm to 80 mm, achieving a length folding ratio of about 3.67. Figure 4.9(c) illustrates the unfolding process of the robotic arm. During deployment, the FC-ori units deploy sequentially from top to bottom.

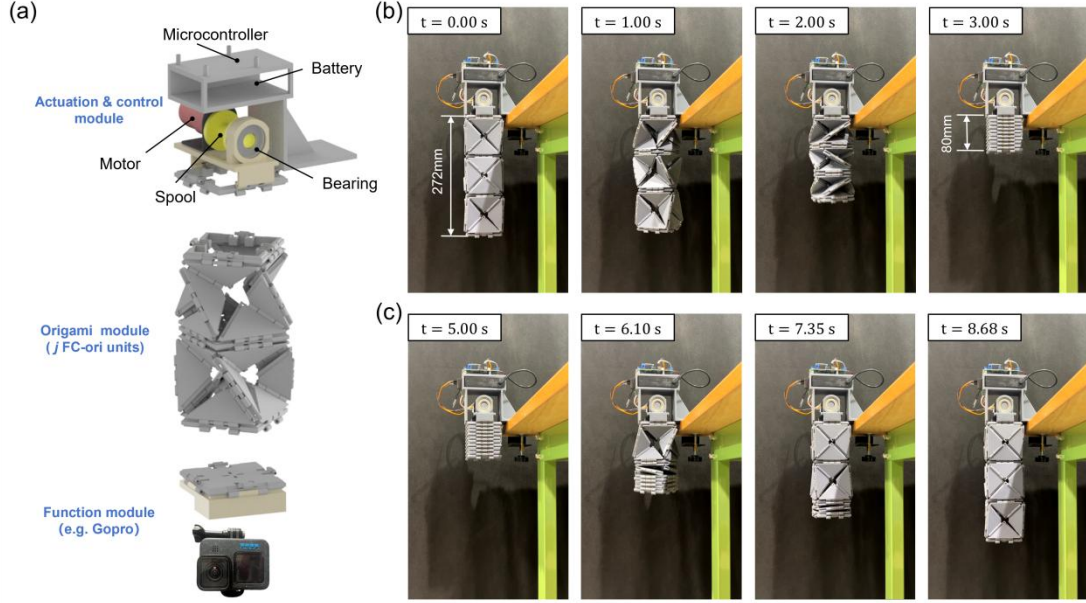


Figure 4.9 Multi-unit serially connected robotic arm. (a) The schematic diagram of the components of a serially connected robotic arm, consisting of three modules: Actuation and control module, origami module, and functional module. (b) The folding process of the serially connected robotic arm. (c) The deploying process of the serially connected robotic arm. When placed in a vertical orientation and with a uniform spring distribution, the deploying sequence of the FC-ori units progresses from top to bottom.

4.4.2 Programmable parallel connected robotic arm

In addition to the serial configuration, I also developed a programmable parallel actuation strategy for FC-ori-based robotic arms. In this approach, as illustrated in Fig. 4.10(a), two FC-ori units are positioned on either side of the actuation unit, with their tendons denoted as red and blue lines, respectively. Since the two tendon systems are independent, I can program the deployment sequence by pre-winding different numbers of turns on the spool for each unit.

I demonstrate two pre-winding modes. In the first mode, both tendons are wound equally, resulting in synchronous deployment of the two units, as shown in Fig. 4.10(b). In the second mode, the two tendons are wound unequally so that one unit is initially flat-folded and the other fully deployed. This results in alternating motion, as shown in Fig. 4.10(c), where the two units fold and deploy in succession. However, since it is difficult to ensure that the initial lengths of the tendons in the two parallel units are perfectly identical, and the tendons inevitably undergo elastic deformation under load, these imprecisions may lead to incomplete deployment in some cases. In future work, I plan to use

low-stretch tendons and adopt more precise connection methods between the tendons and the spool to address these issues.

When combining the serial and parallel configurations, the effect of gravity becomes non-negligible. Since the FC-ori unit is a multi-DOF structure, placing multiple units horizontally causes the system to bend during the folding process due to gravity. To address this issue, one effective solution is to design the external support structure such that the rotation axes of all top panels are aligned, eliminating undesired bending [32]. Moreover, if the system is deployed in microgravity environments, such as in space applications, the axisymmetric distribution of torsion springs and tendons is sufficient to ensure consistent and synchronized motion of all limbs, similar to the vertically and serially connected multi-unit FC-ori demonstrated previously. Therefore, space will emerge as an ideal and promising application scenario for the complex FC-ori system.

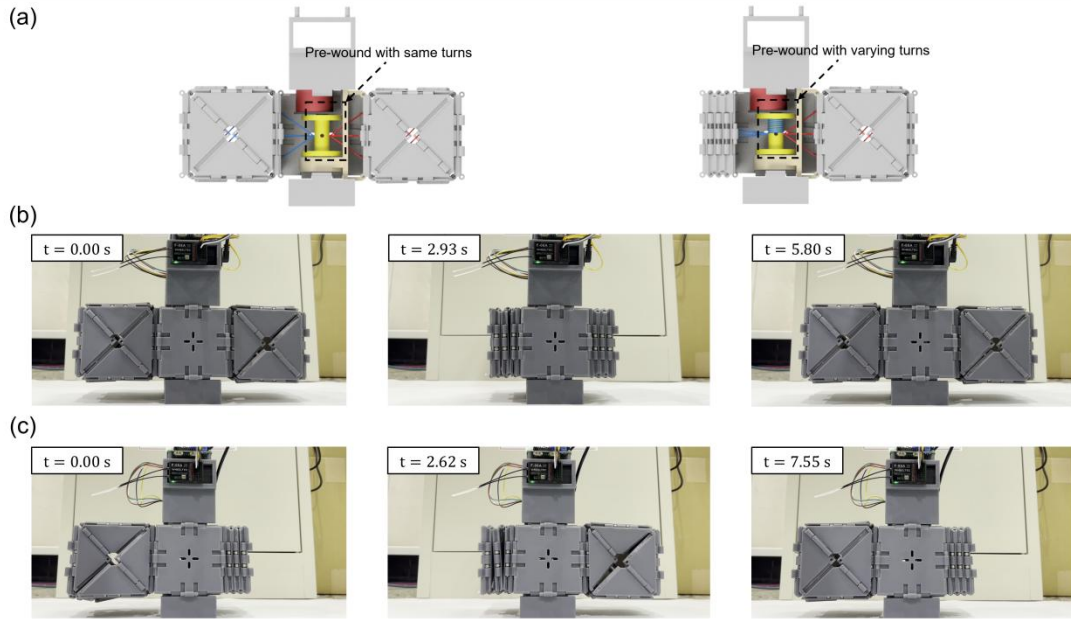


Figure 4.10 Programmable parallel-connected robotic arm. (a) The schematic diagrams of the two pre-wound modes. (b) Synchronous motion of the two parallel FC-ori units. (c) Alternating motion of the two parallel FC-ori units: one FC-ori unit deploys while the other one folds.

4.4.3 Comparison with existing tendon-driven origami robotic arms

Common research on tendon-driven origami robotic arm primarily focuses on multi-DOF bending under multi-motor actuation [20, 51-61]. In contrast, the thick FC-ori robotic arm proposed in this study does not possess the same level of motion flexibility. However, due to its inherent self-locking capability, it can be actuated by a single motor meanwhile maintaining a high load-carrying capacity in deployed configuration. To more clearly illustrate the advantages and limitations of the FC-ori structure, a comparative analysis was conducted with similar research based on a foldable cylindrical structure. Specifically, I evaluated compression performance using three metrics: volumetric folding ratio, R_V , length folding ratio, R_L , and area folding ratio, R_A . For instance, according to the definitions of folding ratios, the volumetric fold ratio of the FC-ori unit is given by $6tl^2/(l+2t)^3$, the length fold ratio is $6t/(l+2t)$, and the area fold ratio is $l^2/(l+2t)^2$, where t denotes the panel thickness and l is the edge length of the square panel. These expressions indicate that both R_V and R_L are highly

sensitive to panel thickness, which means that their values can vary significantly across different origami structures due to thickness variations. In contrast, R_A is less influenced by thickness and primarily reflects the change in footprint of the origami structure. Moreover, the ease of actuation was evaluated by the number of motors required, n . The load-carrying capability was evaluated based on the structure stiffness k , the effective modulus, $\bar{E}$ and whether the structure exhibits locking capability.

In Table 4.1, I compare the folding-related parameters of several representative cylindrical origami-inspired structures. Among them, the FC-ori, MUTOIS [112], Sarrus linkage [9], and the Kirigami cuboid [32] share several common features including a cuboid deployed configuration, rigid and flat-foldability, and uniform panel thickness. The Kresling origami truss structure [4] shares the same self-locking mechanism as the FC-ori, as both are inspired by the Kresling origami geometry. In contrast, the Miura-derived origami tube [12] represents a flexible origami structure for comparison in load-carrying and actuation. As shown in Table 1, R_V does not vary significantly among the selected origami structures. However, R_L of Sarrus linkage robotic arm is notably higher, primarily due to its exceptionally thin panel material (only 0.35 mm in thickness). In terms of R_A , the FC-ori demonstrates the best performance, which can be attributed to its square footprint in both the folded and unfolded configurations. Therefore, from the perspective of compressibility, the FC-ori exhibits clear advantages. Regarding the ease of actuation, structures such as MUTOIS, Kirigami cuboid, and the Kresling origami truss require external assistance for folding and are not compatible with remote actuation using electric motors. In particular, MUTOIS requires a relatively long transformation time, approximately 40 minutes. In contrast, both the FC-ori robotic arm and a foldable arm using Sarrus linkage can be folded using a single motor to actuate multiple units, and both systems demonstrate relatively short actuation times. The Miura-derived origami tube, on the other hand, can achieve multi-DOF motion through the coordinated actuation of multiple motors. In terms of stiffness, the Miura-derived origami tube, made from flexible materials, exhibits the lowest stiffness of approximately 0.19 kN/m. The proposed FC-ori structure achieves a stiffness of approximately 18.70 kN/m, and with the application of stoppers, the stiffness can be enhanced up to 81.97 kN/m. Meanwhile, the MUTOIS structure demonstrates highest stiffness, with a reported maximum value of up to 1875 kN/m. However, the reported stiffness values vary significantly across studies because of the strong influence of structural scale. To enable a fair comparison, I introduce a normalized measure of stiffness that accounts for geometric scale. Specifically, I define an effective modulus, $\bar{E}$ as

$$\bar{E} = kL/A \quad (4.11)$$

where k is the structural stiffness, and L and A are representative length and cross-sectional area, respectively. This definition follows the familiar relation $k = EL/A$ for a bar under axial loading, but here $\bar{E}$ should be interpreted not as a material property but as a mechanism-level modulus that allows stiffness comparisons across different scales. These results reveal that the $\bar{E}$ of MUTOIS and the Sarrus origami robotic arm is remarkably high, whereas $\bar{E}$ of FC-ori and the Kresling origami truss is comparatively lower, but still significantly greater than $\bar{E}$ of the Miura-derived origami tube. In addition, the Young's modulus and thickness of material also affect structural stiffness, making comparisons across studies difficult. Finally, in terms of locking capability, both MUTOIS and a foldable arm using a Sarrus linkage rely on additional mechanical locking components. In contrast, the FC-ori and the Kresling origami truss structure exploit inherent axial self-locking mechanisms derived

from their geometric configurations. However, the Kresling origami truss cannot achieve rigid foldability, since its folding relies on the elongation of springs within the truss. The Miura-derived origami tube, on the other hand, does not possess self-locking capability. Thus, FC-ori remains the only structure among these examples that integrates both self-locking capability and rigid foldability.

In summary, the tendon-driven FC-ori structure demonstrates multiple advantages, including high folding compressibility, small footprint, rapid transformation, single-motor actuation, and inherent self-locking capability. However, its current limitations lie in its insufficient stiffness and inability to achieve multi-DOF motion, which are important challenges to be addressed. In future work, I aim to address the current limitations of the FC-ori design and further optimize its performance for practical applications.

Table 4.1 Comparison of cylindrical origami-inspired structures

System	R_V	R_L	R_A	n	k (kN/m)	$\bar{E}$ (kN/m ²)	Locking capability
FC-ori unit without stoppers	4.44	3.67	1.21	1	18.70	212.55	Self-locking
FC-ori unit with stoppers	4.44	3.67	1.21	1	81.97	931.48	Self-locking
MUTOIS [112]	4.09	8	0.51	Manual	1875	11957.91	Using sliding locks, gusset plates
Sarrus linkage robotic arm [9]	2.92	17.5	0.17	1	180	11250	Using locking mechanism
Kirigami cuboid [32]	2.95-4.64	4.2-33	0.14-0.70	Manual	Unknown	Unknown	Not available
Kresling origami truss [4]	2.91	2.91	About 1	Manual	480	2841.81	Self-locking while lacking rigid-foldability
Miura-derived origami [12]	2.38	2.38	About 1	8	0.19	2.40	Not available

4.5 Discussion

This chapter presented a tendon-driven robotic arm based on a thick FC-ori structure with intrinsic self-locking capability. The origin of the self-locking behavior is examined through geometric constraints and folding singularities. To overcome the folding difficulty caused by this self-locking, a tendon-driven actuation strategy is introduced in which the tendon passes through both the square panels and the side panels. Thick FC-ori units fabricated via 3D printing, combined with a tendon-spring mechanism, enable smooth and rapid folding and deployment. This approach effectively resolves the challenge of remotely actuating thick, self-locking origami structures. Mechanical performance was evaluated through tensile tests measuring the driving force required to lift different loads and the stiffness of a three-unit system. To address stiffness degradation caused by panel

misalignment near incisions under axial compression, a stopper design was implemented, improving unit stiffness by a factor of five. FC-ori units were then assembled into serial and parallel robotic arms, each driven by a single motor, and functional prototypes were experimentally validated. In the parallel configuration, unit motions can be selectively programmed via different pre-wound tendon lengths.

Overall, FC-ori offers high folding ratios, rapid deployment, simplified control, rigid-foldability, and inherent self-locking capability without auxiliary mechanisms. These results demonstrate the suitability of thick-panel FC-ori for compact, rapidly deployable, and load-carrying robotic systems. The modular structure also supports scalable manufacturing and on-site assembly, providing a cost-effective framework for reconfigurable robotic platforms.

4.6 Supplementary Materials

4.6.1 Calculation method for rotating coordinates around an arbitrary vector in three-dimensional space.

Assume an arbitrary point in 3D space P is rotated by an angle θ around an arbitrary axis. The new point P' can be computed using Rodrigues' rotation formula. The calculation step is as follows:

First, translate the point P so that the rotation axis passes through the origin,

$$Q = P - O,$$

where O is an arbitrary point on the rotation axis. Next, normalizing the direction vector of the rotation axis, we obtain the unit vector u , as

$$u = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}.$$

Using Rodrigues' rotation formula, where the rotation matrix is

$$R = \begin{bmatrix} \cos\varphi + u_x^2(1 - \cos\varphi) & u_x u_y(1 - \cos\varphi) - u_z \sin\varphi & u_x u_z(1 - \cos\varphi) + u_y \sin\varphi \\ u_x u_y(1 - \cos\varphi) + u_z \sin\varphi & \cos\varphi + u_y^2(1 - \cos\varphi) & u_y u_z(1 - \cos\varphi) - u_x \sin\varphi \\ u_x u_z(1 - \cos\varphi) + u_y \sin\varphi & u_y u_z(1 - \cos\varphi) + u_x \sin\varphi & \cos\varphi + u_z^2(1 - \cos\varphi) \end{bmatrix}.$$

Then, multiply the rotation matrix with the translated point Q , as

$$Q' = R \cdot Q.$$

Finally, translate it back to the original coordinate system, and the coordinates of the target point P' can be obtained as

$$P' = Q' + O.$$

4.6.2 Materials and methods

Prototype fabrication

In this Chapter, the FC-ori units were fabricated using an SLA 3D printer (Form 3+, Formlabs, MA) with Grey Resin V4 (Young's modulus is 2.8 GPa) as the printing material. The structural panels were connected using metal shafts with a diameter of 2 mm and a length of 20 mm. The torsion springs

installed at the hinges had an initial angle of 135° , an inner diameter of 5 mm, a wire diameter of 0.5 mm, five active coils, and a spring stiffness of 0.112 N·mm/deg. The tendon used for actuation was made of fluorocarbon fishing line with a diameter of approximately 0.285 mm and a rated strength of 14 lb (≈ 62.3 N).

For actuation, a 12-V DC gear motor with a 1:30 reduction ratio, rated torque of 1 kg·cm, rated current of 0.36 A, and power output of 4 W was employed. The system was powered by a 12 V, 1800 mAh lithium battery and controlled via an STM32F407VE microcontroller (STMicroelectronics NV, Switzerland), receiving commands from a radio-control transmitter and receiver commonly used in model aircraft systems.

Mechanical testing

The experiments were conducted using a universal tensile testing machine, MCT-1150 (A&D Company, Ltd., Japan). In the tendon tension test, the displacement ratio was set to 300 mm/min. In the compression test for evaluating the load-carrying capability of the FC-ori units, the speed was set to 20 mm/min.

Schematic diagrams of 3D print model

Figure S4.1 illustrates the four side panels of a clockwise-rotating FC-ori unit. Each panel corresponds to a thick right triangle with a hypotenuse length of 80 mm, a maximum thickness of 4 mm, and a reduced thickness of 2 mm at the central groove. The panels are equipped with male and female hinges, which are connected by metal shafts. Along the hypotenuse, two installation positions for torque springs are provided. Near the vertex, a hole is placed for tendon routing. To obtain a counterclockwise-rotating FC-ori unit, all the components in Fig. S1 should be mirrored.

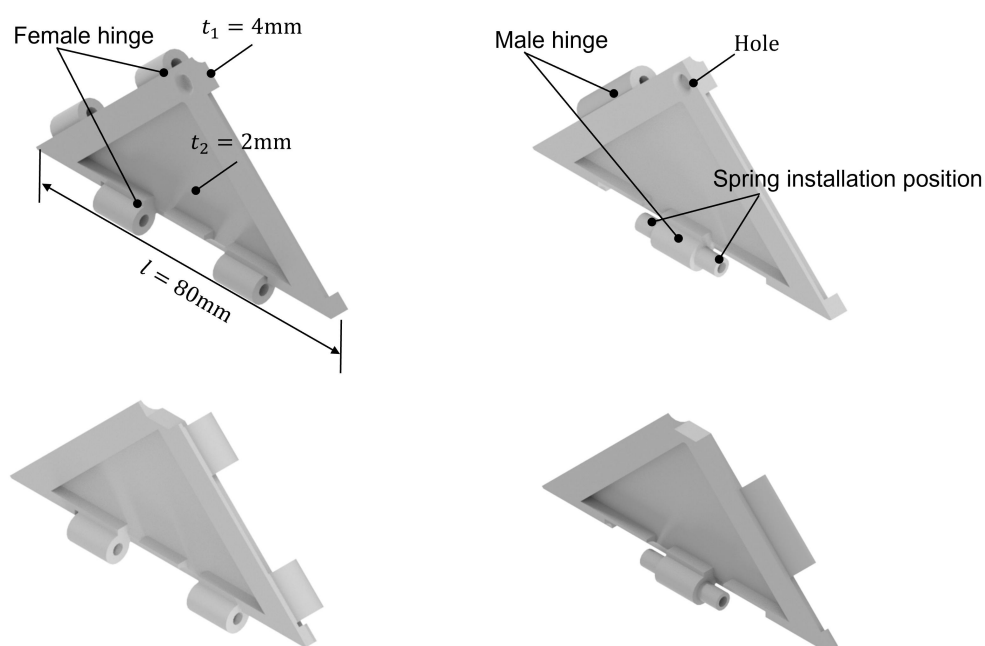


Figure S4.1 Schematic diagrams of four different side panels

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Although origami originated as an ancient art form in East Asia, its unique folding characteristics have increasingly attracted attention from researchers and enabled a wide range of engineering applications. An ideal deployable structure should possess properties such as rigid-foldability, flat-foldability, a small footprint, rapid deployment, and the ability to maintain stiffness in specific configurations. In this thesis, the proposed origami structures satisfy all of these requirements, providing a robust foundation for expanding the use of origami-based mechanisms in practical engineering scenarios.

Chapter 2 proposed origami-inspired structures called foldable prism origami (FP-ori). Although Kresling origami can form multi-prismatic configurations, facet deformation during folding is unavoidable. FP-ori is developed on the basis of Kresling origami by introducing additional diagonal incisions on the side facets, which endow the structure with rigid-foldability. It was also found that the geometric parameters of FP-ori determine whether the structure is flat-foldable or self-locking, and the geometric condition for flat-foldability was analytically derived. For FP-ori in the self-locking configuration, depending on the geometric parameters, it exhibits either monostability or bistability. This conclusion was verified through finite element method simulations, energy modeling, and experiments, meanwhile the relationships between geometric parameters and tunable mechanical behaviors were summarized. In addition, FP-ori with a cubic configuration can be assembled into metamaterials exhibiting a three-dimensional negative Poisson's ratio.

Based on the origami structures proposed in Chapter 2, the cubic configuration was identified as particularly notable because it simultaneously possesses rigid-foldability and flat-foldability, making it highly suitable as a deployable structural element. This origami structure is referred to as the Foldable Cube Origami (FC-ori). However, the kinematic analysis of FC-ori is derived from a zero-thickness model in Chapter 2, but when the panels have finite thickness, the thick FC-ori loses its flat-foldability due to interference among adjacent panels. To address this issue, Chapter 3 introduces the sliding crease method, in which an additional axial translational degree of freedom is incorporated into selected creases, enabling the thick FC-ori to fold smoothly into a seamless square configuration. Using Denavit-Hartenberg (DH) transformation matrices, the kinematic relationships of the thick FC-ori are established, and the correlation between the sliding distance and panel thickness is derived. By configuring different numbers of springs and magnets, the 3D-printed FC-ori units are endowed with programmable multistability, which is further

verified through energy modeling and tensile testing. Assembling multiple multistable FC-ori units, a prototype of an origami mobile robot was developed, capable of achieving multiple transformation modes that allow the robot to adjust camera height and traverse diverse terrains. Moreover, the proposed structure also shows significant potential for applications such as deployable robotic manipulators and temporary shelters.

However, A significant limitation remained in Chapter 3, as the transformations of the origami mobile robot depended on manual operation, greatly restricting its deformation speed and range of applications. The difficulty in achieving automatic folding mainly arises from the self-locking behavior of FC-ori in its deployed configuration, where applying forces or torques on the top panel cannot initiate folding. In Chapter 4, two causes of this self-locking behavior are identified, including geometric constraints and force transmission ratios. It is found that forces or torques applied to the top panel are difficult to transmit to the side hinges, whereas them applied from the sides are easily propagated. Therefore, a novel tendon-driven strategy was adopted, in which a tendon is routed sequentially through the side panels to ensure effective force transmission. For the tendon-driven FC-ori, I examined optimal tendon-routing positions, friction-reduction strategies, and methods for enhancing the load-carrying capacity in its deployed configuration. Using the optimized FC-ori units, robotic manipulators were constructed through both serial and parallel configurations. These manipulators require only a single actuator to achieve rapid folding and deployment within 3 seconds, and by adjusting the initial number of tendon windings, the motions of the two branches of the parallel manipulator can be programmably controlled.

5.2 Future work

The work referring to the following aspects should be explored in the future:

- In this thesis, the kinematic analysis of FP-ori is based on a single-degree-of-freedom assumption, in which a constraint is imposed so that the top and bottom faces rotate about the same axis. Future work will investigate the kinematics of FP-ori under multiple degrees of freedom. Such research will facilitate the application of FP-ori in multi-DOF platforms and continuum robotic arms.
- In the future, I will explore additional engineering applications of the FC-ori structure, such as constructing large-scale foldable temporary shelters using metallic components, developing FC-ori based truss structures, and creating origami micro-robots. These studies will enhance the application potential of the FC-ori.
- At the current stage, the deployment of the tendon-driven origami robotic arm relies on the elastic force stored in springs. As the number of units increases, the friction acting on the tendon during deployment also grows, while the spring force remains limited. Consequently, when the number of units exceeds a certain threshold, the total friction experienced by the tendon becomes greater than the force provided by the springs, preventing the units from

fully unfolding. In future work, I will explore more suitable actuation methods to address the deployment challenges of FC-ori.

- In this thesis, the FC-ori structures were assembled using conventional hinge connections. In future work, I intend to integrate functional material creases, such as shape-memory alloy, with rigid panels to develop FC-ori structures capable of more complex functionalities.

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List of publications

Chapter 2 is created by modifying the following article.

Liu, F., Terakawa, T., Long, S., Komori, M. Rigid-foldable cylindrical origami with tunable mechanical behaviors. *Sci Rep* **14**, 145 (2024). <https://doi.org/10.1038/s41598-023-50353-4>

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Chapter 3 is created by modifying the following article.

Liu, F., Terakawa, T., Lin, J., Komori, M. Design of modular deployable structure with programmable multistability. *Int. J. Mech. Sci.* **288**, 110037 (2025). <https://doi.org/10.1016/j.ijmecsci.2025.1100373>

Chapter 4 is created by modifying the following article.

Liu, F., Terakawa, T., Liang, Z., Komori, M. A self-locking, tendon-driven robotic arm inspired by cubic origami. *Mech. Mach. Theory* **217**, 106230 (2025).
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