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# An origami-based design approach to self-reconfigurable structures using 4D printing technology

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## Abstract

Owing to the ability to achieve structural changes after manufacturing, reconfigurable structures have great application potential in the products of the future, and should be naturally addressed in engineering design. However, most of the reconfigurable structures require the introduction of new optional components, or the removal of existing components from the system itself, even replacement of components in order to switch from one structural configuration to another, which brings a lot of difficulties and complexities in design, manufacturing and usage phases, that can be partially solved by deploying modularity through the product lifecycle. Another inherent aspect of such structures concerns the self-transformation functionality and the related sequence planning issue that require a specific and different attention in preliminary design. To solve these problems, this paper proposes a new method based on smart materials and 4D printing technology to design and fabricate more compact structures that can realize self-reconfiguration via environmental stimulus without the need to alter sub-structures or components. A tentative design case is presented for the method demonstration. The experimental result shows that the proposed method is capable to achieve more complex reconfigurable structures.

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*Keywords:* 4D printing; origami-based design; reconfigurable structure; self-folding

## 1. Introduction

With the rapid development of manufacturing technologies, people can now develop more complex and customized products to satisfy their requirements. However, for many products, once manufactured, they can only passively accept the influence of environmental changes but can hardly respond to the environment as the change of shape, function or properties. In these twenty years, intelligent structures, equipped with diverse characteristics e.g. self-perception and adaptability, are now widely used in structural vibration control, quality inspection, deformation control, etc. [9] to meet specific application requirements. Among them, reconfigurable structures attract more and more attention due to their specific properties of switching their own shape structure after processing into a product. It can achieve the mutual transformation of two or more configurations, which means that the structure has two or more functional/lifecycle states. Reconfigurable structures usu-

ally need to consider the components' positions and geometric relationships about the states before and after transformation. This makes the design of these structures more complicated and time-consuming. Therefore, new design and realization approaches are always needed.

Nowaday, literature presents interesting design methods for reconfigurable structures such as modular robots [17], reconfiguration of large deployable aerospace structures [11] [13] distributed reflectors with piezoelectric actuators [1] just to name a few. This offers the great inspiration for reconfigurable structure design. However, there are still many remaining issues that require to be tackled, such as:

- **Connectedness:** most of the methods are changing the shape of the whole structure by connecting and disconnecting the parts, which makes the transformation of the whole structure extremely complicated.
- **Geometric:** since the reconfiguration structure needs to consider the situation before and after the transformation, most of them have very complicated geometric shapes, which increase difficulties to the design, manufacture and usage stages.

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- Actuation: most of the reconfiguration structures need external force to operate the transformation, which generally leads to additional actuation components.

The first aforementioned issue could be probably solved by utilizing origami technique, enabling the establishment of complex three-dimensional structures through specific two-dimensional crease patterns. Origami is a folding method originated from ancient Japanese art, which makes the structural transformation possible [10]. Researchers used folding method to simplify the reconfiguration process by turning 3D shape into 2D patterns [15]. These unique properties of origami lead to a wide range of potential applications, including micro-robotics[3], stretchable electronics, and metamaterials [2] to name a few. As for the other two research issues, 4D printing technology seems to be the most convenient and promising solution.

4D printing is a new paradigm where time is regarded as the fourth dimension [5]. It can be considered as the combination of 3D printing and smart materials. Additive manufacturing gives the possibility of complex geometry implementation, while smart materials (SM) own the ability to change their properties in response to a specific stimulus in environment. In this emerging materials category, shape memory materials – exhibiting the shape memory effect (SME) – are able to recover their original shape following environmental changes such as changes in humidity, pH, irradiation and temperature. This means they can automatically convert the shape to a pre-programmed state with specific stimulus [7]. So with the association of smart materials and additive manufacturing techniques, physical parts can change their shape or properties over time as a response to the applied external stimulus.

In this paper, an origami-based design approach to self-reconfigurable structures considering stimulus-responsive materials is proposed. The rest of the paper is organized as follows. Section 2 introduces the objective and gives the overall approach description. Next, Section 3 presents an illustrative case to explain the key steps of the approach. Then, Section 4 gave a case study to validate the application potential. Finally, conclusions and future work are drawn in Section 5.

## 2. Origami-based design approach

Our proposed design approach aims at converting complex 3D problems into 2D planar problems. This technique enables the combination of two functional states then converts the origami features into mechanical elements. Simultaneously, the structural model can be constructed using advanced computer-aided design systems. In addition, analyzing the transformation sequence and the required behavior, it is then possible to assign 3D printable conventional and smart materials. With the appropriate stimulus, these stimulus-responsive materials can be folded and the whole structure can be reconfigured automatically in three dimensions that extend proactive design. As shown in Fig.1 four main stages have been introduced: origami

design, mechanical hinge allocation, geometry model design and behavior simulation.

Fig. 1 also presents a detailed flowchart of this origami-based design approach with input/output information and procedures. Built on this, we can realize the automatic transformation of two different 3-dimensional functional states with the same contour expansion, which provides guidance for the reconfigurable structure design. Since there are a large number of unfolding algorithms that can convert 3D origami into the unfolded plats [6, 8], here we only focus on the design after obtaining the 2D pattern information, the unfolding algorithm is then not discussed in depth. In such a context, to make our approach more comprehensive, we use two most basic 3D origami patterns with the same expanded contour as the input of the proposed design approach. The two basic origami patterns, Waterbomb Base and Preliminary Base are shown in Fig. 2(a)(b), as an illustrative case to demonstrate this reconfigurable self-folding design method, the expanded view of both of them can be seen as a square. In the following subsections, steps of Fig.1 are progressively described.

## 3. Approach development

### 3.1. Origami design

Due to the input setup, we can assume that the expanded views of the given 3D origami structures are known and have the same contour. First, we expand the two origami structures separately to get the corresponding expanded view. In our case study, the expanded view of Water-bomb base and Preliminary base are all squares, which means their outlines are identical. Here we just need to adjust them into the same size to provide the necessary conditions for the combination. For two expanded views with the same shape, it is very easy to combine them, just put all the crease information in the same expanded view, in other words, find the union of the crease patterns is enough. We can see in Fig. 2 that (e) is a common expanded view of crease information with two origami structures (a) (b).

### 3.2. Mechanical hinge allocation

In order to be able to model and simulate later in advanced CAD system, we need to convert new base containing origami information into the mechanical language. To do so, it is firstly needed to identify the composition of the origami. As such, Turner et al. [16] give the main origami elements namely creases, vertices, faces, the margin of the sheet, and so on. Each part of the new base in our case study is shown in Fig. 3(a). After identifying the composition of the new base, we need to analyze the folding relationship and the constraints between the links. In the domain of origami, many creases function as linkages typically allow only a limited angle of rotation between them. Here two faces connected by an ideal linkage relatively rotate to each other about a fixed axis of rotation: all other translations or rotations being prevented, and thus a joint has one

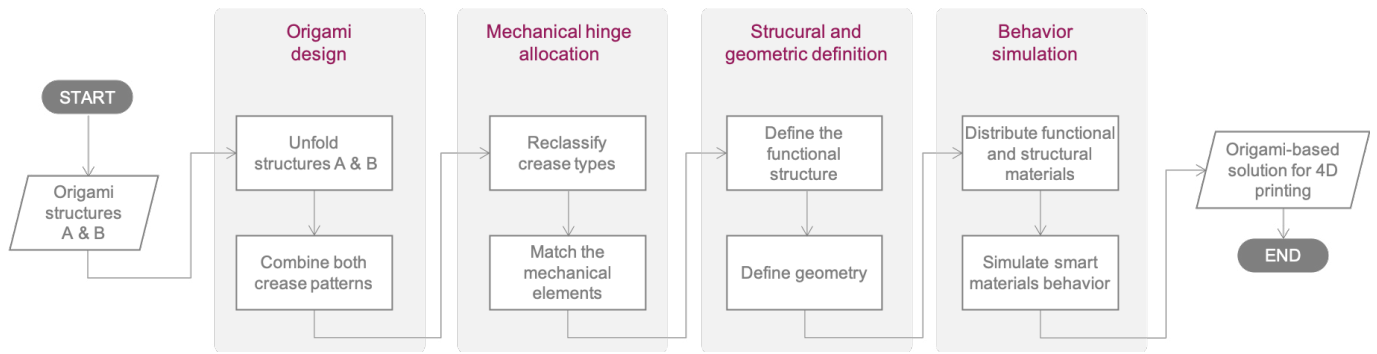


Fig. 1. Flowchart of the proposed origami-based design approach to self-reconfigurable structures

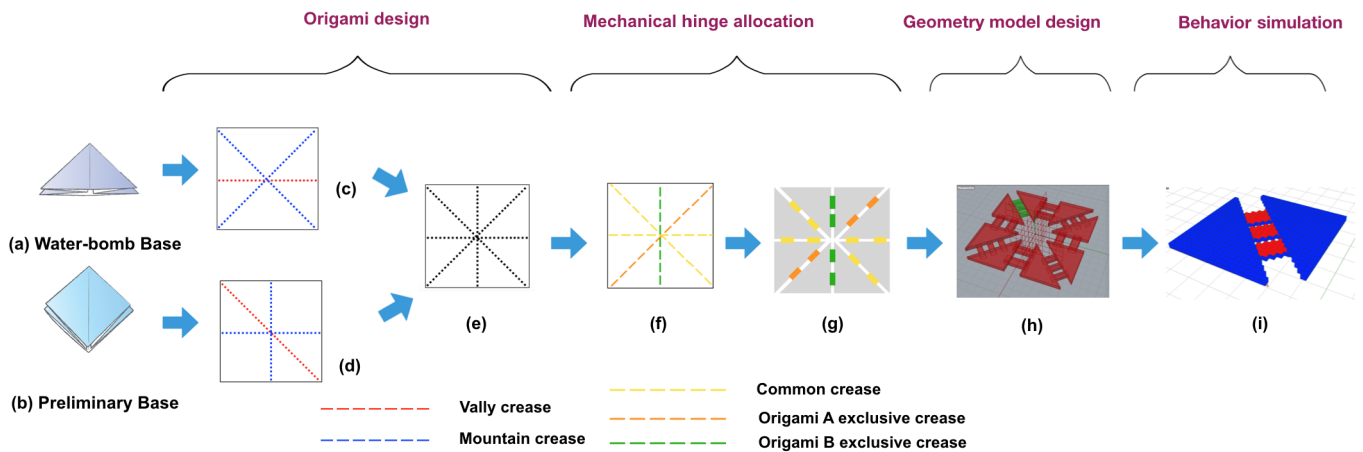


Fig. 2. Origami-based design approach through an illustrative case

degree of freedom. Linkages may be made of flexible material or moving components.

To match the origami composition with the mechanical elements, we can derive from the nature the main elements of the two sides, the face can correspond to the panel, the edge paper can correspond to the edge, and the crease can correspond to the link. Studies in literature show that links can be divided into hinge types and bend types, which provide more design freedom [16]. Our new base in the case study is then transformed into mechanical elements as shown in Fig. 3. It can be considered as consisting of 8 isosceles triangle patches and 8 linkages (the number of hinges can be changed, here is an example with one hinge for each crease). They are indicated by the yellow dotted line, the orange dotted line and the green dotted line, respectively.

In order to achieve the self-folding of the entire structure and the specific manufacturing process, we consider the definition of the functional structure and also 4d printing technology to achieve self-reconfiguration of the studied origami-inspired structure. Here, we propose classification methods that are more suitable for reconfiguration structures. It is based on the final shape classification of the generated structure, so these structures can be directly classified into state A exclusive linkages,

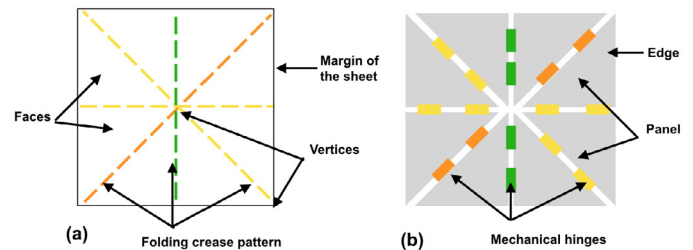


Fig. 3. (a) Origami elements and (b) mechanical elements

state B exclusive linkages, state AB common linkages, normal hinges (produced by auxiliary creases) and panel faces.

### 3.3. Structural and geometric definition

For the different parts, there are different folding mechanisms can be selected, including shape memory polymers (SMPs), bilayer structures, and active hinge-based structures [4]. To achieve the self-folding of the entire structure, the material distribution of the different parts of the structure should be considered, especially the shape memory polymer used in our study, to achieve the transformation of the active origami

structure. According to the above classification and analysis, the structure essentially consists of an active part and an inert part, wherein the inert part comprises a square panel and an inert hinge. For the inert part, lightweight, printable material is needed to implement this structure. In order to achieve self-folding reconstruction of the structure, we need to use smart materials, especially shape memory materials, to achieve the transformation of the active part. Following the above sections, we can clearly assign the smart material to the active part and the ordinary material to the inert part. Specifically, through giving the exclusive linkage different smart materials, we can manage the folding of the link by controlling the stimulus corresponding to the material. Or giving different parts the same smart material type with different conversion conditions, then we can control the folding of the linkage by controlling the strength of the stimulus as shown in Fig. 2(h).

### 3.4. Behavior simulation

In order to accurately simulate the mutual conversion of the active hinge in the unfolded and folded state, we use the CAD software called Rhinoceros and its plug-in Grasshopper to parametrically model and define the structure. To simulate the corresponding material response of the hinges, we use a Grasshopper add-on developed by Sossou et al. [14]. Called VoxSmart, this add-on enables the voxel-based representation of the materials distribution and their physics-based simulation in the preliminary design phase.

Through this add-on, we can simulate the structural changes of smart materials responded to the corresponding stimulus. If the results of the simulation do not fully achieve the reconfiguration as the target, we need to go back to the previous steps to make adjustments and improvements. If the simulation results are ideal, we can determine the entire design and obtain an integrated expanded view by using additive manufacturing. Now this reconfigurable structure can be self-achieved by allocating the corresponding stimuli. Fig. 2(i) shows this step.

## 4. Case study

The cuboid as one of the most common three-dimensional structures in daily life, how to make the structure changes with the external environment during use is a problem that researchers need to pay attention to. Therefore we decide to use the reconfiguration of the cuboid as a case study to validate our approach. Here is considered the reconstruction between two different volumes (contours) of the cuboid and the automatic deformation under appropriate stimulation. Fig. 5 shows a case of common development, which can fold into two boxes of sizes 1 1 5 and 1 2 3 with the same surface but offering different volumes.

### 4.1. Origami crease pattern definition

As shown in Figs. 5 (a) and (b), the first state is spliced by five cube unites into a 1 by 1 by 5 cube group (defined as State

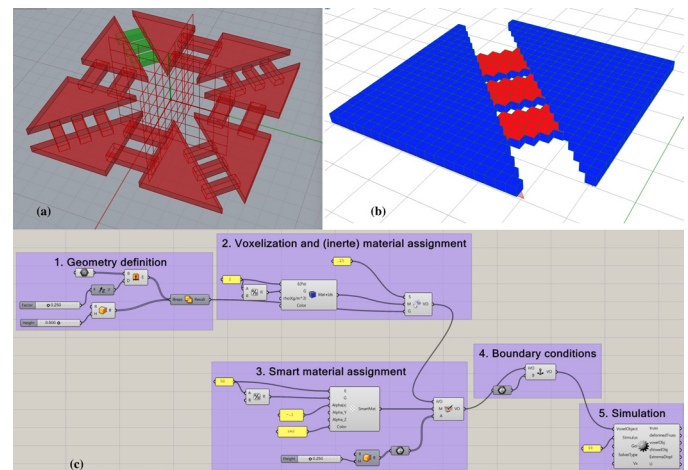


Fig. 4. (a) Geometric representation of the origami-inspired structure in the CAD system Rhinoceros and (b) its voxel-based simulation of smart materials behavior (c) through VoxSmart design flow.

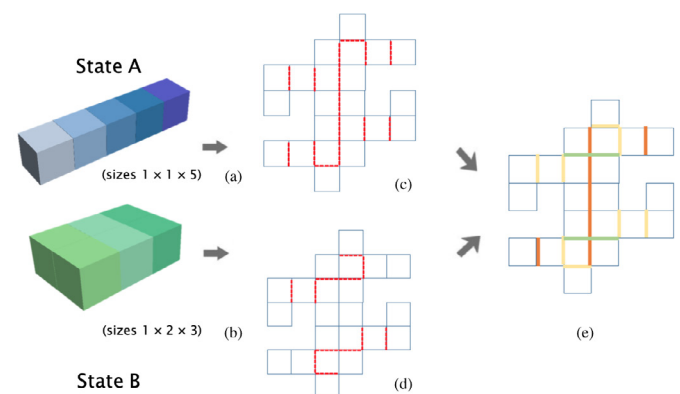


Fig. 5. Two types of cube group (a) State A, (b) State B, and related (c,d,e) unfolded structures

A), while the second state is spliced by six cubes unites into a 1 by 2 by 3 cube group (defined as State B). We take this special case from the space geometry knowledge, in order to achieve the mutual switching of both states, we process both structures according to the strategy proposed in the previous section, based on the [12], we can get the expanded view of State A as shown in Fig. 5(c), with the red dashed line above representing the mountain fold, and Fig. 5(d) corresponding to State B. After combining Figs. 5 (c) and (d), we can analyze Fig. 5(e), where the yellow line represents the common crease, the orange line represents the State A exclusive crease, and the green line represents State B exclusive crease.

### 4.2. Mechanical hinge allocation

According to Fig. 5(e), we first convert the crease into mechanical hinges allocation, the exclusive crease corresponds to the exclusive hinge, the common crease corresponds to the common hinge, and so on. Then we number each panel of the expanded view and analyze the hinge relationships between ev-

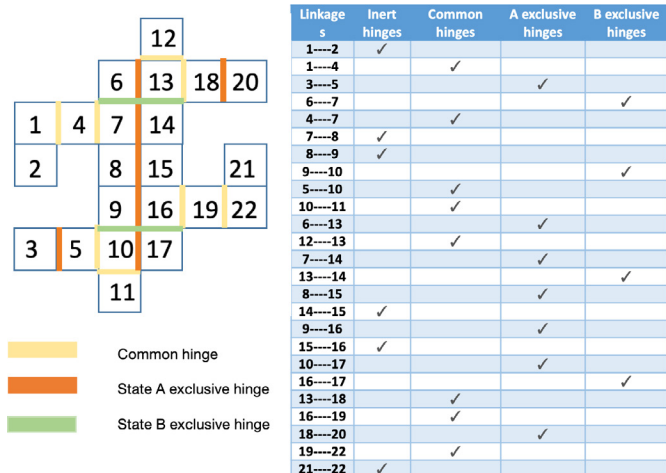


Fig. 6. Classifications of the mechanical hinges

ery two adjacent panels, as illustrated in Fig. 6, the whole structure can be directly classified into state A exclusive hinge, state B exclusive hinges, state AB common hinges, normal hinges (inter pare), and square faces. Then, the structure is re-divided into an active part and an inert part, wherein the active part includes state A exclusive hinge, state B exclusive hinges and inert part includes state AB common hinges, inter hinges, and square faces.

### 4.3. Geometry model design

Since the goal of this case study is to reorganize state A into state B, we can directly fix the shape of the inert part, that is, for the transformation and reconstruction between the two states, only the interaction of the active parts is considered. The essence of such a problem (state A transforms to state B) becomes that the "state A exclusive hinge" changes from the folded state (90) to the expanded state (180), and the "state B exclusive hinge", exactly the opposite, changes from the expanded state (180) to the folded state (90) correspondingly. In order to achieve self-folding of these two active hinges, one proper solution is to use smart materials.

### 4.4. Behavior simulation

For our case study, a preliminary design has been defined through a CAD model in Rhinoceros as shown in Figs. 7(a,b,c). In addition, VoxSmart has been used to simulate the behavior of the active hinge part. Based on the joules effect, we integrate shape memory polymer and resistive wires in order to stimulate with temperature the shape memory effect to activate the folding/unfolding primitive of the active hinges with a stimulus (Figs. 7(d)(e)). PLA materials has been used as the inter materials to the inter parts. Once the behavior checked from a qualitative point of view, the distribution and the geometry are saved in G-code format in order to be printed with our customized

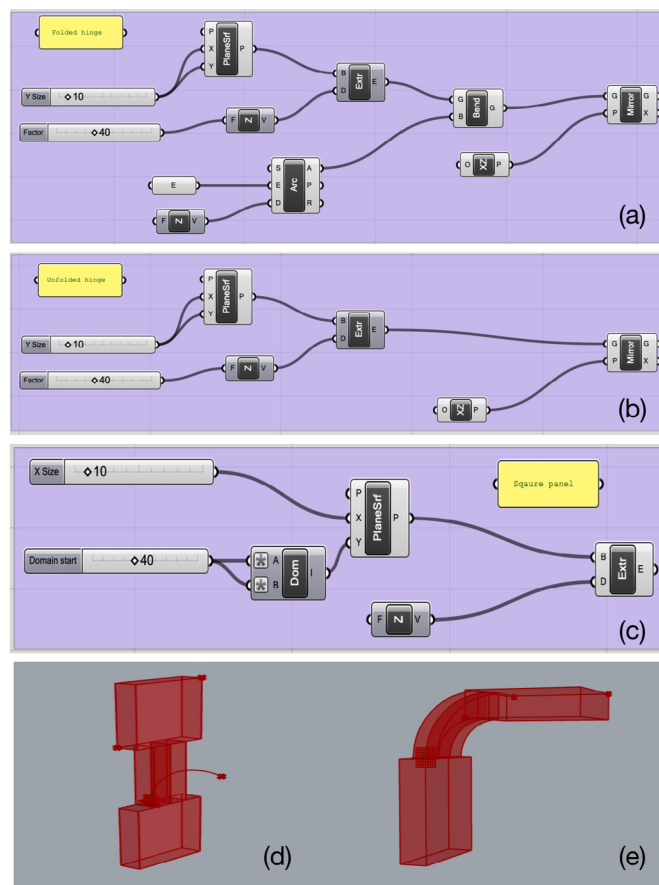


Fig. 7. (a,b,c) Design flow of (d) non-active and (e) active hinges

4D printer which combines Fused Deposition Modeling (FDM) with Direct Ink Writing (DiW) techniques.

### 4.5. Fabrication and result discussion

According to the proposed approach and the way the manufacturing is processing, we obtained similar results as simulated. When the state A is exposed to the stimulus, in this case, is electricity and heat, the original shape will change to the state B. Conversely, we can get a similar transformation from state B to state A. But as seen in Fig. 8, the shortcoming in this procedure like the strength of the whole printed part was still weak to be used as a component in any mechanical system. When the structure returns back to its original shape, some of the mechanical properties of the structure have changed, and the plastic deformation by stimulus has caused some damage to the shape memory effect. More research is needed in this field to make the system more reversible and improve its viability to be used in real-life situations.

## 5. Conclusions and future work

This paper has explored the way of designing reconfigurable structures, by being inspired by the origami art and with an em-

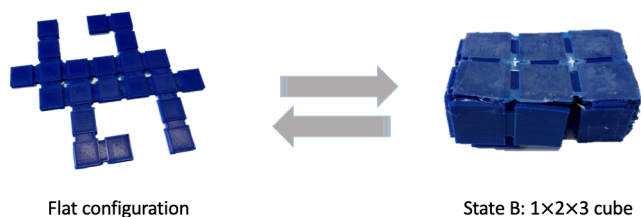


Fig. 8. Reconfigurable structure through its "as printed state" to "final desired state"

phasis on the 4D printing technology. The approach starts from the two functional states of the reconfigurable structure, obtains the synthesized expanded view, and effectively arranges the elements for different functions through reasonable partitioning, then using the smart materials to design the driving part, and realizes the self-reconfiguration. This paper highlights the transformation of the cube groups as the case study to describe the design step of the self-folding reconfigurable structure in detail. The experiment result shows that, by using 4D printing technology, this structure could realize the self-folding reconfiguration, which makes it promising for application to smart deformable structures, multi-stable robots, non-contact devices, and other engineering fields.

For this approach, we only used a single smart material (shape memory polymer) to ensure the feasibility of structural reconstruction. In future work, we will use more functional shape memory materials to realize precisely control, such as materials with two-way shape memory effects. At the same time, we will use more powerful printers, such as printers with multiple nozzles, to integrate different materials at the same time. Secondly, we will also explore advanced algorithms to make different 3D shapes automatically deconstruct the same expanded graphics, generate more efficient methods according to the specific transformation requirements of the structure, and give different solutions to different conditions. In the following work, we will better integrate additive manufacturing constraints in the early phases of origami-based design.

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