Origami-based design for 4D printing of deployable structures

Bingcong Jian

THESE DE DOCTORAT DE L'ETABLISSEMENT UNIVERSITE BOURGOGNE FRANCHE-COMTE
PREPAREE A L'UNIVERSITE DE TECHNOLOGIE DE BELFORT-MONTBELIARD

Ecole doctorale n°37

École Doctorale Sciences Pour l'Ingénieur et Microtechniques - SPIM

Spécialité : Sciences pour l'Ingénieur

par

Bingcong JIAN

Conception basée sur les origamis pour l'impression 4D de structures déployables

Thèse présentée et soutenue à Sevenans, le 18/12/2020

Composition du Jury:

M. ANDRÉ Jean-Claude	Directeur de Recherche CNRS émérite - Université de Lorraine	Président
M. BERNARD Alain	Professeur des Universités – École Centrale de Nantes	Rapporteur
M. ROUCOULES Lionel	Professeur des Universités – Arts et Métiers ParisTech Aix-en-Provence	Rapporteur
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M. COTTINET Pierre-Jean	Maître de Conférences HDR – Institut National des Sciences Appliquées Lyon	Examinateur
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M. ZHANG Yicha	Maître de Conférences – Université de Technologie de Belfort-Montbéliard	Encadrant de thèse

Préparée au Laboratoire Interdisciplinaire Carnot de Bourgogne (UMR 6303 CNRS)

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To remember my grandma.

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Nomenclature

Abbreviation

4DP	**4D P**rinting
AM	**A**dditive **M**anufacturing
CAD	**C**omputer **A**ided **D**esign
CAE	**C**omputer **A**ided **E**ngineering
DF4DP	**D**esign **F**or **4D P**rinting
DFAM	**D**esign **F**or **A**dditive **M**anufacturing
DLP	**D**irect **L**ight **P**rocessing
DOF	**D**egree **O**f **F**reedom
DwSM	**D**esign **w**ith **S**mart **M**aterials
FDM	**F**used **D**eposition **M**odeling
FEM	**F**inite **E**lement **M**ethod
FGM	**F**unctionally **G**raded Material
GH	**G**rass**h**opper
PBF	**P**owder **B**ed **F**usion
PRIAM	**Pr**oactive design for **A**dditive **M**anufacturing
SCM	**S**hape **C**hanging **M**aterials
SLA	**S**tereo **L**ithography **A**pparatus
SLM	**S**elective **L**aser **M**elting
SLS	**S**elective **L**aser **S**intering
SM	**S**mart **M**aterials
SMA	**S**hape **M**emory **A**lloy
SME	**S**hape **M**emory **E**ffect
SMP	**S**hape **M**emory **P**olymer

Chapter 1. Introduction

1. Industrial stakes

Additive manufacturing (AM) technology (also known as 3D printing) has been recognized globally as one of the leading forms of manufacturing process for advanced components, providing great prospects for complex part manufacturing, rapid prototyping and distributed digital manufacturing [1]. Starting from a computer-aided design (CAD) model, materials are added layer by layer to build complex 3D solid components without using other auxiliary resources and special tools for parts, which greatly reduces the geometric complexity and the constraints of topology optimization imposed by the conventional manufacturing. Unlike traditional manufacturing methods, AM has the potential to revolutionize the manufacturing industry with their unique capabilities. It has indeed the ability to build complex shapes and geometries which are not compatible to any other conventional manufacturing technologies.

Nowadays, with the support of high-performance materials and increased efficient AM processes, the freeform building capacity plays a quite relevant role in the production of complex geometries for products of several domains, such as medical industry, tooling industry, automotive and aerospace industry, among others, where conventional manufacturing approaches are not technically feasible due to geometrical complexity [3]. Of course, conventional applications such as special tools, low production parts, biomedical devices and implants, aerospace components, and rapid prototyping will all benefit from the flexibility provided by AM [4]. The unique features of AM give this new technology the potential to completely change the manufacturing industry and the way many parts are made.

In addition, AM can now be seen as an emerging shape forming technology in the last three decades, it has received great attention from academia and industry and has great potential to promote transformative manufacturing and product design in many fields in a wide range of engineering and materials science fields. Their advantages have attracted the imagination of the public and have been called "the fourth industrial revolution" by recent mainstream publications [4]. From the Industry 4.0 mission in Germany to the Made in China 2025, AM is being promoted in the world's major industrial countries as the technological basis for future manufacturing. At present, high levels of manufacturing automation, incorporating AM equipment as well as smart factories are emerging, the standardization for materials, material testing and manufacturing processes is beginning to establish breakthrough standards to harmonize the use of worldwide AM technologies. Now, we can foresee the bright future of additive manufacturing technology in the new decade [3].

3D printing has been developed toward high accuracy, high speed, diverse and robust material properties, and low cost. Meeting these demanding goals requires interdisciplinary collaborations involving mechanical engineering, material science and processes, data processing, and even art designing [5]. While facing challenges and opportunities in many aspects, the lack of high-performance printable materials is a common and perhaps the biggest barrier confronting various 3D printing technologies. Several leading 3D printing commercial companies have established their dedicated material Research & Development teams. At the same time, some traditional material suppliers have also begun to launch printable materials adaptable for various printing processes. Right now, the most advanced commercial printable materials are mainly formulated to be tough, flexible, transparent, colorful or recyclable to meet various end applications. There is no doubt that material development will be the main focus in the foreseeable future [6].

The development of AM advanced materials is a continuous process, which provides a new competitive edge to AM technologies [3]. With the in-depth exploration of smart materials, a revolutionary breakthrough -- 4D printing has emerged. At the 2013 TED Talks [9], Skylar Tibbits demonstrated how the printed static objects could change their shape over time. This marked the start of the 4D printing concept, where the fourth dimension is time. Since then, as a combination of the AM and smart materials, 4D printing has become a new and exciting branch of 3D printing, increasingly gaining substantial attention from scientists and engineers of multiple disciplines since the obtained structure can be transformed in a pre-programmed way [10]. Currently, due to the exploration and rise of commercial printers marketed as “multi-material printing”, like ProJet MJP series by 3D systems and PolyJet Connex series by Stratasys [11][12], also give a restricted chance for the development of 4D printing to which additional efforts are dedicated towards the development of more flexible and customized multi-material 3D printers. Figure. 1 shows the development of 3D printing towards 4D printing.

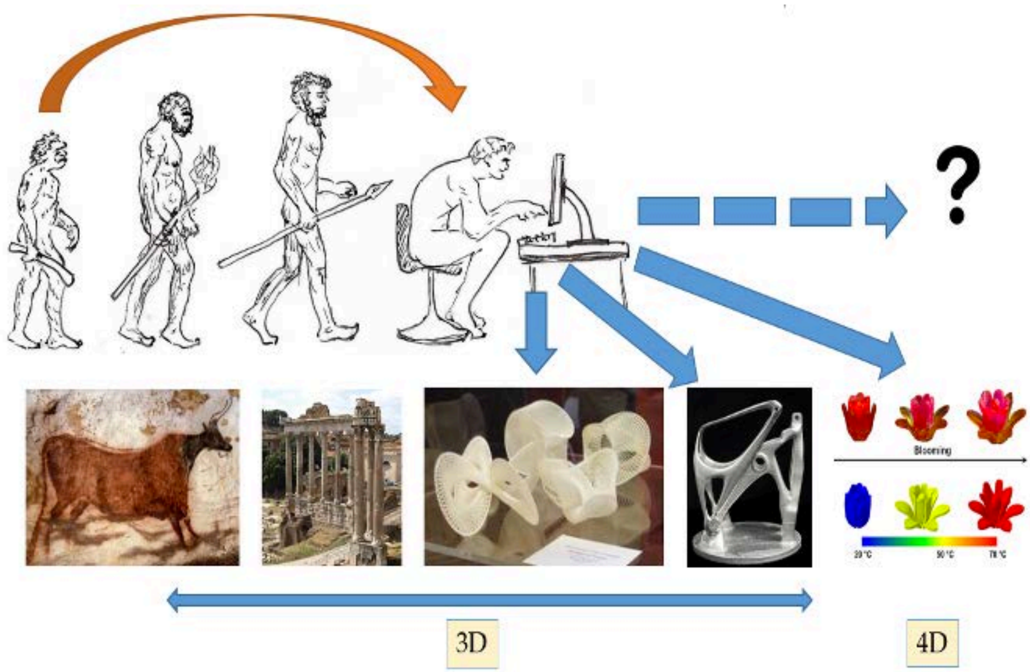


Figure. 1 From additive manufacturing to 3D/4D printing [7]

Due to unique advantages and complex design freedom, many fields have shown a strong interest in 4D printing. The self-assembly characteristics of 4D printing will reduce manufacturing time and labor, which is beneficial to the packaging and transportation industry [13]. Another potential opportunity is that this new technology is expected to be used in deployable solar arrays or antenna arrays in space [14]. In fact, the application of 4D printing has been reported in various fields, such as electronic devices, biomedical devices, organ and tissue engineering, optics and soft actuators [16], smart valves, regenerative design, electromechanical switches and smart clothing [15]. It is believed that this revolutionary technology may influence various other mature applications in the near future [19].

Despite the rapid development of materials AM machines, the research progress of 4D printing is still in its infancy. Since there are many potential applications of 4D printing in renewable energy, the printed soft actuators and soft robotics [16], bioprinting for healthcare [17], material handling and transportation, defense applications and even in fashion domain [18], we cannot ignore that it is a rapidly developing and exciting research field. 4D printing prospects for the next decade will definitively impact business and industrial production models, and even daily life [3]. Therefore, the comprehensive investigation of 4D printing has great significance, especially in the global context of smart manufacturing and Industry 4.0 [20][21].

2. Research background

Deployable structures – which are sometimes known as mobile, extensible, portable, developable, transportable, and expandable structures [23] – have been developed to enable extensive transformation capabilities whether in an autonomous or controlled manner [23]. The most common transformation function is about shifting from a compact and packaged state to a large and deployed state. This significant size change for saving storage volume and transportation during the conversion process is widely used in aerospace, automotive and household appliances applications. From large aerospace systems like satellite solar panels / arrays [24], telescopes [25], airplane deformable wings and space antennas [26] to mobile or temporary architectures (e.g. emergency relief for disaster relief [27] or military operations [28]), deployable structures actually play an important role.

To support the structural load and resist physical interference, the deployable structure needs to have great stability in the deployed configuration. Most conventional deployable structures are highly complex structures that utilize many mechanical components, such as linkages, hinges, motors, and energy storage devices [29].

Although the design of deployable structures traditionally is a structural engineering issue, the relationship between the structures and mechanisms is much closer, the principles of kinematics and geometric analysis need to be considered in the design process [30]. Undoubtedly, this particular structure design process generally will encounter two major difficulties, complicated mechanisms and inconvenient driving. Large-sized mechanisms and complex assembly processes that make the deployable structures heavy, complex and high-cost. These problems associated with limited conventional manufacturing processes have prompted researchers to explore other methods to create advanced deployable structures.

A transformation (possibly reversible) can then be implemented through actuation(s) of 3D printed smart materials [10]. Hence, such 4D printed structures no longer need the external electromechanical system, which significantly reduces the entire system's complexity and greatly decreases the material cost and assembly cycle of the product and even the possibility of failure [24]. These excellent features provide a direction for solving the driving difficulties of deployable structure design.

Origami – an ancient Japanese art of folding – has been inspiring the design and function of engineering structures for decades [31]. Nowadays, with the potential engineering advantages such as compact storage/deployment functions, origami is not only limited to the early oriental art, but it has also developed into an engineering technology and widely appeared in mechanical engineering applications [31]. With the in-depth study of origami theory and the development of related application programs, the origami-inspired structure is being produced as solutions for daily use. The applications of origami have also been applied on various scales ranging from nanometer, micrometer to macroscopic aerospace structures [24][26][32]. The principle of origami and related folding transformation function can enable converting from the two-dimensional planar patterns to the complex three-dimensional geometric shapes [33], which provide the great potential for solving the complicated mechanism problem in deployable structure design. Therefore, it seems that combining origami-based design with 4D printing would be one of the potential solutions to solve the difficulty of deployable structure design and manufacturing. Figure. 2 shows the logical articulation between 4D printing, origami and deployable structures, which is required to meet engineering and industrial applications.

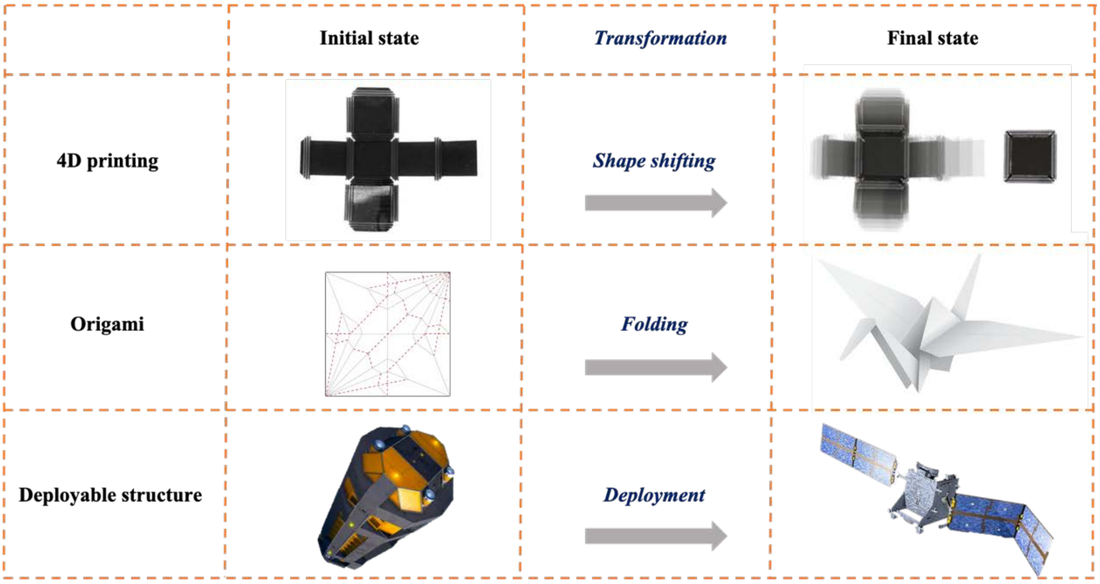


Figure. 2 4D printing and origami can be a potential path for deployable structures design

However, most transformable or deployable systems design strategies are based on intuition or existing mechanisms, which is severely limited and not systematic. Besides, the complex relationship between the geometry of the origami-based deployable structure and the related materials and engineering parameters of 4D printing has not been thoroughly explored. There is no general design process for 4D printing origami-based solutions, making this emerging design method not systematic and complete. To overcome this limitation, decision making supports for materials and process selection, transformation sequence planning and active/inert parts decomposition need to be developed. In this research work, we focus on (i) exploring the internal connections between the different design abstraction levels i.e., from the overall product structure to the specific material allocation and detailed geometric definition, and (ii) addressing decision support to generate the corresponding design strategies within a reference pre-fabrication mode (related to a 4D printing technique) for active deployable structure application.

3. Research problem and objectives

Although there are already plenty of investigations in literature for the design for AM [1] [2], there is little investigation on generic/systematic 4D printing oriented design methods for designers to refer to. In addition, 4D printing is intrinsically an interdisciplinary research field, which gathers chemistry, engineering sciences, chemical-physics, materials science and mechanics of materials domains, respectively. Each domain has its own research challenges. However, a major issue consists of developing a cross-sectoral method for designers to go beyond current 4D printing research efforts on smart material design, actuation mechanism, and numerical simulation. The current 4D printing design research focuses more on specific materials or mechanisms for realizing functionality objective, but rarely paid attention to the design methodology, that is more important for the broad application of 4D printing. In such a context, current proof-of-concepts found in literature could be more developed to reach industrial application requirements and also to be extended to more complex structures.

As for the origami-based design, it provides the guidance for the structural transformation to a certain extent, but the current research is mostly based on known common crease patterns. The mechanism design and synthesis mainly depend on the designer's experience, creativity and intuition. It is not easy for some unfamiliar and complex structures to directly obtain the corresponding creases and design concepts and solutions. In addition, even though many engineering models based on origami have been explored, there is still a gap between the theory and practical applications, and the simulation of active origami still has broad space and prospects.

Regarding the design of deployable structures, there have been many mature transformation models and general methods, but there is no systematic strategy for the design of active deployable structures. As can be seen from the above, 4D printing and origami have a deep connection with deployable structures. However, the specific relationship among the three domains and how to design this structure innovatively remains explored in depth.

In order to answer the questions and solve the problem proposed above, in this work, three research objectives have been defined as follows:

- Propose an origami-based design framework for 4D printing enough suitable to transformable systems.
- Propose a folding planning and control based transformation strategy to drive the detailed geometric design of the product.
- Propose a systematic design method dedicated to active deployable structures based applications.

4. Structure of the Thesis

After this introducing chapter, a literature review will be conducted in Chapter 2 to gain an in depth understanding of the deployable structures, 4D printing through AM processes and techniques, and smart materials. The specific attention will be made to origami-based design and active origami. This chapter will provide an analysis of the current research status and existing difficulties. Then three main contributions will be reported to fill the highlighted gaps identified in the literature review:

- **Chapter 3:** Origami-based design framework for 4D printing, this chapter aims at proposing a decision-making methodology for 4D printing design process.
- **Chapter 4:** Chapter 4 will be focused on the transformation strategy and more particularly on the folding planning and control – as part of 4D printing constraints – to be considered in the detailed design process
- **Chapter 5:** Systematic design method built upon the upper contributions to design active deployable structures which is applied to.

Last, Chapter 6 will provide conclusions and discussions on the significance of the proposed work and will draw short-term and mid-term research perspectives. A synoptic is provided in Figure. 3 to guide the reader through the thesis dissertation by showing the progression and interrelationship between chapters.

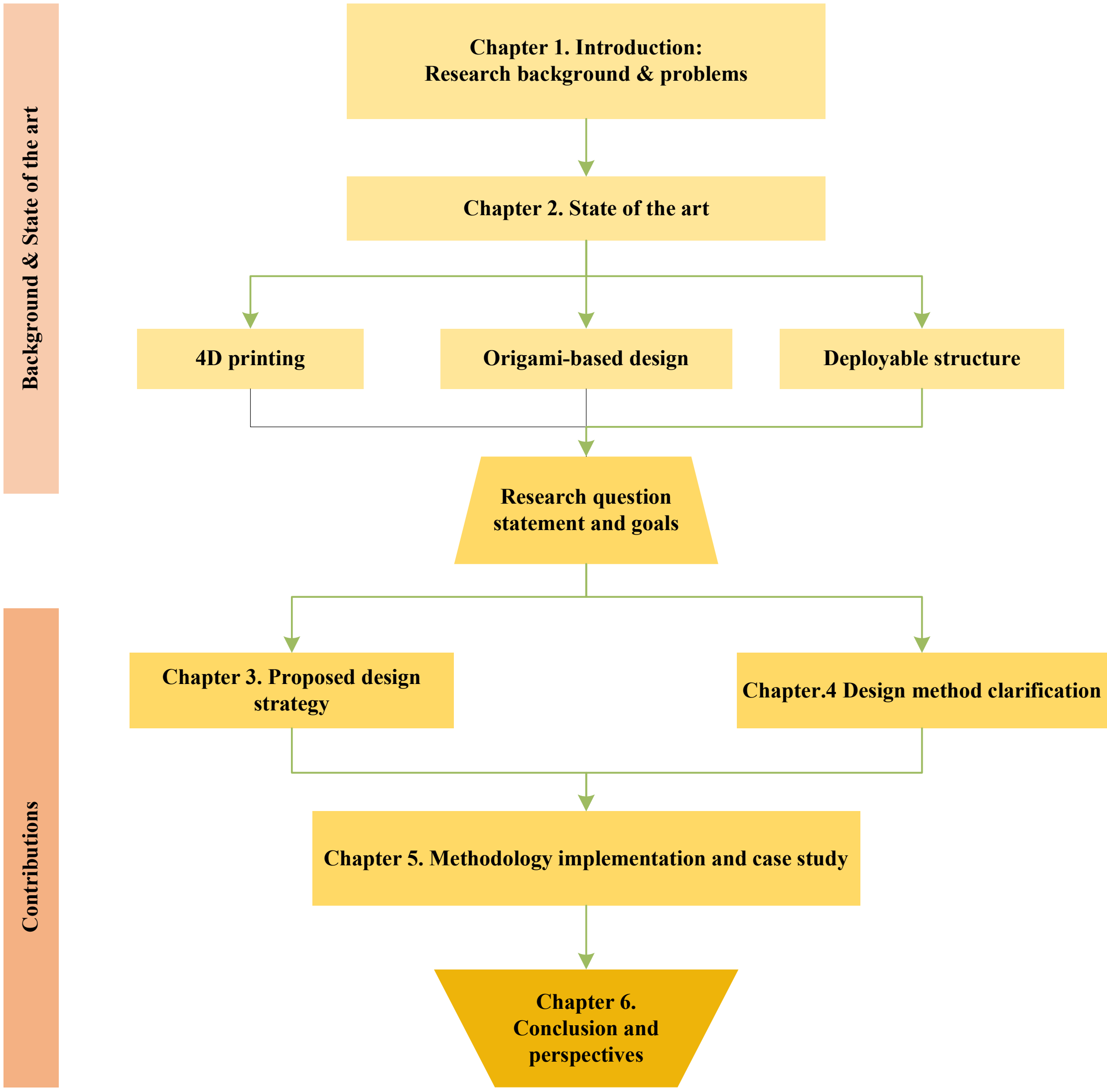


Figure. 3 Thesis synopsis and structure

Chapter 2. State-of-the-art

This chapter is a survey, and an analysis of significant research works on 4D printing, origami-based design and deployable structures. It introduces and summarizes the basic knowledge in each field, as well as the common methods and tools that can be used to design folding structures, especially active origami structures. Finally, the current state of these research efforts is summarized, and the limitations and difficulties of these domains are analyzed.

1. 4D printing

Four-dimensional printing or 4D printing is an emerging technology that has the high ability to produce 3D structures responsive to complex stimuli, offering huge potential for many engineering applications [34]. It is a new paradigm where time is regarded as the fourth dimension, which can be considered as the combination of 3D printing and smart materials (see Figure. 4). AM gives the possibility of complex geometry implementation, while smart materials enable the properties/state/shape/functionality changes in response to a specific stimulus from their environment [35][36].

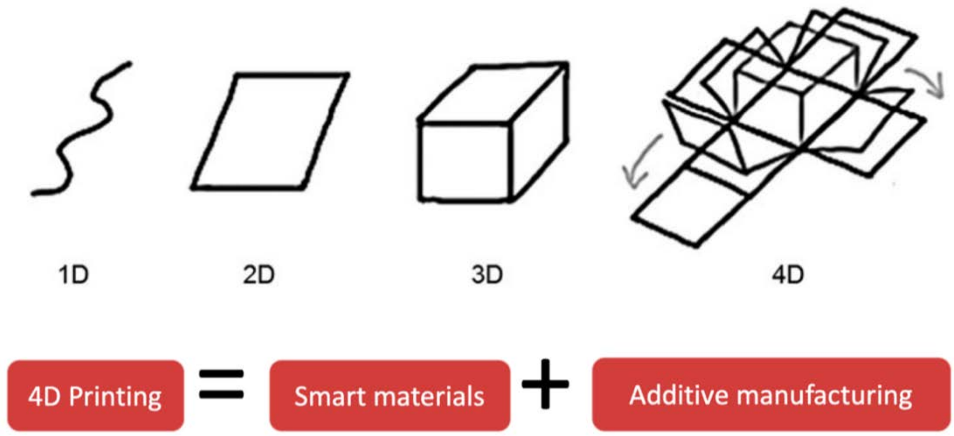


Figure. 4 Concept of 4D printing

Momeni et al. [34] summarized the main pillars of 4D printing as: 3D printing facility, stimulus, smart materials, interaction mechanisms, and mathematical modeling, as shown in Figure. 5. These enablers can realize the targeted and predictable evolution of 4D printed structures over time, which will be studied in the forthcoming sections.

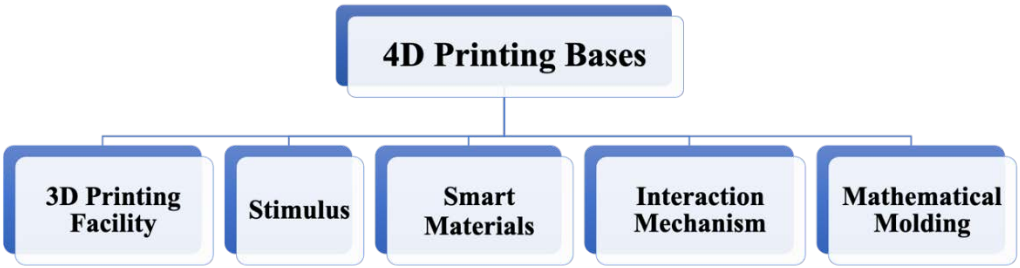


Figure. 5 4D printing bases

1.1.Additive manufacturing technologies

1.1.1. Introduction and generic process

AM – which is also known as three-dimensional (3D) printing or rapid prototyping – has been developed for three decades, allowing researchers to create complex shapes and structures previously inconvenient using traditional fabrication methods [37]. AM process aims at additively building three-dimensional objects from the digital 3D models supported by the computer-aided design (CAD) system via the stacking of simple 2D slices in a classical layer-by-layer manner. Due to its unique layered forming principle, parts with almost no material loss can be produced without any additional tools. As such, AM brings more design freedom than that of traditional subtractive and formative manufacturing processes, giving it a wide range of versatility in terms of design complexity [38].

AM involves many steps from the virtual CAD description to the physical part. Different products will involve AM in different ways and degrees. Small, relatively simple products may only use AM for design review stage and rapid prototyping. While larger, more complex products may involve AM in multiple stages and iterations of the entire development process. Generally, most AM processes involve the following eight steps: CAD model creation, conversion to STL (STereoLithography) file, transfer to AM machine and STL file manipulation, machine setup, part building, part removing, post-processing and application [39]. This process can be illustrated in Figure. 6.

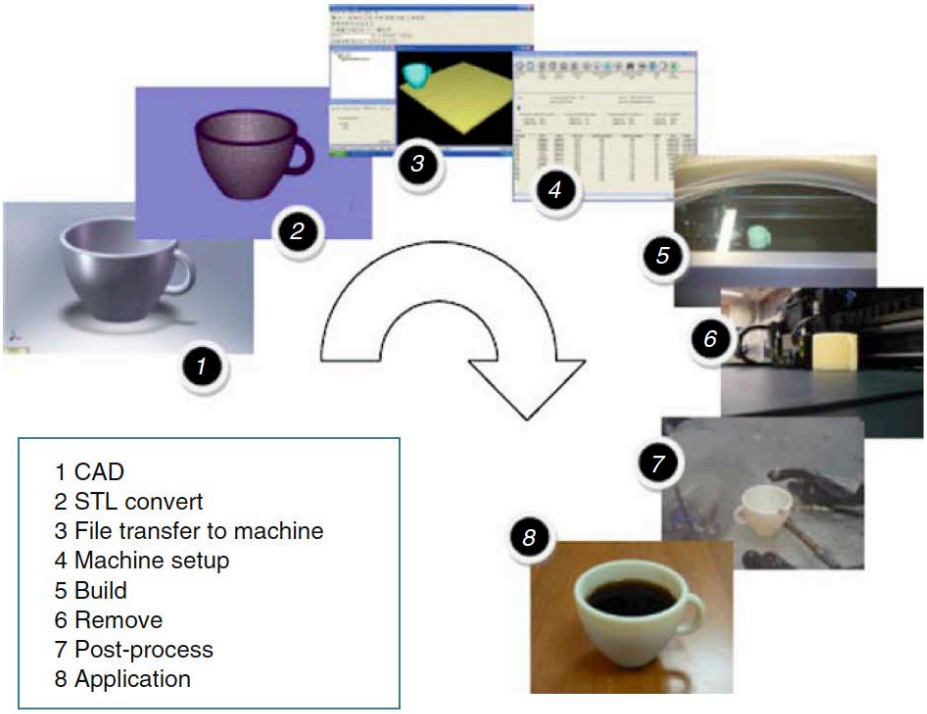


Figure. 6 Generic process of AM process [38]

1.1.2. Classification of AM technology

Nowadays, AM processes have been investigated profoundly and some of them have been introduced commercially by industrial companies. There are several systems to classify the AM processes. The Joint International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) International ISO/TC261—ASTM F42 committee has classified AM processes into seven common distinct categories [40], including material extrusion, vat photopolymerization, powder bed fusion, material jetting, binder jetting, sheet lamination and directed energy deposition. Figure. 7 shows the AM technologies with these seven categories, and the different AM process with their technologies, materials, advantages and disadvantages are summarized in Table. 1 based on this classification method. According to the state of starting material used in 3D technologies, Nannan Guo et al. [41] divided AM processes into the four broad categories: liquid, filament/paste, powder and solid sheet. Table. 2 lists the types of materials the corresponding processes.

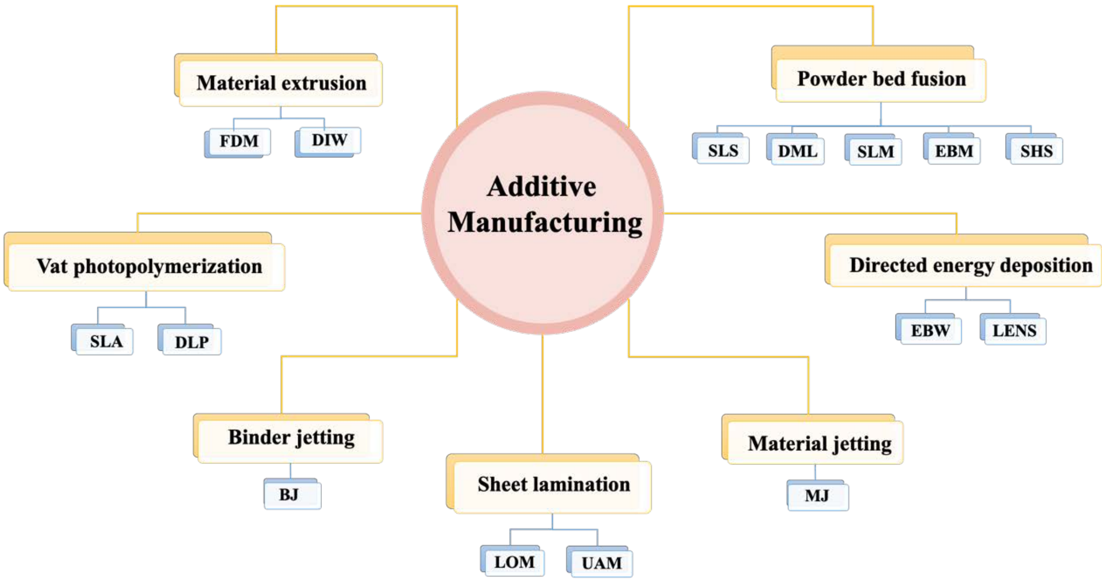


Figure. 7 Classification of AM technologies

1.1.3. The benefit and application of AM

AM technologies have widely applied in various areas due to their characteristics of low-cost, short processing time, high efficiency, customization and personalization. Due to special properties of AM, such as facile and customizable manufacturing, this set of processes and techniques is being broadly used in many areas such as electronics, aerospace, robotics, medical devices, and textile [42]. With the emerging of smart materials, attempts to combine them with AM led to 3D parts that are activated by external stimuli and/or environment over time [43]. Current initiatives in the development of AM tools involve the development of multi-material 3D and 4D printing. Using multi-material 3D and 4D printing, it is feasible to improve the quality of parts by altering composition or type of materials within the layers; that is not easy to obtain by conventional manufacturing methods. A wide range of materials such as polymers, metals, ceramics, and biomaterials has been used in various AM methods to obtain multi-material products [44].

Table. 1 Classification of AM process [40]

Family process	**Technologies**	**Materials**	**Advantages**	**Disadvantages**
Materials extrusion	FDM/ FFF DIW	Thermoplastic, ceramic slurries, metal pastes	Inexpensive extrusion; Multi-material printing	Limited part resolution; Poor surface finish
Photopolymerization	SLA	Photopolymer, ceramics	High building speed; Good part resolution	Over-curing, scanned line shape; High costs for supplies and materials
Powder bed fusion	SLS DMLS SLM EBM	Polyamides/ polymer, Atomized metal powder, Ceramic powder	High accuracy and details; Fully dense parts; High specific strength and stiffness	Powder handing and recycling; Support and anchor structure
Material jetting	Polyjet/ inkjet printing	Photopolymer, wax	Multi-materials printing; High surface finish	Low-strength materials
Binder jetting	Binder 3DP	Polymer powder, Metal powder, Ceramic powder	Full-color objects printing; Wide material selection	Require infiltration during post-processing; High porosities in finished parts
Sheet lamination	LOM	Plastic film, metallic sheet, ceramic tape	High building speed; Cheap material	Waste of material; Weakness of material; Slow and difficult “decubing”
Directed energy deposition	LENS EBW	Molten metal power	Repair of damaged/ worn parts; Functionally graded materials printing	Require post-processing machine

Table. 2 Working principles of AM processes [41]

Material state	Process	Layer creation technique	Phase change	Typical materials
Liquid	SLA	Laser scanning/ light projection	Photopoly-merization	UV curable resin, Ceramic suspension
	MJM	Ink-jet printing	Cooling & photopoly-merization	UV curable acrylic, plastic, wax
	RFP	On-demand droplet deposition	Solidification by freezing	Water
Filament/ Paste	FDM	Continuous extrusion and deposition	Solidification by cooling	Thermoplastics, waxes
	Robocasting	Continuous extrusion	-	Ceramic paste
	FEF	Continuous extrusion	Solidification by freezing	Ceramic paste
Powder	SLS	Laser scanning	Partial melting	Thermoplastics, Waxes, Metal, Ceramic
	SLM	Laser scanning	Full melting	Metal
	EBM	Electron beam scanning	Full melting	Metal
	LMD	On-demand powder injection and melted	Full melting	Metal
	3DP	Drop-on-demand binder printing	-	Polymer, Metal, Ceramic, etc.
Solid sheet	LOM	Feeding and binding of sheets with adhesives	-	Paper, Plastic, Metal

1.2. Smart materials

Smart materials (SMs) – also called intelligent, active, programmable or stimulus-responsive materials – describes a group of material with unique properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, moisture, electric or magnetic fields, light, temperature, pH or solvent. SMs related research has been growing rapidly in the past thirty years, they have made progresses and applications in many areas, including sensors and actuators, medicine or artificial muscles, deployable structures, to name a few [45]. With the rapid development of both AM techniques and SMs, 4D printing is gradually emerging, especially with multifunctional polymer [43][46].

1.2.1. Materials types

Smart materials can be divided into two categories: advanced structured materials and stimulus-responsive materials [47]. Advanced structured materials include specific lattices, metamaterials and auxetic cellular, multi-materials topological optimization. Stimulus-responsive materials include shape changing materials and shape memory materials (SMMs), these materials have the ability to change shape, size or other properties when they are faced with a specific stimulus [34]. The shape-changing material is a kind of one-way or reversible material which can spontaneously change its shape on the application of a stimulus and may regain its original shape the stimulus is removed. However, its deformation type was predetermined by the original material structure [48]. The shape memory materials do not need any predetermined transformation as prepared, but the shape memory materials require a programming step, allowing much more complex and versatile shape transformations [48].

Furthermore, the shape memory materials also can be categorized into two classes: one-way shape memory materials and two-way shape memory materials [49]. In one-way shape memory materials, after the original shape is recovered from the temporary shape, a new programming step is required to recreate the temporary shape in each cycle. In contrast, the two-way shape memory materials do not need the reprogramming process to regain temporary shape. Both of these materials belong to the dual shape memory materials and a dual shape memory effect includes one permanent shape and one temporary shape. As for the triple shape memory materials, the triple shape memory effect has one permanent shape and two temporary shapes. The classification of smart materials and their corresponding schematic illustrations are shown in Figure. 8 and Figure. 9, respectively.

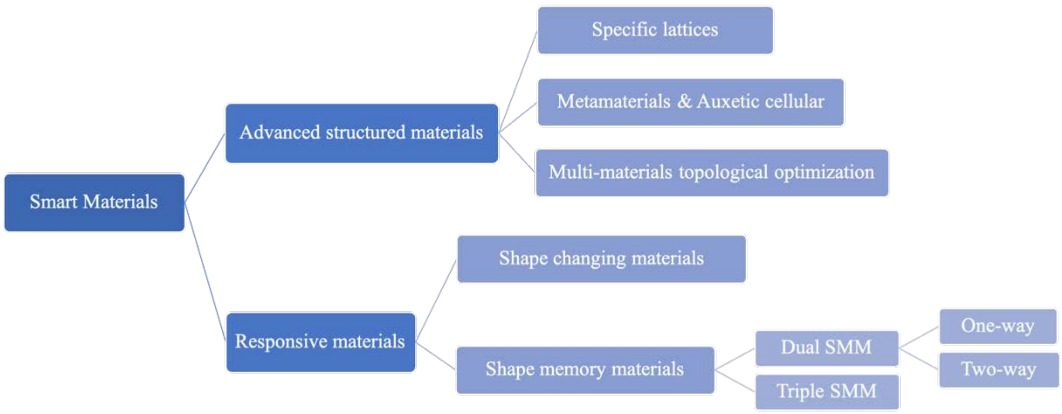


Figure. 8 Classification of smart materials.

1.2.2. Stimulus and mechanism

A stimulus is required to trigger the alterations of shape/ property/functionality of a 4D printed structure. The stimuli that researchers have used in 4D printing thus far mainly include water [43][50], heat [51][52]], a combination of heat and light [53][19], and a combination of water and heat [54][55]. The selection of the stimulus depends on the specific application requirements, which also determines the types of smart materials employed in the 4D printed structure. In some cases, the desired shape of a 4D printed structure is not directly achieved by simply exposing the stimulus's smart materials. The stimulus needs to be applied in a certain sequence under an appropriate amount of time, which is referred to as the interaction mechanism [34].

A 4D-printed structure can alter its shape, properties, or functionality based on one or more stimuli. However, an interaction mechanism needs to be identified for which the printed smart structure can respond to stimulus in an appropriate way. The mechanisms can be divided into various categories, including unconstrained-hydro-mechanics, constrained-thermo-mechanics, unconstrained-thermo-mechanics, unconstrained-hydro-thermo-mechanics, unconstrained-pH-mechanics, unconstrained-thermo-photo-mechanics, osmosis-mechanics, and dissolution-mechanics [34][49]. An illustration of the aforementioned mechanisms is provided in Figure. 10.

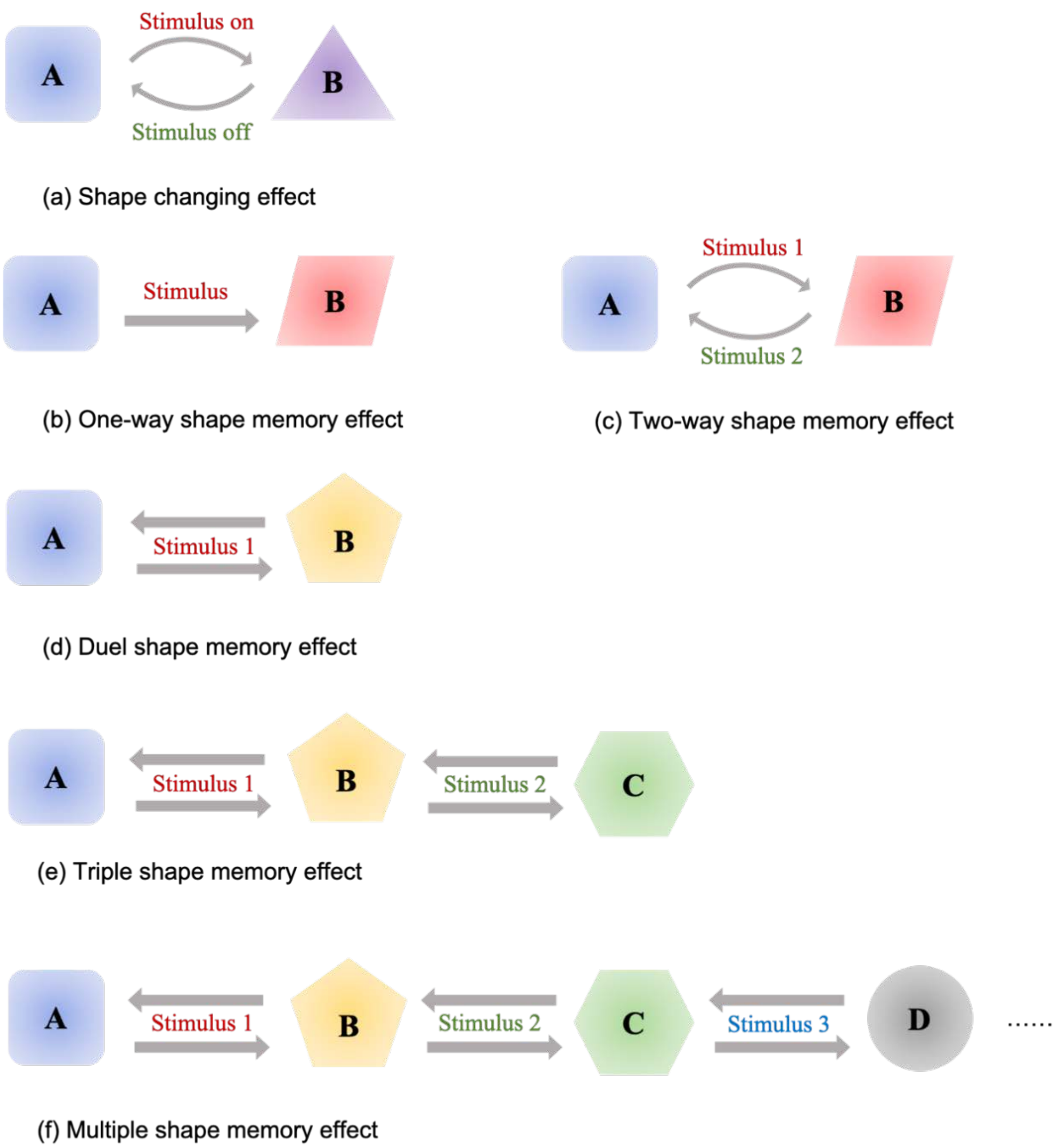


Figure. 9 Actuation effects

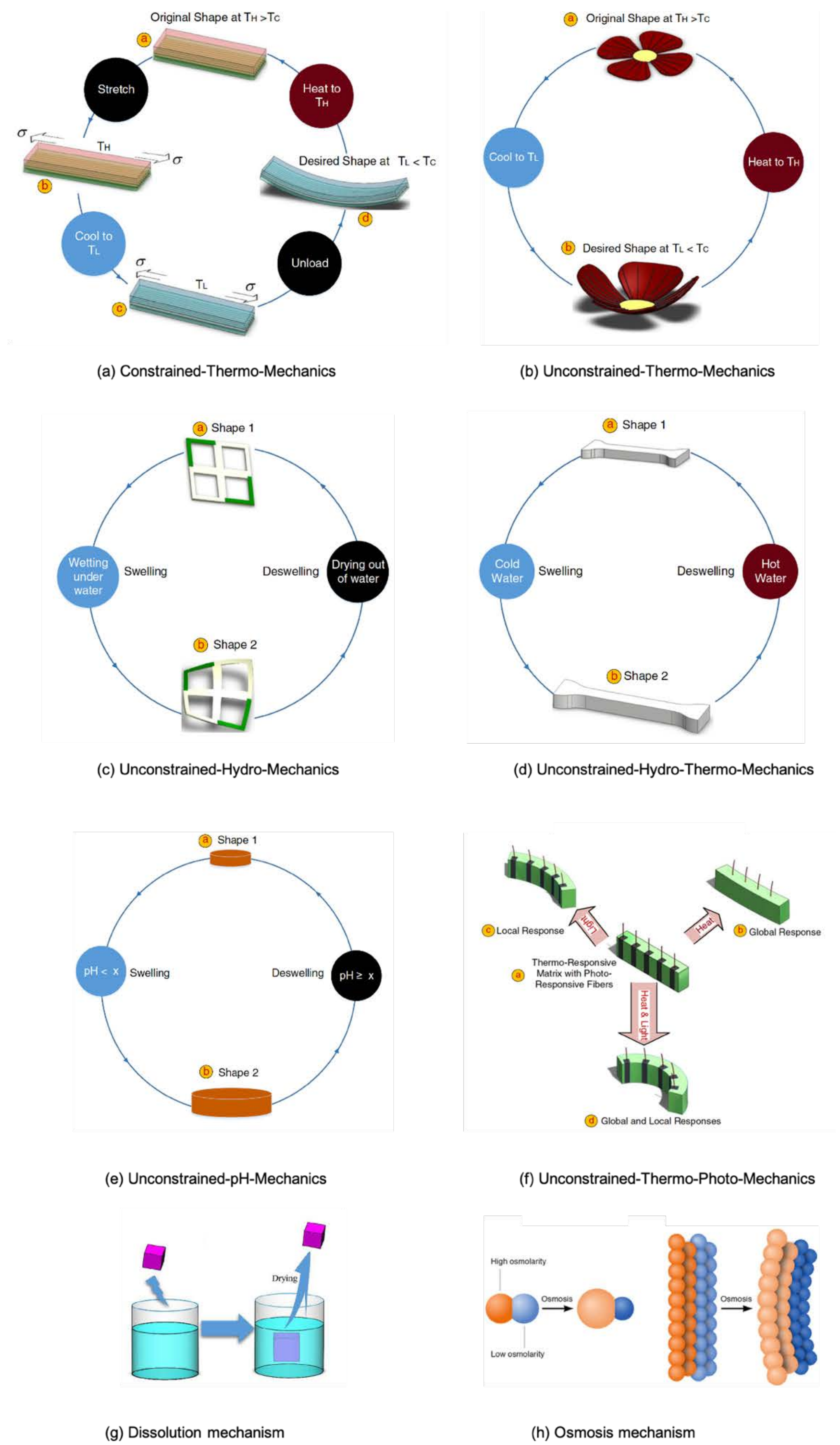


Figure. 10 Shape-shifting mechanisms, adapted from [34][49]

1.3. Design for 4D printing

Mathematical modeling is very important for 4D printing in order to design the material distribution within the structure so as to achieve the desired change in shape, property, or functionality. Momeni et al. [34] proposed that the material structure, the required final shape, material properties and stimulus properties are the core elements for establishing theoretical and numerical models. Since the materials and stimuli have been discussed in the previous section, here only 4D printing related approaches methods are reviewed.

1.3.1. 4D printing approaches

As a novel technology, 4D printing can switch the geometric configuration of 3D printing projects under the appropriate stimuli. Based on the current research, shape memory effect (SME), deformation mismatch, self-assembly of elements and bi-stability are regarded as the four main generic approaches falling under 4D printing [56]. Here is a brief discussion of the main features of these methods to illustrate the principle of 4D printing for shape-changing function. Based on some existing mechanisms, these approaches can be applied to achieve shape shifting in a controlled manner.

Shape memory effect (SME) is the most common way to achieve 4D printing. It introduces shape memory materials (SMMs) that can change their shape in a predefined spatial orientation [57]. To do so, the desired shape has to be printed as the initial state. Then a full SME cycle of SMMs includes two steps [56]: (i) the programming step and (ii) the recovery step in terms of shape that is achieved with the application of a suitable stimulus. So, the ability of the SMM to "memorize" its permanent shapes is called SME [58][59][60].

As part of SMMs, shape memory polymers (SMPs) can be actuated by heat or light [58] [46]. For example, thermo-responsive SMP requires a switching temperature or glass transition temperature T_{sw}) to which a shape-shifting behavior can be operated. When the printed structure is heated to the T_{sw}, external force is applied to it to change its shape. When the new structure is obtained, then cool-down the new structure while maintaining the external force until the new structure reaches an equilibrium state, then release the external force. When the temperature rises above T_{sw} again, the temporary shape will recovery into the initial shape [59], the principle is illustrated in Figure. 11.

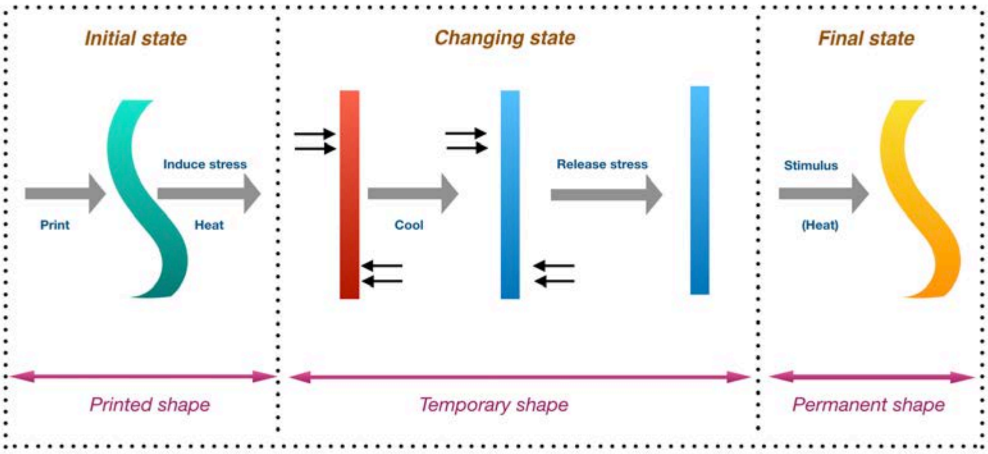


Figure. 11 The programming/actuation SMP process by heating effect [60]

In addition, shape memory alloys (SMAs) usually exist in two different phases with three different crystal structures, which are twinned martensite, detwinned martensite, and austenite, thereby giving rise to six possible transformations [61][64]. There are three categories of shape memory characteristics for SMAs [62][63], namely, one-way shape memory effect, two-way shape memory effect, and pseudo-elasticity [62] as depicted in Figure. 12. At lower temperatures, the martensite structure is stable, but the austenite structure is more stable at higher temperatures. There is a temperature range for transformation depicting the start and the end of the transformation: The start of the transformation of martensite is the martensite start temperature (M_s), and the completion of the transformation is the martensite finish temperature (M_f). SMA is usually found naturally in the twinned martensite structure. When the load is applied to the SMA, it forms a detwinned martensite structure. When the SMA is unloaded, it retains the detwinned martensite structure. The start of the transformation of austenite temperature is A_s and the completion of the transformation is the austenite finish temperature (A_f). When heated beyond A_s, the detwinned martensite structure begins to contract and transform into the austenite structure, resulting in shape recovery. If the austenite is heated beyond the temperature of detwinned martensite (M_d), the highest temperature at which martensite can no longer be stress induced, the SMA will be permanently deformed. Once the SMA is cooled below M_s again, the transformation will cause the austenite to revert back to the martensite structure, and the transformation will be completed below M_f [46].

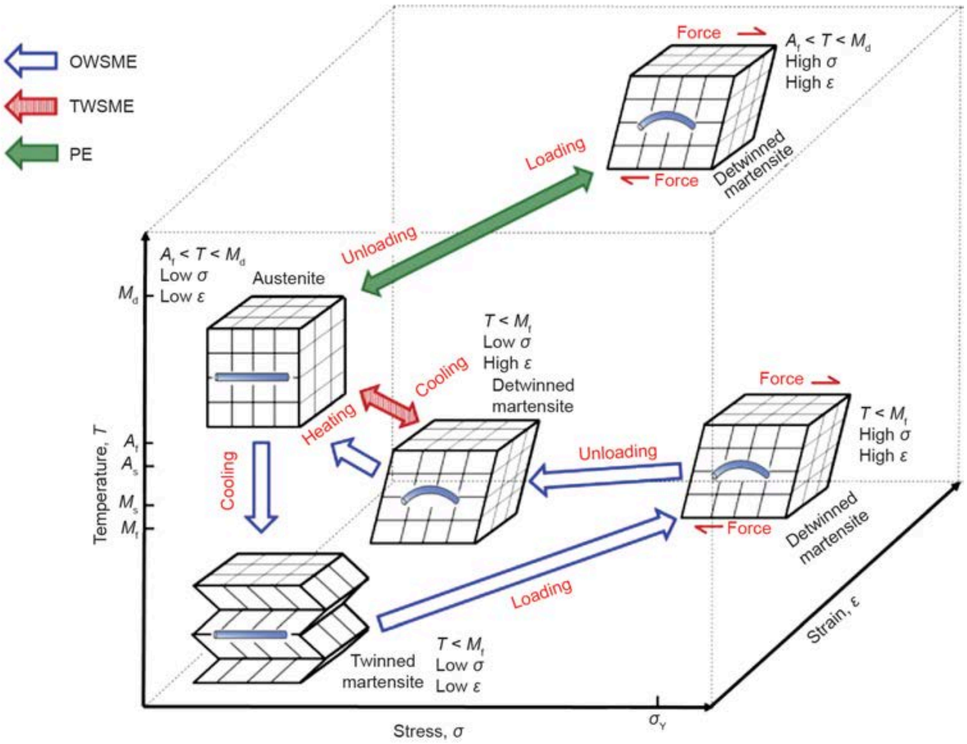


Figure. 12 SMA phases and crystal structures [46]

Deformation mismatch is a common phenomenon which can be observed directly. It may be caused by differences in some certain physical properties, such as the coefficient of thermal expansion and swelling rate, or sometimes induced by the gradient stimulus field. The common structures that result in this phenomenon are the bi-layer structures, sandwich structures and fiber-reinforced structures, these special structures can be realized by using current 3D printing technology to be able to print a variety of materials [66], which we will introduce them in detail in Section 1.3.2.

Besides, Self-assembly is a process by which disordered parts build an ordered structure through only local interaction. It is ubiquitous in nature, occurring at molecular, mesoscopic, and macroscopic scales, therefore, self-assembly can be classified into molecular and nanoscale self-assembly and meso- and macroscopic self-assembly [67]. Some self-assembly processes are random such as molecular, colloidal, interfacial self-assemblies. Others are directional to some degree, such as atomic and biological self-assemblies [68].

Under certain conditions, a structure with zero degree of freedom (DOF) may have two (or even more) stable positions, and the structure is able to switch from one stable position to another if properly loaded to induce slight deformation [69][70]. Technically speaking, this type of structure is called the bi-stable structure.

1.3.2. Materials structure and distribution

According to the material composition, the material structure can be divided into the single-material structure and multi-material structure [71]. A classification of materials structures and distribution is presented in Figure. 13. The easiest way to achieve 4D printing is to 3D print a single smart material, as shown in Figure. 14 (a). As we have introduced the SME in the previous section, it can be known that the SMM can be used as the SM to realize the desired deformation, and the most widely used one is SMP [58][59]. However, due to the outstanding characteristics (especially its reversible effect) of liquid crystal elastomer (LCE) [72][73], it has also attracted the attention of researchers.

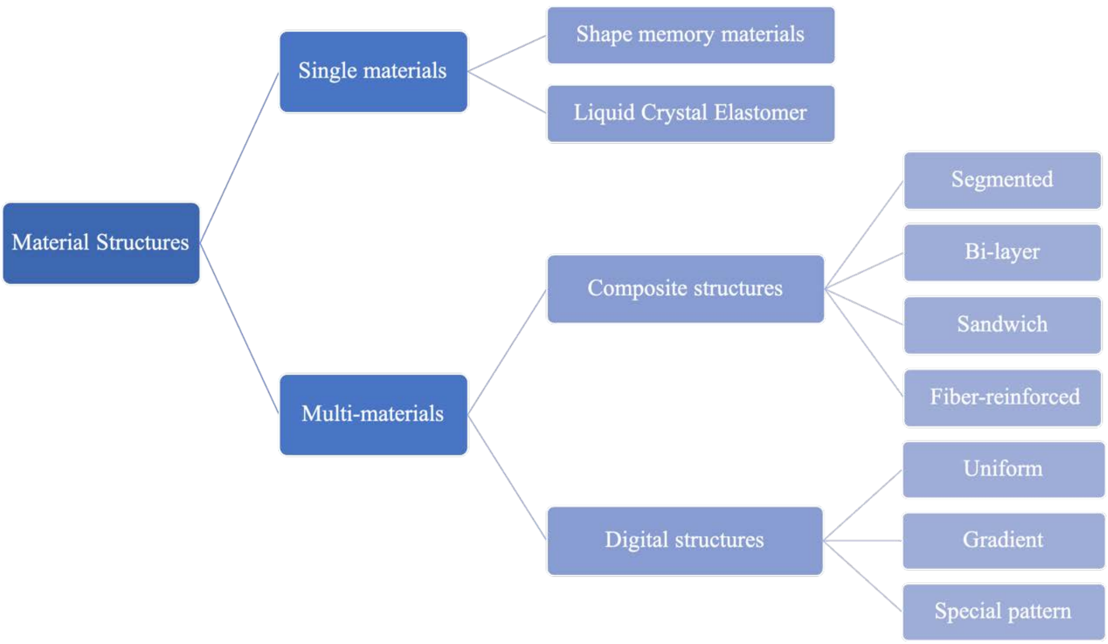


Figure. 13 Classification of materials structures and distributions

Multi-materials composite structure

3D printing has been explored to create components with locally controlled chemical compositions and mechanical properties, or the so-called components with multi-materials. In a multi-material structure, eigenstates can be generated due to environmental stimuli. These eigenstates depend on the relative position and volume fraction of different materials and can drive changes in the shape of the structure. the relative positions and volume fractions of different materials and can drive the shape change of the structure. 3D printing has a tremendous advantage of offering the great flexibility of placing different materials at different spatial locations, and thus the opportunity of controlling the generation of eigenstates and creating many innovative shape-shifting structures [71]. In this section, we summarize the most widely used multi-material composite structures systems, including segmented structure, bi-layer structure, sandwich structure and fiber-reinforced structure.

Segmented structure

Segmented structures mostly combine rigid materials and active materials in segments, as shown in Figure. 14 (a), the composite hydrogel is one of the representatives of this structure, mainly divided into water-response and thermal-response. For the water-responsive composite hydrogel, 4D printing can be developed by constructing a series of primitives (or hinges) with a rigid plastic base and a hydrophilic rubber (hydrogel) that swelled upon exposure to water [43][74]. This hydrogel expansion induced the eigenstate in the hinge and triggered a bending deformation. The folding angle of the printed active hinges could be precisely controlled by changing the spatial distribution of the two materials (the rigid plastic and the hydrogel). Chemical- and temperature-responsive hydrogel composites have also been used to achieve 4D printing through non-uniform swelling-induced eigenstates by modulating both the crosslinking density and location of the responsive gels [75][76].

Bi-layer structure & sandwich structures

The bi-layer and the sandwich structures have similar principles, both of them using

4D printing to combine the active and constrained layers to form an actuator, as shown in Figure. 14 (b)~(c). Generally, a laminate strip was printed with the elastomer and the SMP, the as-printed elastomer layer had a compressive strain, which could be tuned by adjusting key printing parameters, such as layer printing time. This direct 4D printing can incorporate internal stress during printing or heating steps without applying external force for shape programming, avoiding a series of tedious thermomechanical programming steps involved in 4D printing SMP [77][78].

Fiber-reinforced structure

The fiber-reinforced structure is printed by a laminate composed of a pure rubber lamina and a composite lamina with parallel fibers in the rubber matrix, as shown in Figure. 14 (d). Once the laminate is printed, it is heated, stretched, cooled and released. After releasing the external stress at the low temperature, the composite turned into a complex temporary shape. Depending on the fiber distribution and orientation, various complex 3D configurations could be obtained, including bent, twisted, coiled, and folded shapes. The SMP composites could be used as smart hinges to enable active origami for creating complex 3D architectures [51][52].

Multi-materials digital structure

Multi-material structure can be considered as a combination of smart materials and conventional materials or a mixture of different smart materials. The multi-material 3D printing offers the opportunity to create digital materials, which is defined as an assembly of various physical voxels [79][80]. The spatial arrangement of voxels plays a major role in determining the features of a 4D-printed structure [74]. In digital materials, each voxel contains only one material and has its own properties [34]. Adjacent voxels can be composed of different materials (see Figure. 14 (h)). The three most important categories of digital materials distributions are uniform (see Figure. 14 (e)), gradient (see Figure. 14 (f)), and special patterns (see Figure. 14 (g)). The multi-layer structure and the fiber-reinforced structure mentioned above can be regarded as special patterns.

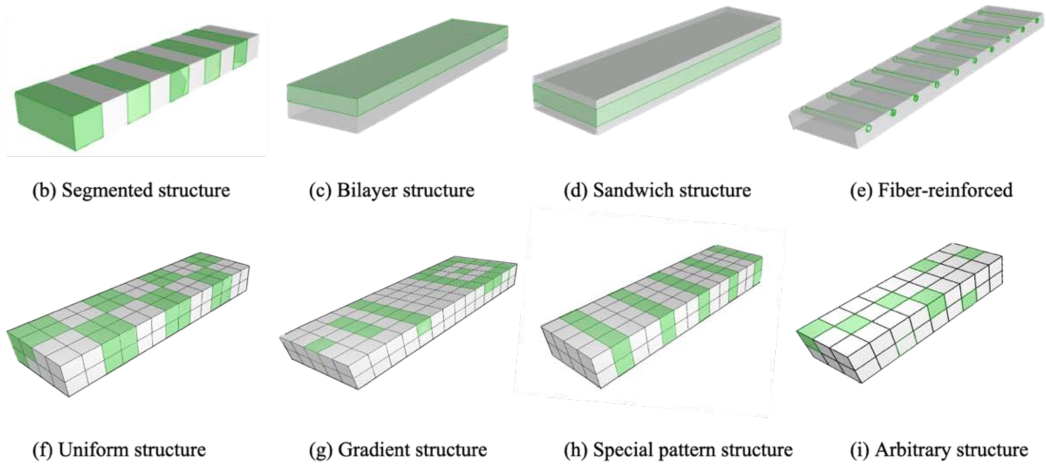


Figure. 14 Material structures and distributions

1.3.3. Typical shape-shifting behavior

4D printing adds a new dimension to the progress of AM, where structures can morph after being exposed to triggers. The totally new structures can result from the small or radical changes of the manufactured constituent. In order to better study these characteristics, we classify shape-changing behaviors into three categories basic shape-changing, complex shape-changing, and a combination of shape-changing. A taxonomy of shape-shifting behaviors of 4D printed parts is summarized in Figure. 15 [81].

1.3.3.1. Basic shape-shifting behaviors

Basic shape changing behavior results in a single deformation and the transformation occurs as a one-step process which produces a completely uniform effect. Basic shape-changing behaviors include folding, bending, rolling, twisting, helixing, buckling, curving, topographical change, expansion and contraction [81].

Folding

The crease is essentially a kind of deformation, in which the internal distance between the two different points of the sheet is maintained without self-intersection [82]. A fold is a sharp curvature along the crease caused by deformation. Folding is the localized deformation of the material which emphasizes a narrow hinge area using sharp angles [83][84]. Folding deformation is caused by the stress mismatch between the rigid and active materials, which is possible with various swelling ratios [34].

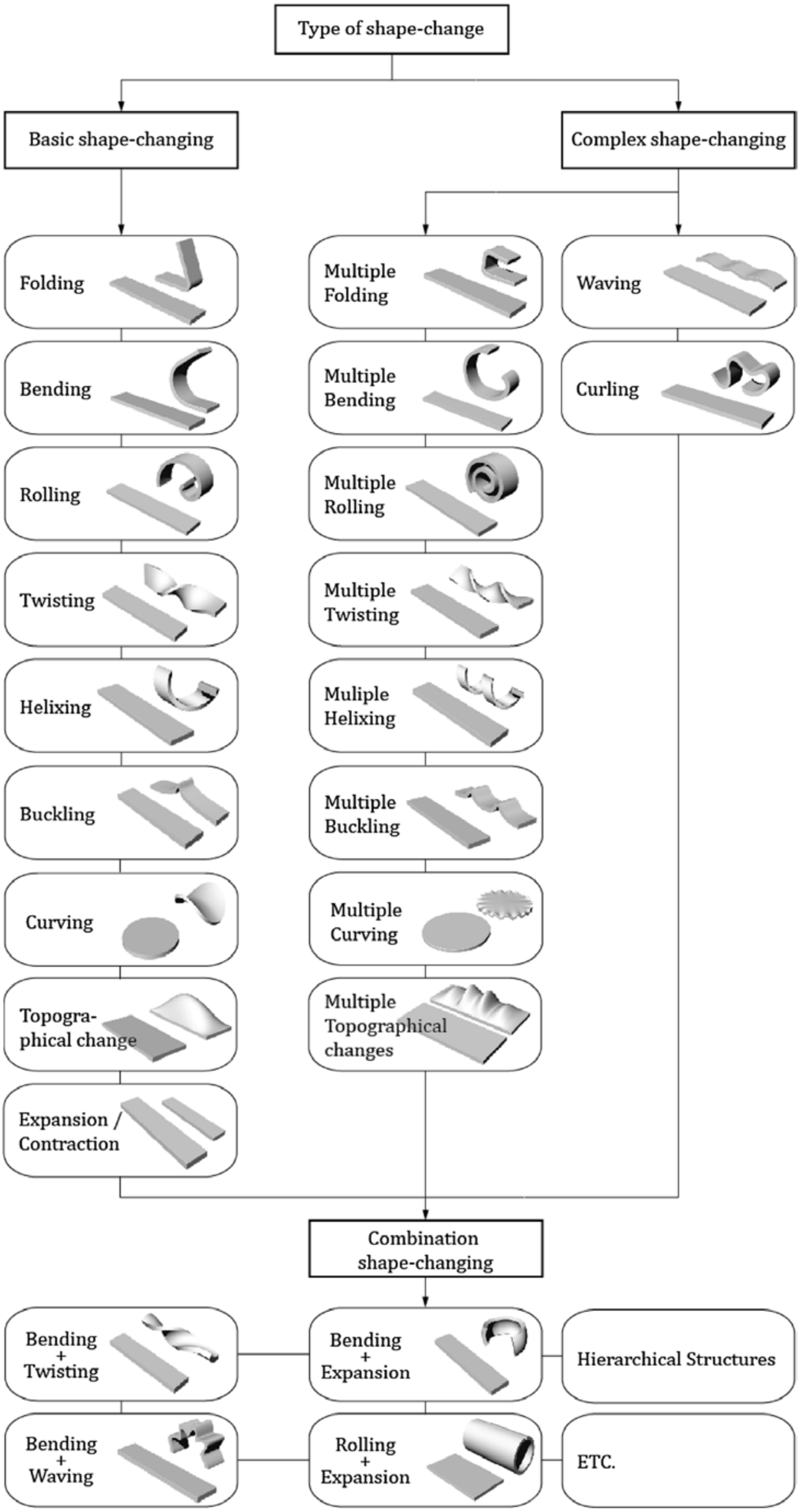


Figure. 15 A taxonomy of shape-shifting behaviors of 4D printed parts [81]

Bending

Bending refers to the distributed deformation of the material along the deflected area that creates the curvature [83], which has two positive and two negative gradients. The difference between folding and bending is that folding has a sharp angle occurring within a narrow hinge area; but bending is a global deformation that results in a smoother curvature [84]. When a force is applied to the bending effect continuously, the rolled shape deforms.

Rolling

Rolling can be seen as a shape-changing behavior in which the shape moves by turning over and over on its own axis. This deformation process has the ability to maintain a constant cross-section throughout the deformation process. This behavior is usually triggered by heat in the common shape memory cycles with programming and recovery steps [34]. Generally, the rolling consists of various gradients. The curvature's size depends on many design variables, such as the geometry, the composite, and its properties; the applied mechanical load; and their thermal history [51].

Twisting

The twisting action is dominated by in-plane stretching [85]. By combining two similar types of anisotropic active layers with primary straining directions perpendicular to each other, self-twisted strips can be made [86]. Moreover, the stretching energy increases rapidly by increasing the twisting widths. Twisting is favorable for small widths for shape change behaviors [85]. The twisting behavior is dominated by the in-plane stretching and the axis of the twist is centered.

Helixing

Helixing is a smooth space deformation in which a curve occurs in a three-dimensional space. The twisting behavior of the helix can be changed by adjusting the active fibers' print angles. The bending energy of the helix components is only linearly related to the width of the part and the helixing shape change has various axes [87].

Buckling

The characteristic of buckling is the sudden sideways failure of a structural member subjected to high compressive stress [88]. Buckling behavior can be activated and stimulated by using different temperatures. The stretching energy's scale is usually linear with the thickness of the material, and the bending behavior shows a cubic reliance on the thickness.

Curving

Curving shape-changing behavior is the amount by which the surface of a geometric object deviates from a flat plane. In the experiment Led by [43], mountain and valley features can be generated from concentric circles in the presence of an appropriate stimulus. Rigid and active materials have different swelling characteristics once in contact with water, resulting in a mismatch in stress, thus realizing this shape change behavior.

Topographical change

The topographical change causes the distorted shape, similar to the physical features of a ground terrain. Shells with different curvatures near and far from the central apex. Although the hypotenuse is completely straight near the apex, it becomes more curved further away the apex [89].

Expansion and contraction

Generally, the materials will expand when they are heated and will contract when they are cooled. Their shape, volume, and area of the material change as temperatures fluctuate. And the shape-changing behaviors of expansion and contraction are based on a shape-memory cycle, including the programming and recovery steps for thermo-responsive SMPs. Researchers [90] demonstrated expansion and contraction behaviors of linear free swelling and shrinking of a thermo-responsive hydrogel being immersed in cold/ hot water.

1.3.3.2. Complex shape-shifting behaviors

Basic shapes can be programmed to undergo a specified sequence of deformations over time to subsequently achieve complex shapes, sometimes also known as "sequential" shape shifting [88]. Complex shape-changing behaviors consist of multiple basis deformations, which can be obtained by extending the early form of a basic shape-shifting or the completely multi-faceted form. Such as, multiple folding, multiple bending, and so on, are extended behaviors of the basic shape change. Other complicated shape-changing behaviors include waving and curling. The waving behavior can result in undulating features or a wavy up-and-down form. Depending on the thickness of the layer and the induced strain, the waving and curling can be programmed effectively. By changing the position and materials of each layer, various wave shape-changing behaviors can be achieved [91]. Using surface curling by creating continuous surfaces can be an alternative to curved creases. A larger surface provides an even expansion force and usually displays the curling effects far more visibly [50].

1.3.3.3. Combination shape-shifting behaviors

In terms of mathematical analysis, all shape deformations are the result of different stress along the plane, which are affected by different strains, gradients and shapes. Combining shape-changing behaviors consists of merging different types of shape-changing behaviors that result in an amalgamation of different deformation results to the component. Two or more component behaviors can be programmed to appear in the component either simultaneously or in a carefully temporal sequence. Ge et al. [52] demonstrated the feasibility of combining twisting and bending; as well as bending and waving, as for Manen et al. [92], they addressed the combination of expansion and contraction.

2. Origami-based design

In the field of origami, the target shape is obtained from the initially planar sheet through the folding operation exclusively, which provides great convenience for the structural transformation, especially from 2D to 3D [93]. Nowadays, origami has been utilized across scales through its applications ranging from the nano- and micro-scales [94][95] to deployable aerospace structures at the macro-scale [96][97]. In this section, we will explore more possibilities by introducing the origami structure, the basic concepts of active origami and existing origami-based design approaches.

2.1. Origami structure

Traditionally, the term 'origami' has been associated primarily with the art of folding paper. The term origami has the Japanese roots 'ori' meaning 'folded', and 'kami' meaning 'paper' [98]. Origami was and remains the art of folding sheets of paper into decorative and often intriguing shapes, either abstract in form or representative of realistic objects. To realize the useful engineering origami structure rather than just staying at the level of paper art, designers must consider the basic concept of origami structure first.

2.1.1. Fundamental Concepts

In origami, the creases, folding directions, folding magnitude, and folding sequence determine the ultimate shape of the structure [99]. Table. 3 has been introduced to define related concepts of origami for the sake of clarity to which an illustration is also presented in Figure. 16 (a).

Table. 3 Definition of related concepts of origami

Term	**Explanation**
Kirigami	Kirigami is defined as the art of folding and cutting paper. Kinetic kirigami models are often LEMs, especially kirigami pop-up models
Hinge crease	The locations of localized folds on the sheet are formally called creases. In traditional origami hinge creases define the boundaries between flaps. In the context of mechanisms, they are creases along which lies an interface between two planar faces and it is the axis about which both facets rotate
Construction creases	Creases used to create references in the construction of the mechanism are not directly used to create motion, are referred to as construction creases. In

	some cases, they coincide with hinge creases
Structural crease	Structural creases are used to define the shape of flaps; they can be hinge creases as well. These creases are not needed in most mechanisms and they are not feasible for many materials. They may/can be substituted or eliminated in various ways
Fold	A fold is an action, and a crease is the product of that action
Crease	. Creases may be folded in one of two ways: mountain or valley
Mountain crease	A convex crease
Valley crease	A concave crease

Built on this, the additional parameters can be allocated to describe the magnitude of a fold, such as the folding angle and the radius of curvature at the fold line. These parameters are schematically shown in Figure. 16. In the view that a finite thickness sheet cannot provide sharp folds and for the purposes of discussion, it is assumed that a finite region centered at the fold is bent and has a radius of curvature R. The internal fold angle θi is the angle at the intersection of two-line segments stretching collinearly with respect to the folding faces. The external fold angle θe is defined as$180^{\circ} - \theta_i$.

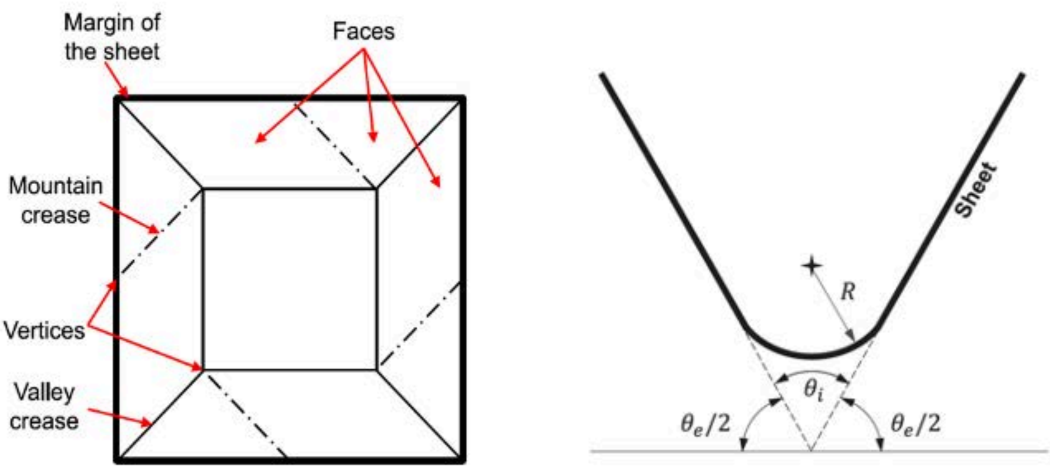
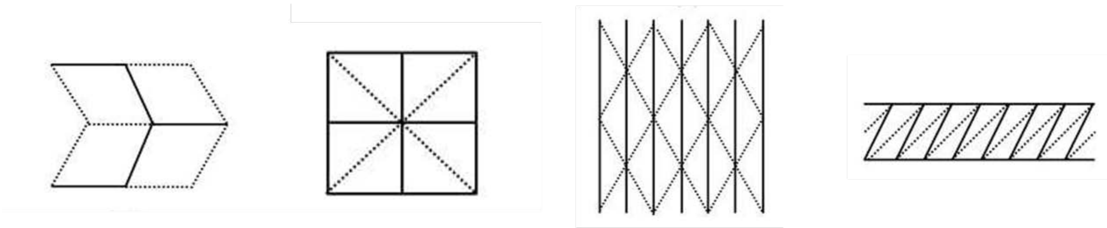


Figure. 16 (a) Schematic of a pinwheel crease pattern illustrating various origami concepts and (b) the parameters defining the magnitude of a fold [100]

2.1.2. Common crease patterns

The Miura-ori, waterbomb base, Yoshimura and diagonal patterns are all common rigid foldable crease patterns [101]. Figure. 17 shows these four crease patterns, which can be tessellated to form structures at any scale. The major features can be analyzed to distinguish these designs, the waterbomb base, and the Miura-ori can expand and contract in all directions. And the Yoshimura pattern has the capability of translational motion and the diagonal pattern allows for rotary motion [100].



(a) (b) (c) (d)

Figure. 17 (a) Miura-ori, (b) Water bomb base, (c) Yoshimura and (d) Diagonal patterns [100]

Miura-ori pattern

The Miura-ori pattern has a negative Poisson's ratio, which means that when the pattern is stretched in one direction, the folded sheet will expand in the orthogonal, planar direction, flat and rigid foldability, and one degree of freedom actuation. It can be used in space solar panels [102]. Figure. 17 (a) shows the folding motion of a Miura-ori pattern. This variation of this pattern uses trapezoids instead of parallelograms and is used to create concave or convex structures, which is useful in architectural applications. The Miura-ori pattern has been extensively used in engineering [102].

Waterbomb base pattern

The waterbomb base has applications in smart materials and actuation due to its simple geometry and multiple phases of motion [103]. It is commonly used as a base for more complicated designs. The folded states are shown in Figure. 17 (b) It is easily manufactured, has a transferable crease pattern, is readily scalable, is rigid foldable, can be expanded for different designs, and can be actuated in different motion phases [103]. The waterbomb base can also be folded and will form an axial contraction section when tessellated, and the Poisson's ratio between the radial and axial directions is negative.

Yoshimura and diagonal patterns

The Yoshimura pattern is inlaid with diamonds, and all mountain or valley folds along diagonals. The curve of the folded sheet yields the radius of a cylinder or curve, is a product of the shape of the diamonds in the pattern. If additional creases are made along the diagonal of the diamond, a hexagonal variation of the crease pattern is also possible, as shown in Figure. 17 (c).

Diagonal pattern

The diagonal pattern is also common in folding cylinders. However, instead of contracting in a translational manner, it rotates as it collapses [101]. It was first observed as the natural reaction when torsion is applied to a cylinder [104], as illustrated in Figure. 17 (d). The crease pattern is made up of parallelograms that are folded in one direction along their diagonals and in the opposite direction along their parallels (i.e., either mountain or valley). The valley folds of the Yoshimura pattern form a planar polygonal line, and the valley folds of the diamond pattern form a helical polygonal line [105].

2.1.3. Origami benefit

For decades, origami has inspired the design of engineering devices and structures. The underlying principles of origami are very general, which has led to applications ranging from cardboard containers to deployable space structures. Potential engineering advantages of origami structures include compact storage/ deployment capabilities [106], potential for reconfigurability [107], and reduction of manufacturing complexity [108] (reduced part counts and improved assembly using collapsible/deployable components). These features provide a great direction for deployable structure design [93].

2.2. Origami-based design

In the past few decades, there has been increasing attention from the mathematics, architecture, science and engineering communities given to theoretical models and computational design tools for origami [110][111]. Creating an origami structure having desired characteristics, particularly the desired shape, is known as origami design [112]. Origami-based design can be divided into three approaches: origami-applied, origami-adapted, and origami-inspired. These regions define classifications of origami-based design from direct to abstract applications of origami to the design. Figure. 18 demonstrates how each of these classification with supporting examples [113]. As the complexity of origami shapes increases and the importance of characterizing design constraints for application development increases, theoretical and computational approaches for origami design have become essential for developments in this area of study [98][99].

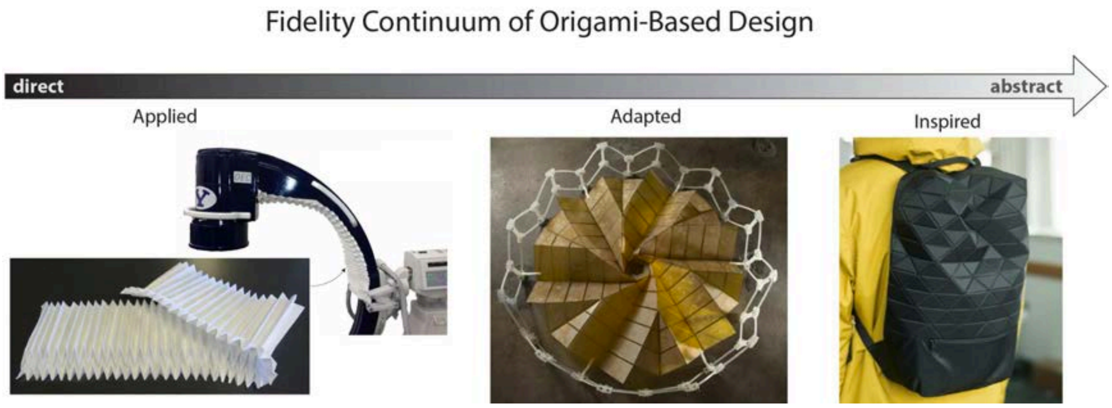


Figure. 18 A fidelity continuum ranging from a direct, idealized use of the mathematical model of origami to abstract applications of origami [113]

Origami-applied design implies a direct application of origami to design requiring minimal or even no adaptation. This mechanism's design involved identifying a fold pattern that met the requirements and applying it without any additional adjustments, which makes it a direct application of origami to product design [114]. The origami-adapted design transforms an origami design away from the base origami model to accommodate design requirements such as rigid-foldability, thickness, and non-crease-like hinges [115]. Origami-inspired design yields a design inspired by origami but does not directly link to origami, utilizing only origami aspects such as folding or geometric shapes [113]. Origami-applied is a direct application of origami, whereas origami-inspired is an abstract application. These design approaches require fewer origami modification tools. This research focuses on origami-adapted design, which requires specialized steps and tools to modify origami for a given application.

Researchers present the four considerations for origami-based design: rigid-foldability, crease characterization, material properties, dimensions, and manufacturing [114]. They have developed tools to address certain origami design problems, including rigid-foldability [116], thickness accommodation [115], hinge selection [117], actuation methods [118], and manufacturing methods [119]. These tools are supplemental to the design process, but how to transform the "paper origami" to the "engineer origami" rationally still needs to be explored. Four common problems and solutions will be elaborated on and discussed in this section.

2.2.1. Rigid-foldable origami

Mathematical modeling and simulation of origami structure help understand its behavior and develop calculation tools for its design [109]. Recently, various approaches have emerged to model origami's structural behaviors, which can be divided into three categories with different complexity and versatility. The first is that analytical solutions for elasticity problems related to origami have been developed [103][122], where typically a unit cell or a portion of the pattern is explored empirically. These analytical approaches are typically suited for one specific origami pattern and cannot be readily used for other origami systems; they also often assume that deformation only occurs as folding along the prescribed fold lines [120]. The other two mechanical modelling methods available for origami folding broadly cover rigid origami simulators [116] or numerical methods describing the paper as thin shells [121]. Among them, rigid origami is the most common and general, which we will introduce in detail below. As for the numerical method, particularly, finite elements (FE) methods [123][109] where the system is discretized in a detailed fashion. The FE approach often provides higher accuracy; however, it tends to be computationally expensive, it may obscure insight into the deformations, and depending on the discretization technique may not be suitable for studying patterns with different geometries [120].

A typical origami consists of flat thin sheet panels that are interconnected by fold lines [120]. Origami mechanisms are modeled with hinge crease as joints and facets as links [124]. An origami where deformation occurs only at the fold lines while keeping the panels flat is called rigid foldable [120]. Origami that is rigid-foldable is a "piecewise linear origami that is continuously transformable without the deformation of each facet" [124]. Rigid origami is the special case of origami for which the planar faces bounded by the folds and the sheet boundary undergo only rigid deformations, i.e., these faces are neither bent nor stretched [116]. Rigid origami is also defined as having regions of the paper between crease lines that do not need to bend or twist in the folding process [116]. Such a structure can undergo a continuous kinematic folding motion. Some origamis can also be flat-foldable, where the structure can fold into a two-dimensional flat state, which can be stored compactly. [120]. Several researchers have conducted research on rigid origami in the past, and the topic is still very active [127]. For example, it has been recently utilized to design the pop-up mechanisms [125] and deployable structures [126].

Various approaches have been utilized for the simulation of rigid origami [116]. For example, truss representations [121] have been considered where the faces of the sheet are triangulated, each fold or boundary edge end-point is represented by a truss joint, and each fold and boundary edge is represented by a truss member. Configurations in which the truss joint displacements do not cause elongations on the truss members [128] represent valid rigid origami configurations. The approach proposed by Schenk. et al. [109] is also based on modelling the partially folded state of a folded pattern as a pin-jointed truss framework. Each vertex in the folded sheet is represented by a pin-joint, and every fold line by a bar element [121]. The analysis of pin-jointed frameworks is well-established in structural mechanics.

Alternatively, Hull [129] has proposed a model for rigid origami in which the deformation caused by folding is represented using affine transformations. This model provides constraints on the fold angles to achieve valid rigid origami configurations and mappings between unfolded and folded configurations. Such a model provided the theoretical basis for origami simulation tools such as the Rigid Origami Simulator [130] and Freeform Origami [131].

2.2.2. Thickness origami design

The behavior and functionality of origami are influenced by the geometry of the fold pattern and the material properties [120]. Traditionally, the concept of origami was generally based on "paper", which can be regarded as an idealized sheet with no thickness. Folding is often obtained by creasing the paper along straight line segments. Thus, a goal shape is achieved exclusively by folding an initially planar sheet of negligible thickness. In this case, a fold is any deformation of the sheet so that the in-surface distance between any two points in the sheet remains invariant and no self-intersection occurs. This idealization of physically folded structures has been useful in analyzing and designing many origami-inspired applications throughout the years. However, such an idealization may not be appropriate for structures with non-negligible fold thickness or maximum curvature at the folds. Currently, the base materials for origami structures extend far beyond paper and include metals, polymers, and other complex materials. One of the problems is that not all the sheet is in the ideal state with no thickness. The inevitable thickness of engineering origami will cause many new problems.

For origami structures having a larger thickness than a sheet of paper or comprised of engineering materials for which direct creasing is not possible or desirable, destructive scoring and creasing might not be performed, and folding is instead obtained by bending localized regions. A fold on the sheet with non-zero thickness is defined as any deformation of the sheet that preserves a continuous neutral surface (i.e., a surface that neither stretches nor contracts) and prevents self-intersection. In engineering applications of origami-inspired design, it is generally necessary to adjust the thickness of the material to achieve the design purpose. The existing thickness adjustment methods can be divided into two categories: first, methods that preserve the range of motion, and second, methods that preserve kinematics. Figure. 19 shows a side-by-side illustration of some of the methods described below using a simple four-panel accordion fold.

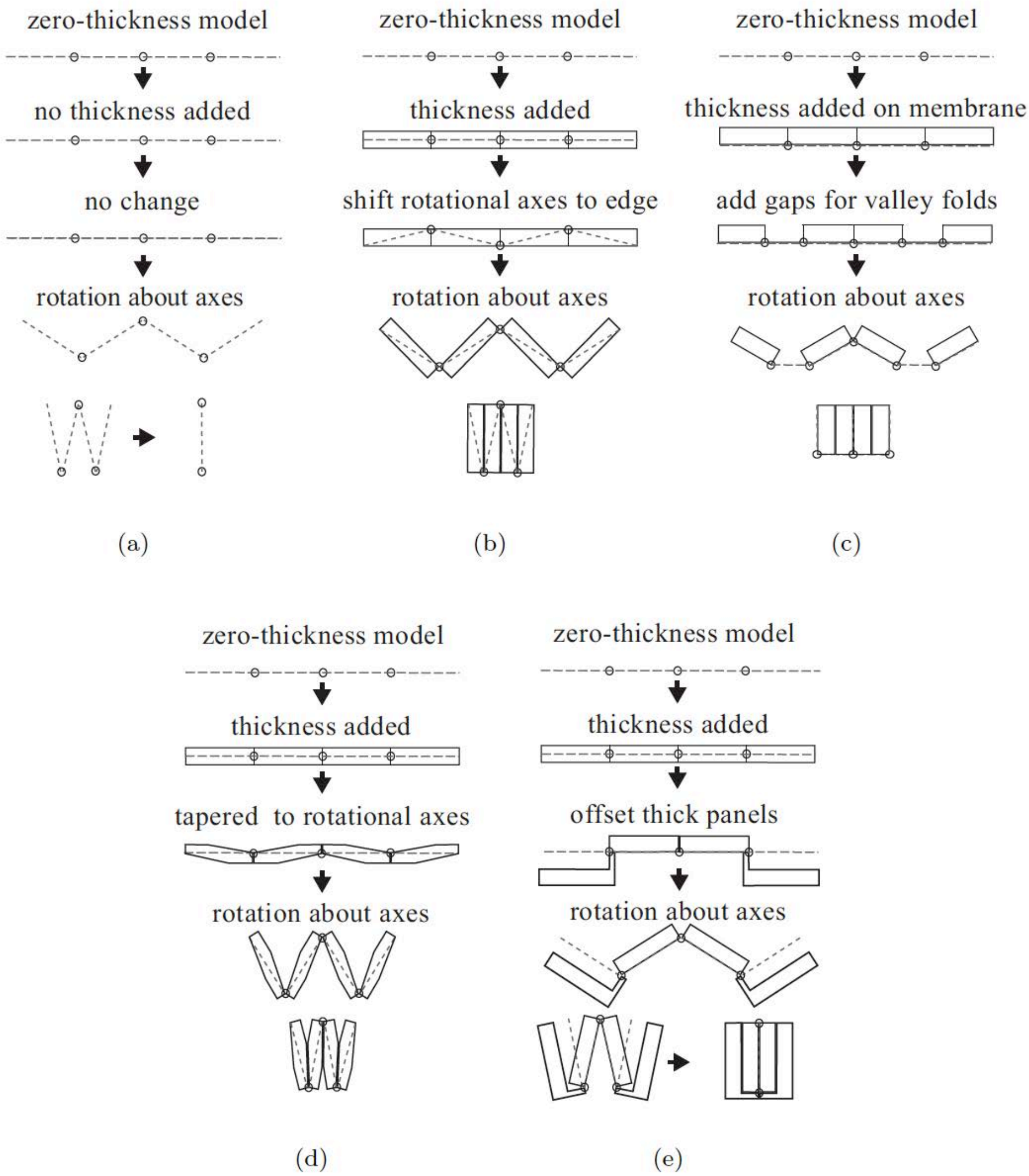


Figure. 19 Existing methods for thickness accommodation (a) zero-thickness model, (b) offset joint method, (c) membrane folds method, (d) tapered panels method with limited range of motion, and (e) offset panel technique [132]

The axis-shift method can maintain the motion range of the origami source model. This method allows the panels to fold by shifting all joints' rotational axes from the center plane to the panel edges (see Figure. 19 (b)). The vertices with an inner degree of 4 are folded, so that there are two inner panels and two outer panels. The inner panels fit within the outside panels in thin materials but not in thick materials. A disadvantage is that in many origami patterns of interest, the vertical offsets break the individual vertices' kinematic motion.

The offset joint method is related to the axis shift method because each hinge is located at the edge of the material (as shown in Figure. 19 (b)). The panel is not limited to be planar, coplanar, or uniform thickness. A gap is created to allow inner vertices full range of motion, tucking the inside panel into the gap created by the offset by extending the hinges away from the panels. Using this method, a completely compact cubic bundle can be created, which can be folded and unfolded sequentially instead of preserving kinematics. By using symmetric single parameter vertices, single-DOF mechanisms can be created in thick material using this method.

In the membrane folds method, all rigid panels are attached to one side of a flexible membrane as shown in Figure. 19 (c). By controlling the spacing between adjacent panels, a full range of motion folding can be achieved. The zero gap between the panels only allows a mountain fold, where a larger gap is required to fold a valley, and the gap width is set by the panel thicknesses and the required maximum rotational angle. This gap also provides additional DOFs with small additional motions that can allow a theoretically non-rigidly foldable structure to be folded in practice. However, it may cause undesirable (and unpredictable) additional motions in the deployment.

The tapered panel method can be designed to preserve the origami source model kinematics. Trim the panels until the edges of panel are coincident with the plane defined by the zero-thickness model (see Figure. 19 (d)). Since the axes of rotation are unchanged, the thick panels' kinematics are equivalent to that of the zero-thickness model. However, the yields models produced by the tapered panel technique may not be foldable to a fully compact state and typically do not achieve the full range of motion of the zero-thickness model.

The offset panel technique can preserve the kinematics and full range of motion of the origami source mechanism, thus enabling origami-inspired designs to more closely mimic properties identified in zero-thickness models (see Figure. 19 (e)).

2.2.3. Origami crease pattern design

One of the most well-known approaches for origami design is Lang's tree method [135], which is illustrated in Figure. 20. This method has been implemented in a software package named TreeMaker [136]. It generates a pattern of creased folds on a squared sheet that allows for folding the sheet into a base, a folded whose projection to a plane is the tree line graph of the goal shape. This planar tree line graph may have arbitrary edge lengths and topology. After the base is folded, it is left to the designer to execute additional folds in order to approximate the goal shape closely.

An origami design method is proposed for goal shapes represented as polygons or three-dimensional polyhedral surfaces [137]. The method is based on folding a sheet into a thin strip and then wrapping the strip around the goal shape using creased folds. Various algorithms for wrapping the goal shape were proposed [137], including one that uses any sheet area arbitrarily close to the goal shape area and another that maximizes the width of the strip subject to certain constraints.

Fuchi and coworkers [138] proposed an origami design method based on topology optimization. In their approach, the location of a predefined set of fold lines is assumed; this given configuration is termed the "ground structure." The fold angles are the design variables. A topology optimization method is then used in an iterative effort to find the optimal set of fold angles that, combined with the ground structure, provide a targeted folded geometry.

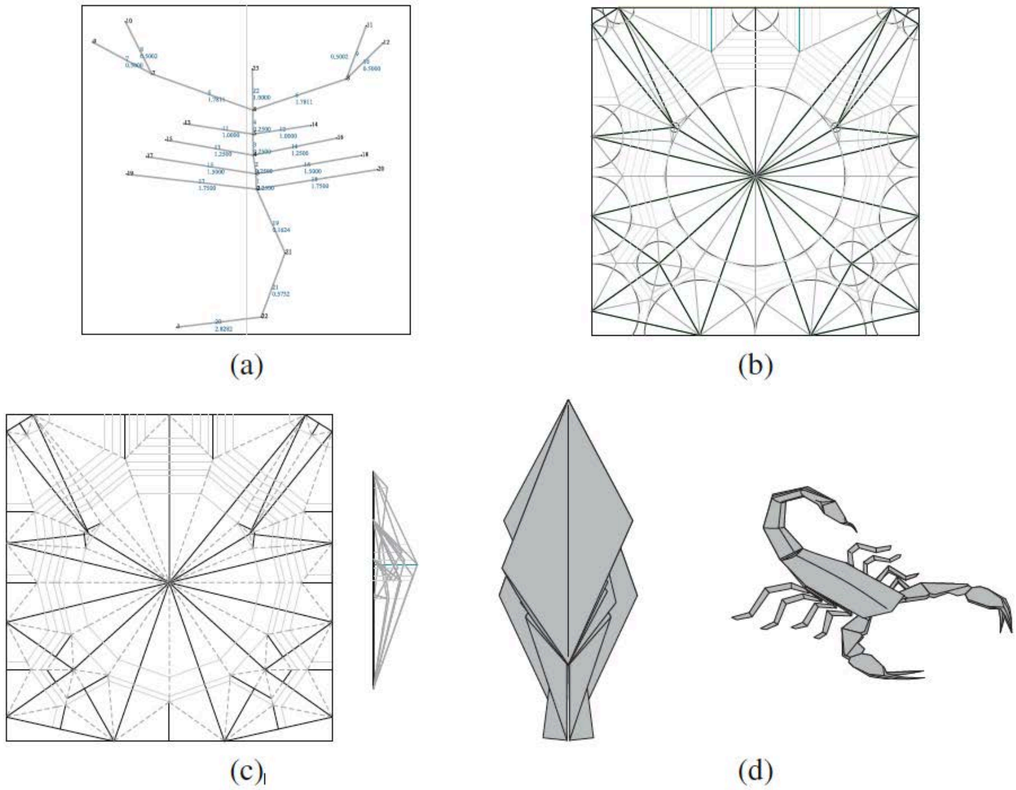


Figure. 20 Application of the tree method using TreeMaker (a) Tree graph for a scorpion. (b) TreeMaker solves the equations corresponding to the packing of “circles” and “rivers”. (c) The layer-ordering problem is solved, which allows one to create an assignment of the mountain (solid black), valley (dashed gray), and unfolded (light gray) creases.(d) The folded base, which includes all of the desired flaps at their specified lengths, and the finished “Scorpion varileg,” after additional shaping folds [136].

Unfolding polyhedral is a method for determining the geometry and pattern of creased folds associated with a planar sheet, and it can be folded to a target polyhedral surface [139]. Unfolding is defined as flattening the target polyhedral into a plane so that the surface will become a planar polygon having boundary segments that correspond to cuts made on the goal polyhedral surface. In general, the unfolding must be a single simply connected polygon having no overlaps and the cuts must be made on the edges of the goal polyhedral surface.

At present, the computational method for origami design applicable to the broadest range of goal shapes was introduced by Tachi in [111]. Tachi proposed a method that can be used to obtain the pattern of creased folds in a convex planar sheet that folds into an arbitrary three-dimensional goal shape is represented as a polygonal mesh [112].

This method has been implemented in a software package named Origamizer [140], which is illustrated in Figure. 21, and is based on the introduction of regions with two rigid faces and three creased folds placed between any two polygonal mesh faces connected by an interior edge. The creased folds are used to tuck-fold such introduced regions to form the three-dimensional polygonal mesh starting from a planar configuration. It has been proven that this method has success on goal polygonal meshes (convex and non-convex) of various complexities in terms of the number of faces and non-regular connectivity.

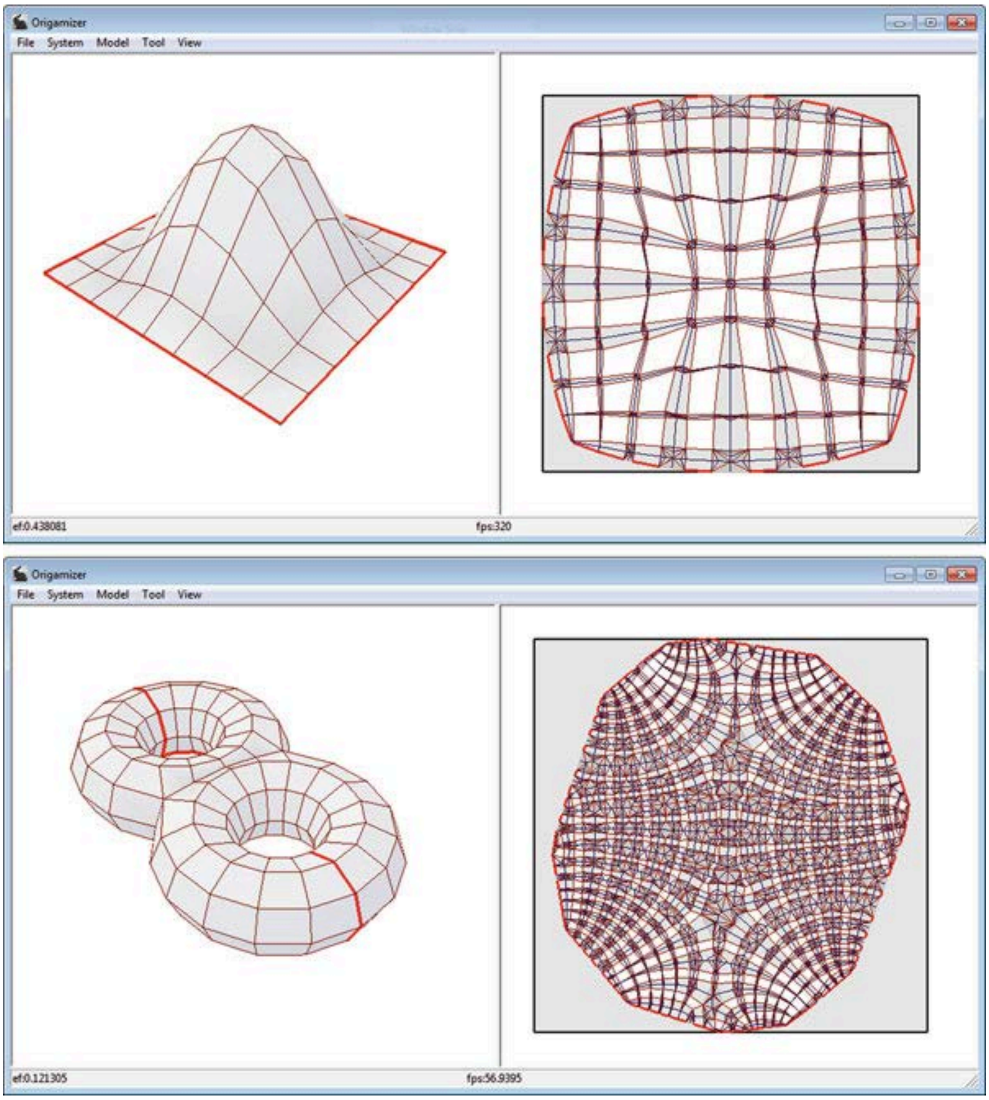


Figure. 21 Graphical user interface of Origamizer showing patterns of creased folds generated for two different goal shapes (left: goal shape, right: planar sheet with fold pattern). The Origamizer software [140].

2.3. Active origami

2.3.1. Active origami definition

In many origami applications, the folding motion of the origami structure is driven by mechanical loads applied externally. However, for certain engineering applications of origami, it is impractical to externally apply the mechanical loads necessary to fold a given structure. This is the case for remote applications or structures at the nano- and micro-scales. In such circumstances, self-folding capabilities are essential [93]. More recently, researchers have become interested in using active materials (i.e., those that convert various forms of energy into mechanical work) to affect the desired folding behavior. With a suitable geometry, active materials can enable researchers to build self-folding structures. Such a structure can perform folding and/or unfolding operations without being kinematically manipulated by external forces or moments. This is beneficial for many applications, such as space systems, underwater robotics, small scale devices, and self- assembling systems [99].

A self-folding structure has the capability of folding and/or unfolding without the external application of targeted mechanical loads. One approach to develop a self-folding structure is to leverage the use of active materials, which convert various forms of energy into mechanical work to generate the desired folding behavior. Such structures are termed active origami structures and are capable of folding and/or unfolding without applying external mechanical loads but rather by the stimuli of a non-mechanical field (thermal, chemical, electromagnetic) [93]. Since many origami structures are manufactured by 3D printing, active origami can also be regarded as applying and exploring 4D printing on origami structures.

2.3.2. Active origami design

Concepts for generating individual folds using active materials can be divided into two categories: hinge type and bending type, as shown in Figure. 22 [99]. In hinge type concepts, folds are clearly restricted to structurally pre-determined hinge locations. Most hinge-type active folds are associated with one of three local actuator concepts:

- *Extensional hinge:* the active material in a rod or spring form with its two ends attached to the faces connected by the hinge and the length of the active element controls the rotation of the hinge. (Figure. 22 (a)).
- *Torsional hinge:* the active material as a torsional spring or a rod that provides twist at the hinge. The twist angle of the active material thus directly controls the rotation of the hinge. (Figure. 22 (b)).
- *Flexural hinge:* the active material has been manufactured or trained to have a preset folded configuration but is then deformed to an initially flat configuration. Upon application of the activation field, the active material itself returns to its preset folded configuration and being bonded to the faces of the passive material, induces the local hinge to do the same. (Figure. 22 (c)).

Unlike the hinge type fold concepts, another approach — bending type may offer the advantage of massive foldability. Unless mechanically restricted, folds can occur at any location or orientation to which the driving field is applied. Furthermore, the concept of bending type can be divided as follows:

- *Multi-layer concept*: self-folding using a two-layer laminate with one passive layer and one active layer. A passive layer generates negligible mechanical work compared to the active layer under the application of the actuation inducing field. When such a field (thermal, magnetic, etc.) is applied, the active layer is driven to deform, generally axially, while the passive layer is not. This difference in expansion or contraction between the two layers generates localized bending of the sheet. (Figure. 22 (d))
- *Single layer concept*: self-folding via bending without hinges using a sheet with a single active layer subjected to a graded driving field. Such a gradient generates a distribution of actuation strain through the sheet thickness, causing the sheet to bend. This design allows for folds in both directions relative to the sheet normal based on the direction of the driving field gradient. (Figure. 22 (e))

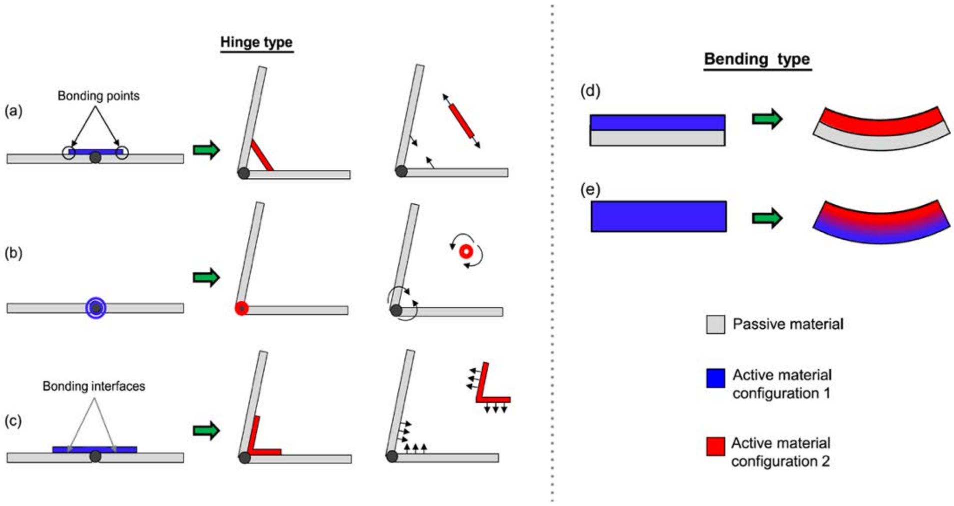


Figure. 22 Basic active fold concepts. Hinge type: (a) extensional (variable length active rod or spring connected to the two faces), (b) torsional (active torsional element at the hinge), and (c) flexural (active element with preset folded shape).

In addition to geometric design, finite element analysis has recently been applied to self-folding origami structures comprised of various active materials. For example, SMA/elastomer composite sheets' folding response has been explored using both finite continuum elements and shell structural elements. Ahmed and coworkers performed a multi-physics simulation of origami structures actuated using dielectric elastomers and magneto-active elastomers. The aforementioned examples demonstrate FEA approaches' capabilities to provide a high-fidelity simulation of active origami structures considering couplings among various physical fields (e.g., mechanical-thermal and mechanical-electrical-magnetic).

Although FEA approaches provide significant advantages in terms of fidelity and generality, they also have drawbacks when applied to the modeling of origami structures. First, the mathematical insights provided in the classical approaches of origami (e.g., geometric constructions) are lost in the complexity and generality of FEA. The kinematic variables associated with FEA models (e.g., displacements and/or virtual rotations at nodes in displacement driven FEA) and the very high number of degrees of freedom are not generally compatible with those of conventional origami (e.g., fold angles defined, one per fold). Moreover, FEA is not as computationally efficient as the alternatives, making it infeasible for modeling origami structures with high complexity in terms of the number of folds and/or the folding sequence's length.

3. Deployable structure

3.1. Definition and classification

Deployable structures are sometimes known by other names, such as mobile, extensible, portable, developable, transportable, and expandable structures [141]. It can be deformed between the different configurations with a predetermined mechanism, showing the great potential in many engineering applications because of its characteristics, such as saving storage volume during the conversion process [142]. Due to its geometry, materials and mechanical properties, it can be expanded and / or contracted, which has practical significance for mechanical engineering [142]. Various shelters and similar buildings and large-scale spacecraft are related applications of deployable structures. Deployable structures are introduced as a distinct class of structures consisting of rigid or transformable elements connected by moveable joints. They have the innate characteristic to control the reconfiguration; the configuration of deployable structures can be changed reversibly and repeatedly [141].

The design of deployable structure can be classified into two main groups: Structural Components and Generative Technique [142]. The deployable mechanism's structural components are its essence and base on the design, it can be divided into four subgroups, Rigid, Deformable, Flexible, and Combined. Moreover, the generative technique concentrates on movement and form inspired by origami and biomimetics that can later be developed with several structural systems, the typologies are shown in Figure. 23. Hailin Huang et al. [143] also divided the mechanism design into two stages: the topological synthesis stage and the kinematic synthesis stage. At the same time, according to the folded morphology, the compact form for deployable units is first classified into three categories: linear compact structure, planar compact structure and hybrid compact structure as shown in Figure. 24. Another classification method proposed by Otto et al. [144] provide a special movement matrix with the different type of movement and direction of movement as shown in Figure. 25.

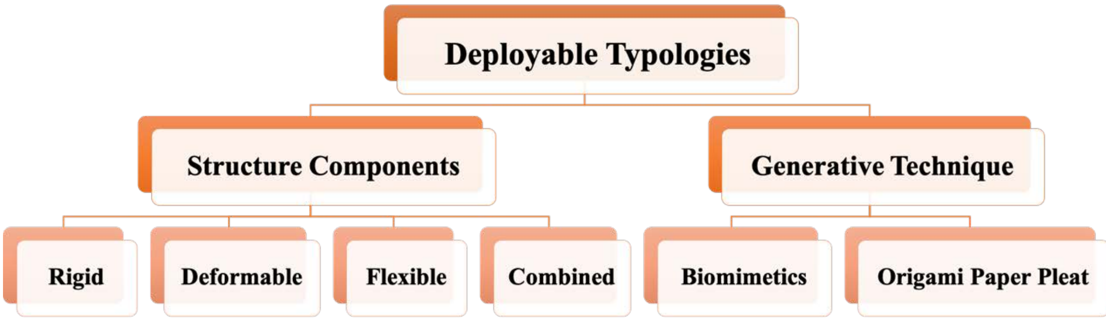


Figure. 23 Deployable Typologies, adapted from [142]

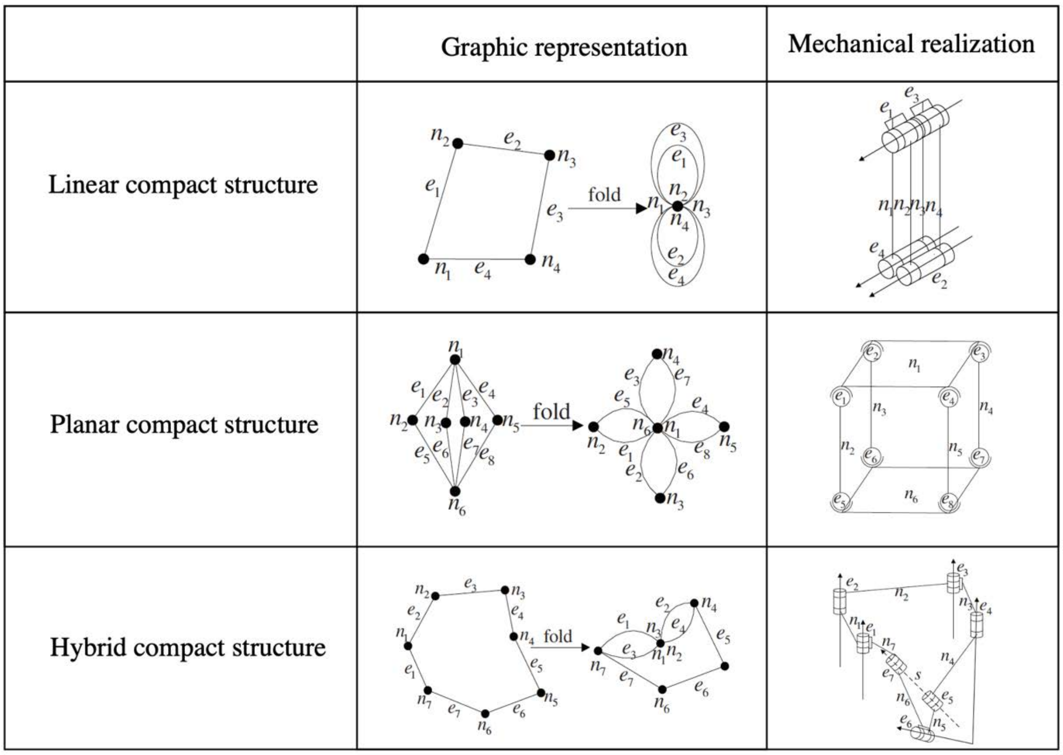


Figure. 24 The classification of compact form for deployable units, adapted from [143]

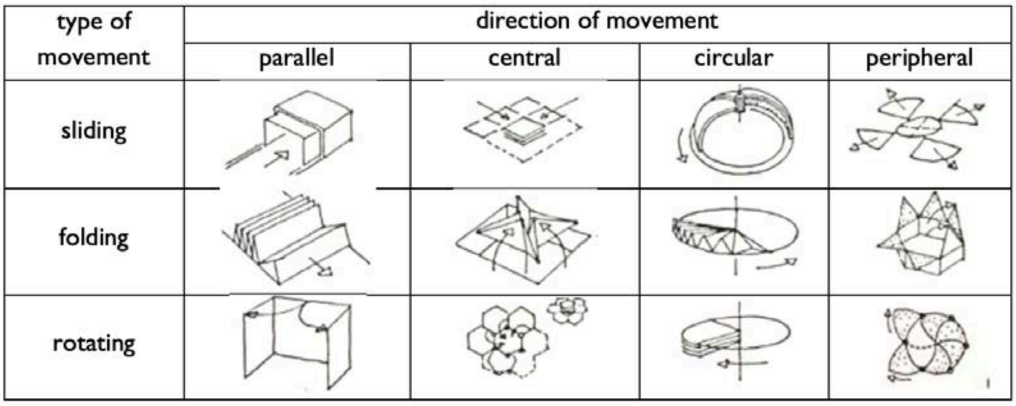


Figure. 25 Classification of deployable structures: the movement matrix [144]

3.2. Common methods

Generally, the deployable structure is connected throughout topologically; most of them are composed by the connections' panels, consisting of rigid links and mechanical joints, called articulated mechanisms [143]. Some panels are in a static equilibrium state in both "open" and "closed" configurations, which do not need any deformation during the deployment process, they can be regarded as rigid elements, and the joints that realize these deformations are called active elements. Through pre-programming the connection of active and rigid elements, structures that are able to rapidly take on new shapes, forms, functions, or character in a controlled manner.

To transform the initial state into the final state during deployment, different mechanisms such as stressing, folding, creasing, hinging, rolling, sliding, nesting, inflating, and fanning mechanisms provide a rich strategy that can be used in the structure [145]. The transform direction and form can be defined by the connection angle and position between movable joints. However, it is still difficult to determine how much angular or displacement target movement each active element will achieve, and how to achieve the required accuracy at the end of deployment to make the structure perfectly connected and stable. Furthermore, even with the simple mechanism and visual operation can realize the deployment from close to open position and make the necessary adjustments, how to control the opening of each mechanism of the structure is still difficult. For example, the hinge can be used to control the degree of freedom, and special parts such as turnbuckles can be used as tensors to control the deployment amplitude. Manual operation is always the most common and convenient method. With industrial manufacturing development, automation and electronic control of openings are increasing, while hydraulic and pneumatic, and mechanical control methods have been gradually developed [145]. However, these applications increase the complexity of structural design while moving and controlling the structure.

The deployable kinetic system is a system that is easy to construct and deconstruct. It can have one or multiple functions and their movement can be controlled in six different ways [146]:

- **Internal Control:** have the potential of mechanical movement, but they do not have any direct control devices or mechanisms. They have the internal constructional control that allows them to move through rotating or sliding. This is the case for deployable and mobile architectures.
- **Direct Control:** the movement is done directly through the source of energy, such as electrical motors, human actions or biomechanical changes in response to environmental conditions.
- **In-Direct Control:** the movement is caused indirectly by the sensor feedback system. The sensor first sends a message to the control device, and then gives an on/off instruction to the energy source to actuate the movement. It is a singular self-controlled response to a unique stimulus.
- **Responsive In-Direct Control:** the operating system is quite similar to the previous system, but the decision is made by the control device based on input received from various sensors. After analyzing the input, it will make optimization decisions, and send it to energy in order to drive a single object.
- **Ubiquitous Responsive In-Direct Control:** the movement is produced by several autonomous motor pairs or/and sensor, which form a network as a whole. The control system uses a predictive and adaptive feedback algorithm.
- **Heuristic, Responsive In-Direct Control:** the movement has the capacity of self-constructive and self-adjusted. Control mechanism in this case has a learning ability. The system learns based on successful experiential adaptation to further optimize the system in an environment in response to change.

4. Conclusion

In this chapter, through the literature review and related knowledge summary of 4D printing (including additive manufacturing, smart materials and 4D printing design), origami-based design and deployable structure, a knowledge base covering these three aspects have been established as shown in Figure. 26. This seems to provide a guarantee for the origami-based 4D printing deployable structural design. However, this potential design method can be seen as a comprehensive discipline involving multiple fields, how to integrate these design factors into the entire design process has not been thoroughly explored. Secondly, 4D printing needs to consider subsequent reaction deformation when designing the initial configuration. Early 4D printing experiments involved multiple repetitions of specific structures to achieve the desired shape [50]. In order to reduce the number of trial and error, to avoid collisions between structural components during the self-assembly operation, and to predict the shape evolution within a period of time after printing, a corresponding theoretical model must be established [54]. Therefore, for 4D printing, the development of a general and systematic design process and appropriate mathematical models are very important [34].

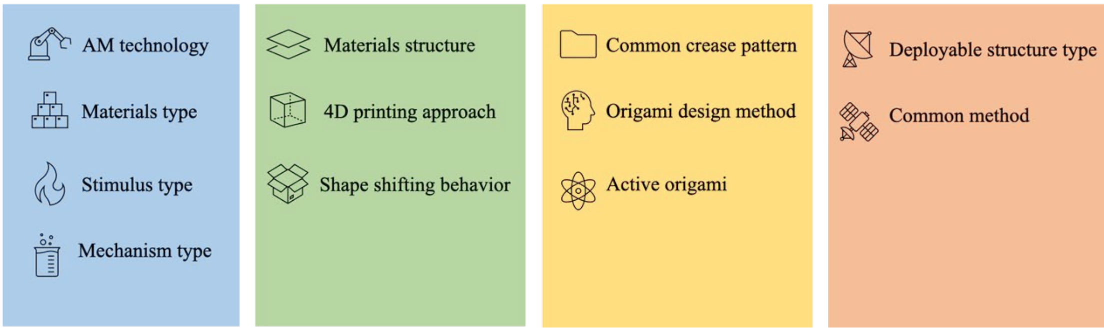


Figure. 26 Database of 4D printing, 4D printing design, origami-based design and deployable structure design

Furthermore, it can be seen that most of the current research work of 4D printing focuses on its manufacturing, for example, the development of new materials [36][140], the demonstration of new manufacturing routes such as 4D printing [43], etc. However, few people provide the complete 4D printing design process based on these knowledges. In other words, compared with the design for additive manufacturing design (DFAM) [148], what can be called 4D printing design (DF4DP) is indeed lagging behind. Although some studies based on voxel by simulating the behavior of SM and conventional materials and quickly evaluating the distribution of materials [149][150] have provided new ideas for the design of 4D printing, the general design process of the 4d printing system is still incomplete. Therefore, in the next chapter, we will introduce how to integrate this knowledge into the complete design process and propose a system design framework.

Chapter 3. Systematic design framework for active structure design by 4D printing

This chapter will propose a systematic framework for 4D printing active/transformable structures to cover the entire process from design concepts to the physical prototype. Firstly, we will clarify the research objectives and the problem that needs to be solved in the 4D printing oriented design process. Secondly, by disassembling and subdividing the overall structure in a top-down way, the overall structure can be regarded as an aggregate of different parts. Therefore, the design of the overall structure can also be decomposed into the design of each part. A top-down design method that includes the four levels of the overall structure, crease pattern design, actuator design, and hinge design will be proposed. To further clarify the specific design process, a design model of "function-structure-parameter" is presented here. Guided by design requirements, the corresponding functions are defined to complete the structural design and parameters setting of different levels. Furthermore, the decision-making of materials and stimulus selection can be made with the knowledge base of 4D printing and origami design. Therefore, the final design strategy is determined. Finally, the systematic framework of 4D printed active structures, including all design and manufacturing steps, is proposed.

1. Research problem analysis and clarification

The realization from product concepts to the actual parts can be achieved through a digital and physical workflow [151]. From a particular perspective, this workflow can be simply seen as the design and manufacturing processes, respectively. For the 4D printing oriented design process, and in addition to the necessary steps and requirements for AM (as discussed in Chapter 2), more factors need to be considered. On the digital side, the main difficulty of 4D printing is that from the initial preliminary design to the establishment of the CAD model, Not only need to build a geometric model, but also need to assign different materials and set printing parameters.

One reason for using 4D printing for manufacturing some unique structures is that it is difficult to obtain the desired final structure directly, so it is necessary to use a temporary state and then obtain the target state after stimulation. Another reason is that two structures need to be transformed to adapt to different environments. However, in both cases, the two states can be regarded as the "printed structure" and the "target structure," respectively (which corresponding to state A and state B in this article). As shown in Figure. 27, the difficulty of 4D printing design is how to get state A, while state A is printed according to the designed pre-printed precursor (which also contains geometric structure information and material distribution information). To better explore the 4D printing design from the "concept idea" to the "CAD model," it is necessary to propose a systematic design process to simultaneously define the geometric structure and material properties.

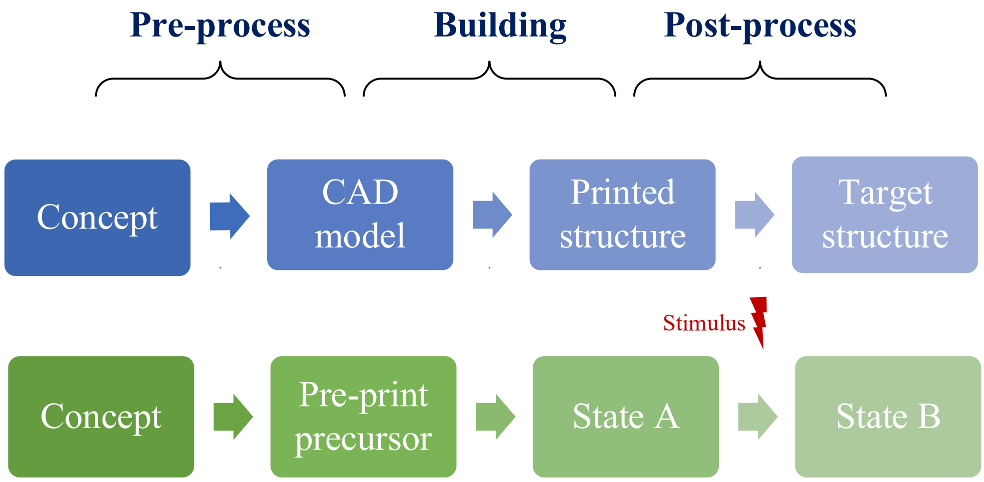


Figure. 27 4D printing process with different representations

2. Top-down design process analysis

At the overall active structure view, a complete structure can be regarded as an ordered aggregate/collection of many different types and functional parts, so the active structure or transformable structures (such as deployable structures and reconfigurable structures) can be regarded as an aggregate of the active and inert materials a specific assembly sequence and process. The active parts are responsible for the specific role of structural transformation, with its unique geometric structure and material distribution, as shown in Figure. 28.

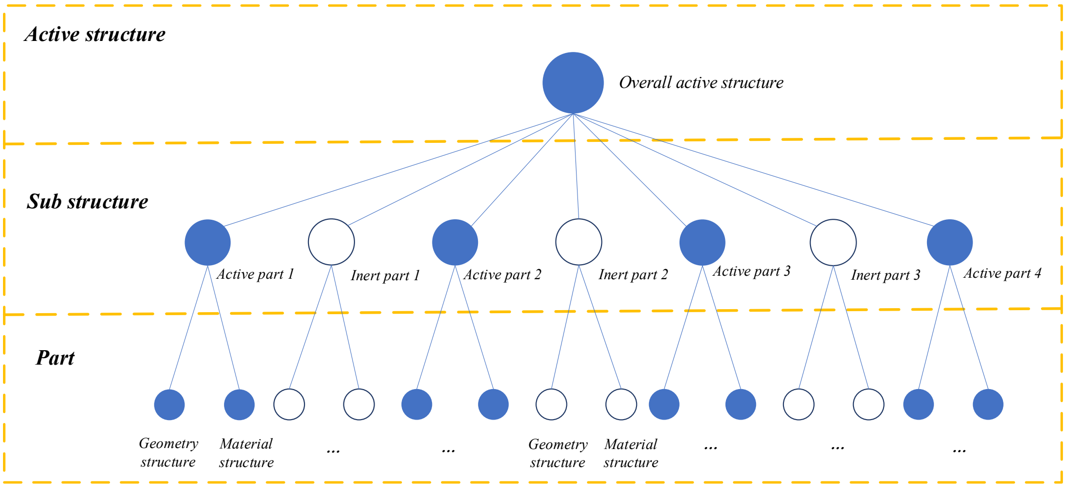


Figure. 28 Top-down analysis of a product structure

According to the classification of structural transformation types in Chapter 2, the whole active structure transformation process can be regarded as multiple shape-shifting, which is the combined effect of all active parts' deformation. This synthesis process can be decomposed into the deformation of each active part and the rearrangement and combination of the active/inert parts' assembly relationships. The multiple material tessellations and material structure distribution result in different shape-shifting, as shown in Figure. 29. Therefore, the active transformable structure design can be decomposed into each active part's structural design, including the geometric profile design and material distribution.

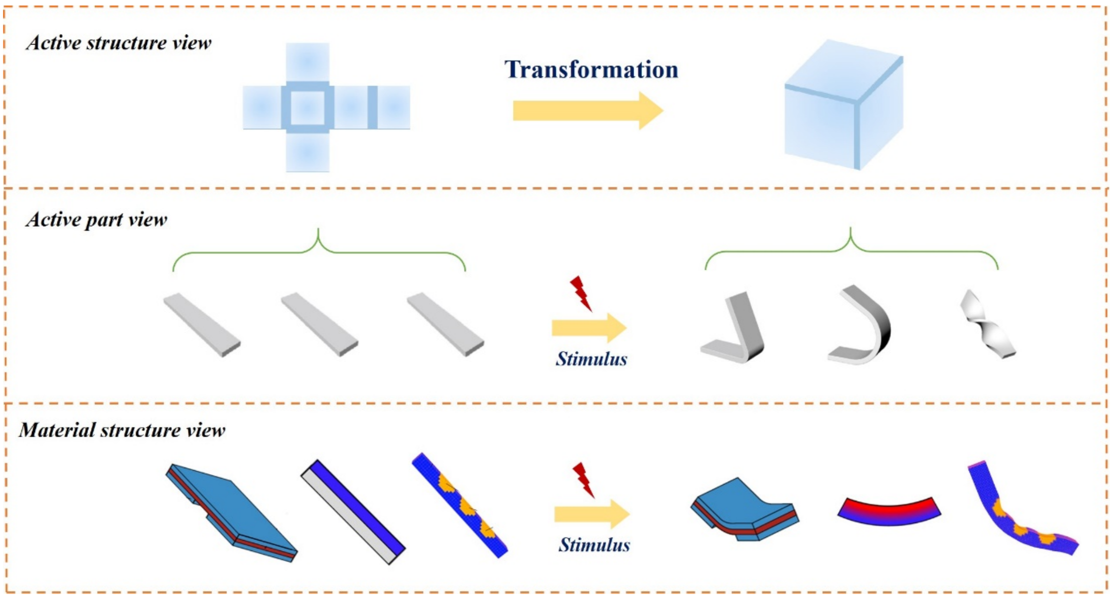


Figure. 29 Top-down analysis of active structure transformation

The top-down hierarchical design concept can be understood macroscopically as deconstructing an actual object layer by layer until the overall structure is decomposed into the smallest manufacturing parts. In this chapter, the transformable structure is designed in a top-down manner through the overall active structure, crease pattern, actuator and hinge levels. The abstract schematic diagram is shown in Figure. 30. As for 4D printing, these four levels represent different functional specifications and design steps, as shown in Figure. 30. The active hinge is defined as the smallest unit that specifically realizes the entire structure's deformation, so the design of the entire transformable structure can be disassembled into the design of each specific hinge.

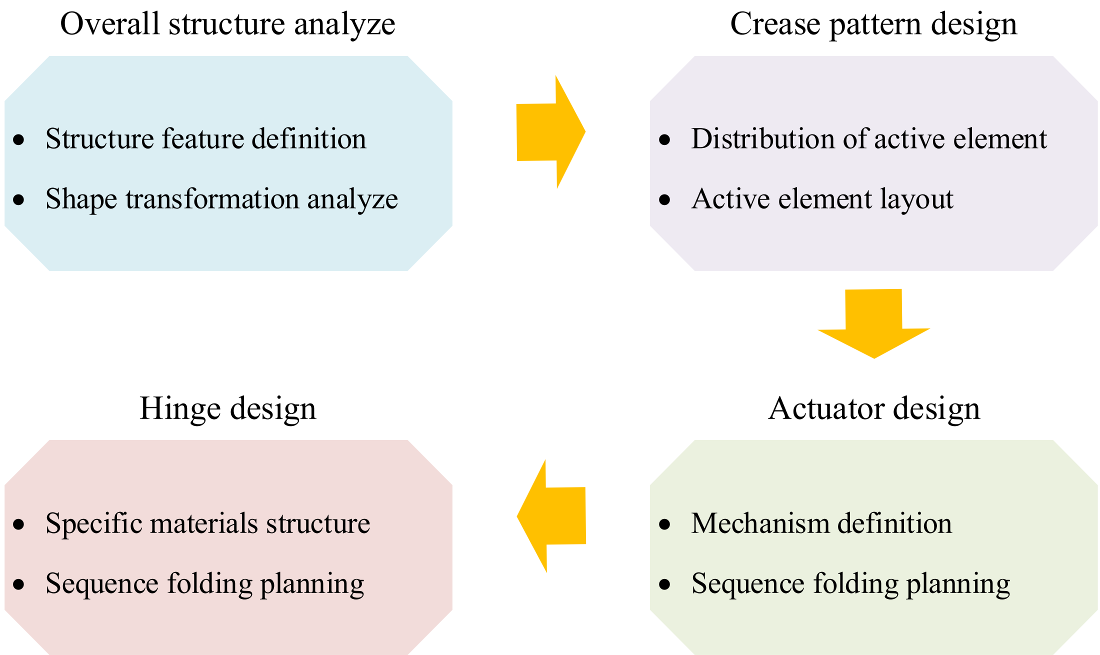


Figure. 30 Top-down 4D printing oriented design process

3. Function-structure-parameter design model

Yu-liang and Wei [152], proposed that the top-down design process of the active structure based on their desired function physical structure, is shown in Figure. 31. In this model, the functions set and their energy, material and signal flows of the product can be first collected according to the customers' requirements, which can be represented by $G_F = (F, D)$; here $F = \{F_1, F_2, \ldots, F_n\}$, D is energy, material and signal flows among these functions. Each F_i can be further divided into a set of sub-functions and sub-flows. When the overall functions and requirements of the structure are zigzag decomposed, physical structures are also be decomposed into a set of sub-structure and has a set of parameters whose values need to be set. These parameters are a set of intervals that values of parameters can range. Each parameter can have one or several variation intervals, when structure are determined level by level; these intervals become smaller and smaller.

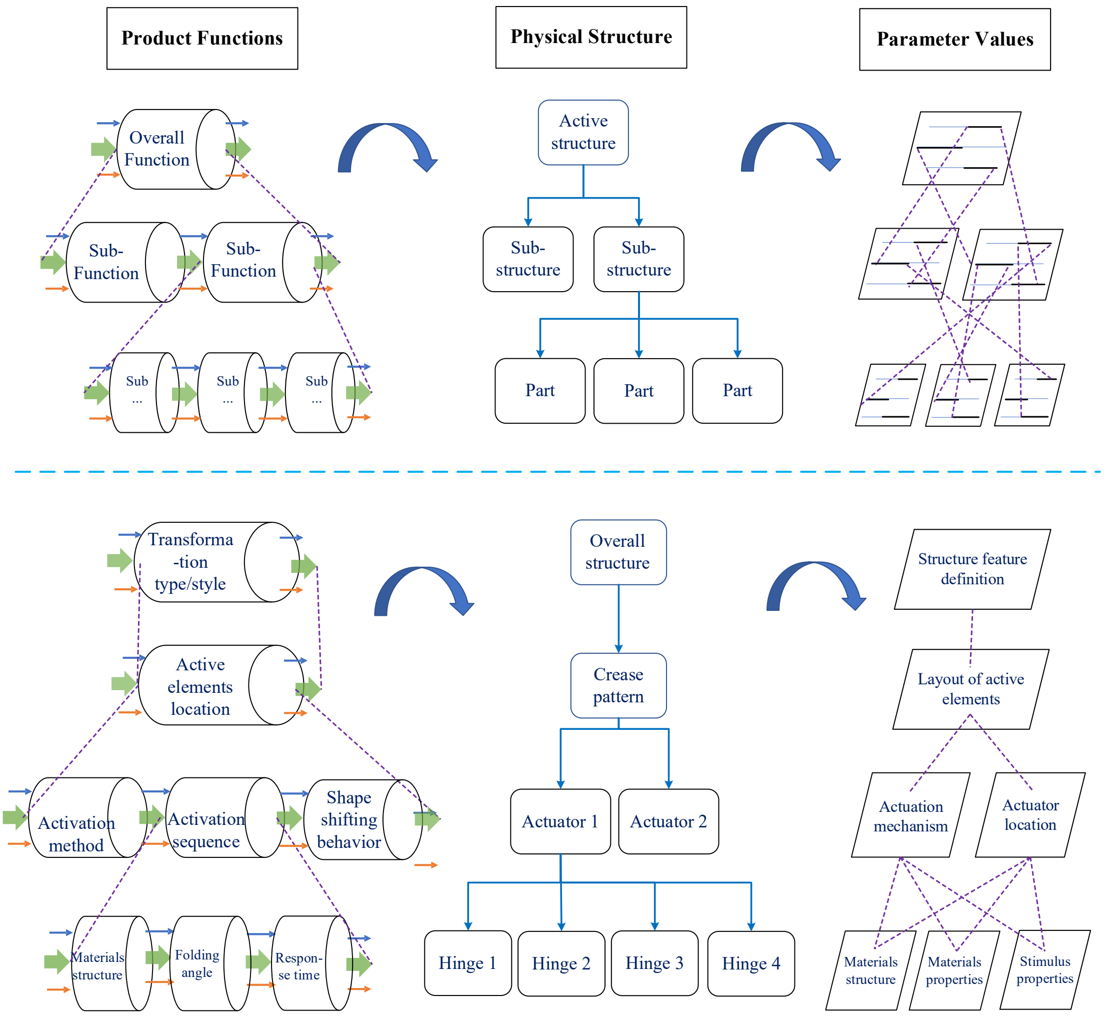


Figure. 31 Product function, physical topologies and parameter values analysis of active structure

We transferred this concept to 4D printing and proposed a 4D printing oriented design framework based on function-structure-parameter integration, as shown in the lower figure of Figure. 31. This model based on product function and physical structure decomposes the top-down product design process into overall structure analyze tasks, crease pattern design tasks, actuator design tasks, hinge design tasks, and their design parameters and dependencies. That is, the physical structure can be correspondingly designed by refining the product function, the value of the variable can be confirmed, and the final design plan can be determined.

The most fundamental function or requirement is to achieve structural transformation. At the overall structure view, the specific structural transformation type requirements need to be analyzed first, such as 1D-1D linear transformation or 2D-3D space structural transformation. Whether it is a stretch-contraction change or a deployable change, even the deployable type can also be divided into linear and central deployment. This level aims to find the changed and unchanging places during the two states before and after the structural transformation, which corresponds to the active element and the inert element, respectively. The active element is regarded as the feature of the structure (corresponding to the origami structure, the feature quantity is mountains, valleys, vertices, and other information), and then use 4D printing to realize the change of these features. The functions can be further subdivided into the requirements for the placement of these active elements to realize structural transformation. At the crease pattern design level, the concept of origami can be used to obtain the feature information's position through the decomposition and unfolding, that is, to find the specific position distribution of the active element and the inert element. Continuing to refine the requirements and clarify where the active elements are laid out, actuation (folding) sequence planning, and actuation method are also important. Therefore, it is necessary to determine the stimulus, material, interaction mechanism and distribute the different actuators in different positions according to different actuation (folding) sequences at the actuator design level. Furthermore, after planning the folding sequence, the next layer requires to ensure that the structure can be deformed in a programmed way. Therefore, to achieve the sequential folding control at the hinge design level, specific hinge types and materials structure need to be designed.

4. Systematic design process

So far, based on the analysis of the three phases of pre-processing, printing, and post-processing, the design based on origami and the objective of combining top-down design, through the integration of all the above information, we propose a systematic 4D printing active structure design process, as shown in Figure. 32. Through the overall structure analysis, crease pattern design, actuator design, and hinge design, it is possible to realize the output "complete printing strategy," which including each hinge's geometric configuration, material distribution, and printing parameters, etc. from the input "design requirements/concepts". The specific steps of each level will be explained and illustrated in detail in the next chapter.

5. Conclusion

In this chapter, we first clarify the requirements for the systematic 4D printing oriented design process and then analyze the design perspective of 4D printing based on the related concepts of AM and origami-based design. Next, by reviewing and dividing the 4D printing research into the different abstraction levels, the problem's specific design issues were defined, the concept of top-down design was put forward, and the trinity framework of "function-structure-parameter" was established. According to the characteristics of 4D printing, each abstraction level of this strategy is analyzed. Finally, a systematic 4D printing design process is proposed, which comprehensively covers the problems and steps that need to be solved in the 4D printing oriented design process and provides guidance for new product development using 4D printing. The detailed steps and methods of the overall structure analysis, crease pattern design, drive design, and hinge design will be addressed in the following chapters.

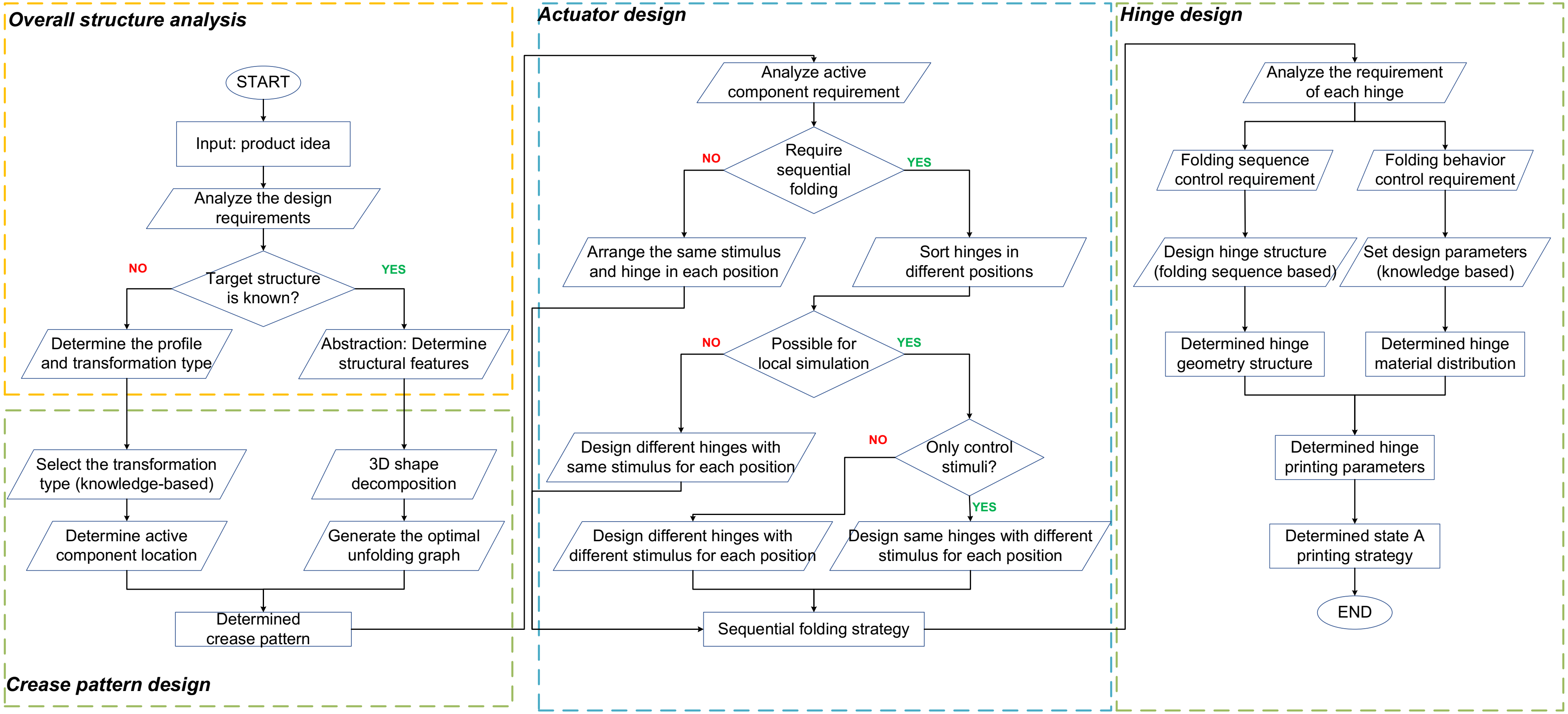


Figure. 32 The systematic design process for 4D printing

Chapter 4. Design method for 4D printing active structure

Unlike 3D printing, 4D printing encodes the stimulus-response to be triggered after manufacturing [153]. This feature is that the printed structure has the potential and possibility to respond to the stimulus to produce the desired deformation. It means that the pre-printed CAD model and the corresponding G-code have already contained the structure and material information to meet the requirements for responding to the stimulus in the post-process. At present, the major design space related to 4D printing is concentrated on the sheet-like surface through the exploration of new mechanisms [154], new materials [155], and new technologies [156] to achieve local shape changes. At the same time, few studies start from the perspective of the overall structure arrangement. The overall structure programming can be realized through the design and layout of "active hinges" in different positions. Based on the systematic design process proposed in chapter 3, this chapter starts with "overall structure analysis," through "crease pattern design," "actuator design," and "hinge design," to decompose the complex structure transformation problem in 4D printing into the most basic hinge design and layout problem in details.

1. Introduction

The so-called "top-down design method" is a design driven by functional requirements. Starting from the initial idea, each abstraction level has its own "task" that needs to be met, and at the same time, it puts forward the sub-design requirements for the next level. Correspondingly designing each level, so as to arrive at the final complete design plan. At the overall structure, the transformation from state A to state B can be regarded as the combined effect of multiple shape-shifting at different positions. Therefore, in the design process, the concept "3D-2D-3D "can be used for decomposing the complex space multiple shape-shifting to the planar level, and designs at the level of the crease pattern. The 2D origami precursor with multiple shape-shifting can be regarded as the combined effect of actuators' sequential trigger action in different positions. Therefore, it is crucial to plan the actuation sequence at the actuator design and clarify each hinge's specific objective, like the folding angle and the trigger time.

The process will go through the following steps. First, analyze the overall structure, find/search the entire structure's feature elements, and clarify the change part and the unchanged part in the structural transformation process. Secondly, according to the known feature elements, the two-dimensional intermediate state can be obtained through decomposition and unfolding steps to simplify the design and manufacturing. Furthermore, the origami-based design method (thick panel/ rigid origami, etc.) can be used to transform these crease patterns into hinge models suitable for engineering origami. Then, assigning the active elements and inert elements to the places that need or do not need to be deformed separately to obtain a 2D origami precursor. After determining which positions on the plane structure to layout the active elements (hinge), it is necessary to clarify the folding sequence and how to trigger each active hinge. Therefore, the next level will determine the specific folding sequence planning and interaction mechanism through the specific actuator design. Next, to achieve a planned folding sequence, a specific hinge structure (including the geometric structure and material structure) can be designed to achieve precise folding control. Finally, the final printed structure (in state A) will be achieved through specific printing strategies.

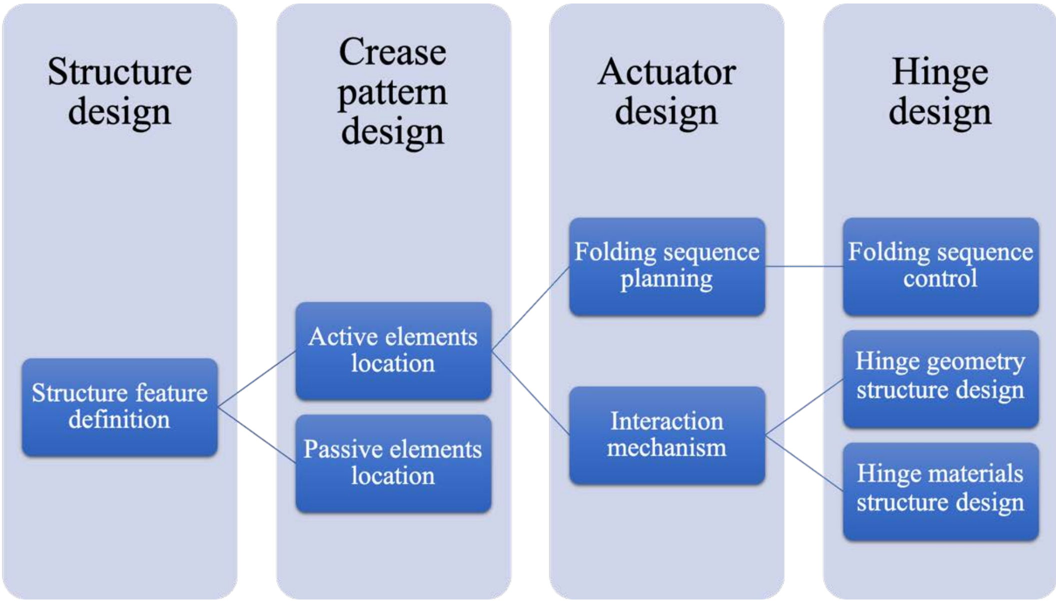


Figure. 33 Design tasks and objectives for different abstraction levels

2. Structure design

In practical applications, the reasons why researchers use 4D printing can be mostly divided into two situations. One is that the target shape is not easy to manufacture. It is necessary to obtain a transition structure that is easy to print and then transfer it to the final structure, such as a hollow structure. Another situation is that two different states/structures are needed to adapt to different environments/conditions, such as deployable structures and reconfigurable structures. Both of these two situations need to clarify the transformation type of the first state and the second state. Since our objective is to design the first state as the intermediate state to obtain the second state (target state), it is important to determine the active part which plays the changing role in the structural transformation process. Therefore, the first level of the entire design process is the overall structure analysis.

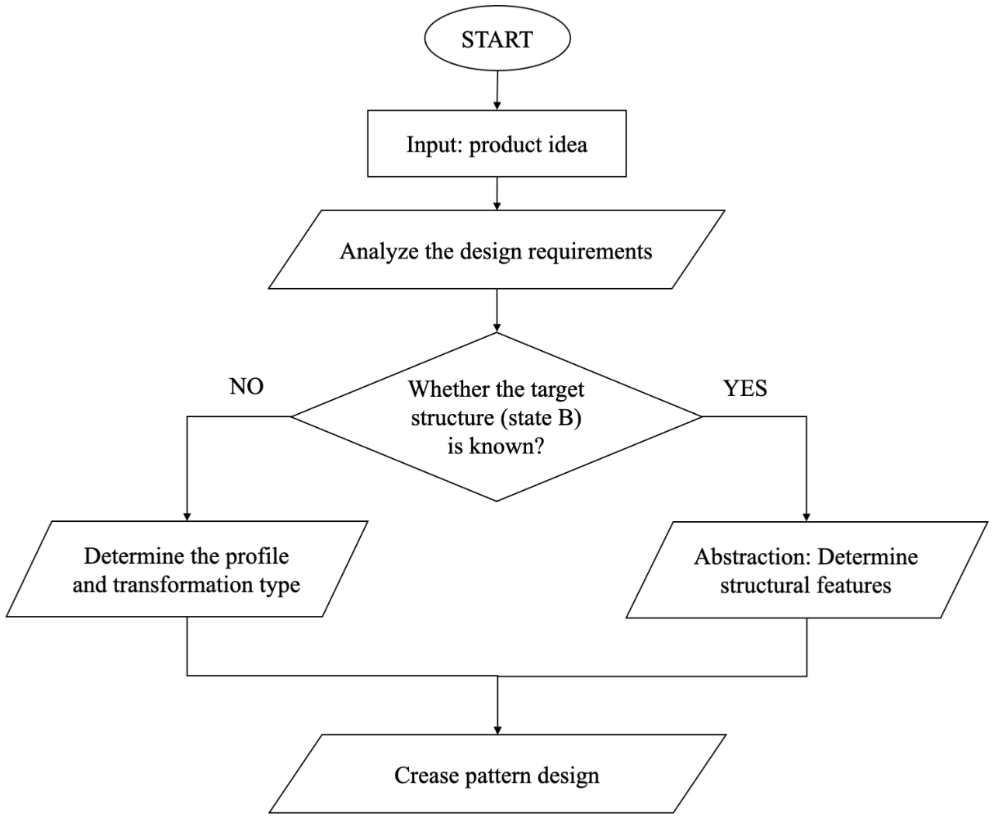


Figure. 34 Design steps of "overall structure analysis"

2.1. Structural transformation type analysis

The analysis of structural transformation types can be divided into two cases. In the first situation, the two states A and B (before and after transformation) are unknown, and the transformation type needs to be matched and designed according to the design target and requirements. As shown in Figure. 35, we have summarized several primary plane structural transformation types. The graphics with red vertices can be regarded as state A before the transformation, and the graphics with blue vertices can be considered state B after transformation. In the description of the structural transformation process, only the vertices and edges are retained as the characteristic/feature elements of the entire structure, which are used to describe and refer to the entire structure, thus simplifying the complicated design steps. Designers can then select or combine these types to design structures according to specific requirements. In the other case, both states A and B, and their specific transformation methods are known, such as deform, fold, deploy, retract, slide, revolve, etc. As shown in Figure. 36, Stevenson [157]. summarizes the common types of morphological aspects and transformation strategies in kinetic architectural structures. In this case, both states are already specified, so in this case, it is easy to find the active element which is responsible for the specific structural change.

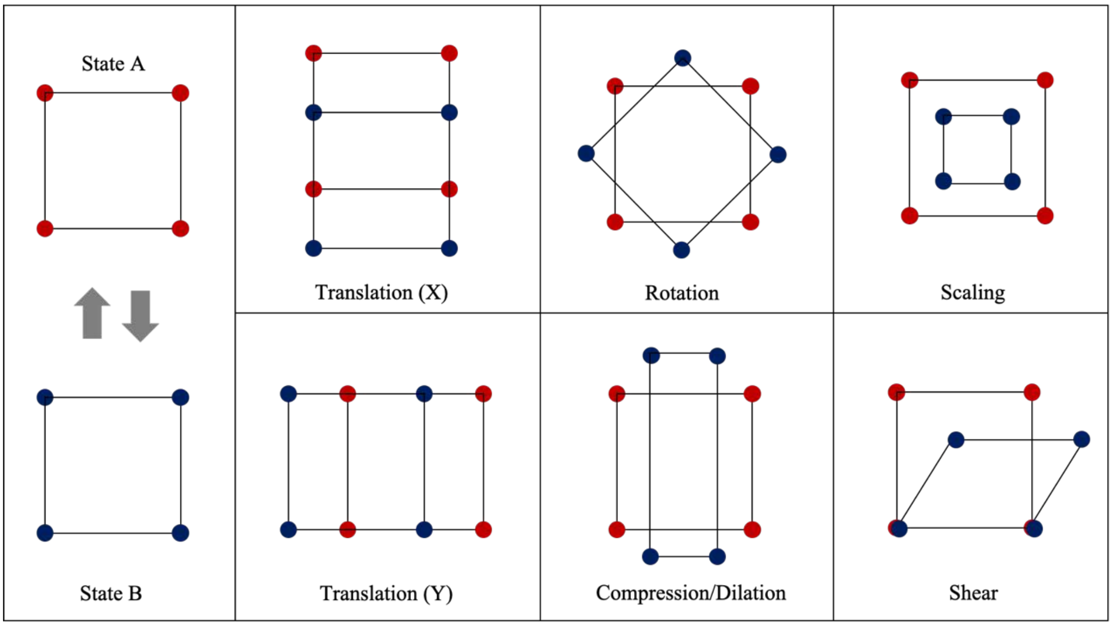


Figure. 35 Primary plane structural transformation types

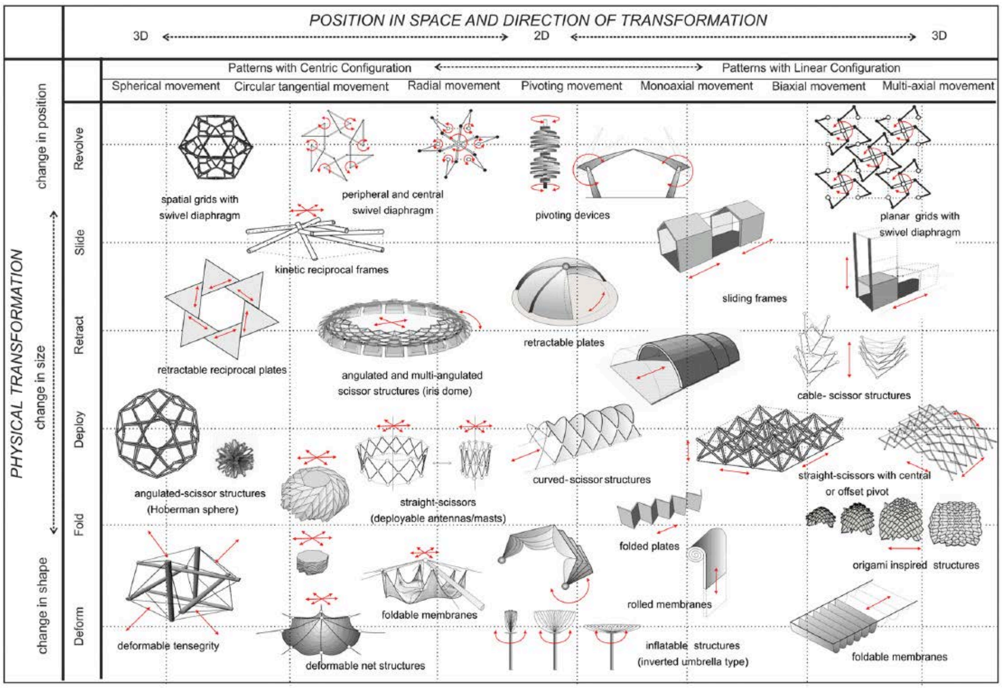


Figure. 36 Morphological aspects and transformation strategies in kinetic architectural structures [157].

2.2. Mesh 3D model and structure feature definition

Since not all target structures have precise edges to be considered mountains or valleys, the structures with smooth surfaces need to be meshed first, thus giving a vision of the possible cutting lines. Although this meshing step can be implemented by existing computer-aided design (CAD) systems easily, it should be noted that this will produce numerous extra line information as shown in Figure. 37. In order to solve this problem, it is important to find feature and characteristic information during the folding transformation process to distinguish the intermediate folds and redundant lines. The feature and characteristic elements of origami include crease pattern, vertex, degree of the vertex and folded state [158]. The skeleton of the topology optimization result can be extracted to ensure shape preservation, and a filtering method can be used to ensure characteristics preservation [159]. According to this information, it is possible to build the corresponding 3D meshed structure by removing the irrelevant lines, leaving only the Mountain-Valley related lines that can reflect the characteristics of origami. 3D mesh model called M can be defined as a graph $G(M) = (V, E)$, where V is the set of vertices and E the set of edges. As illustrated in Figure. 37, the feature elements are represented by the straight blue lines.

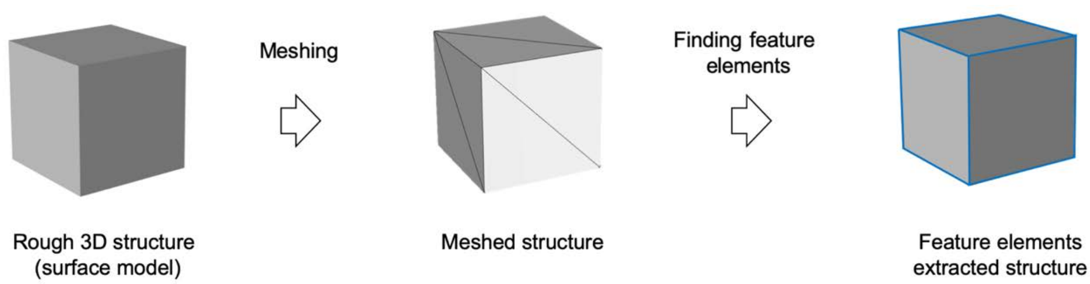


Figure. 37 Example of a rough 3D hollow structure with its related mesh representation composed of edges and surfaces, and the selected feature elements for 3D shape decomposition

3. Decomposing and unfolding: Crease pattern design

The crease pattern is a proper term from origami technology, a crease pattern is basically an origami model that has been unfolded and shows all the creases on the original flat piece of paper. Because it contains information about the valley and mountain folds, crease patterns can be used as a quick and easy way to record how to fold an origami model. A flow diagram is presented in Figure. 38 to explain how to determine the crease pattern of state A.

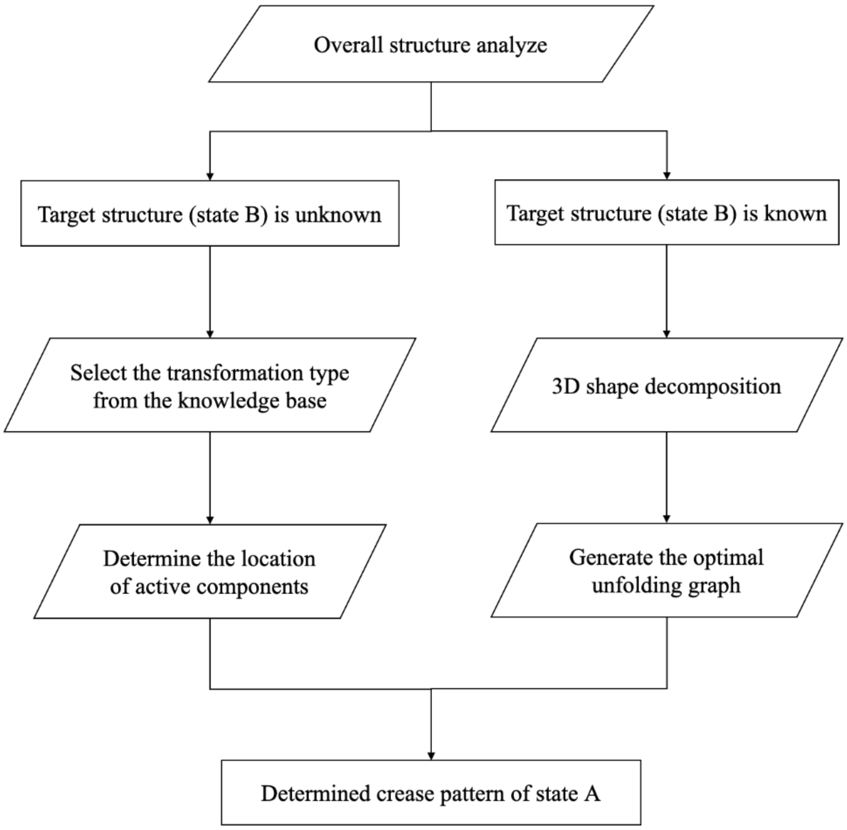


Figure. 38 Procedures to determine crease pattern of state A

3.1 3D shape decomposition

As part of the embodiment design stage, the initial step consists of decomposing a rough 3D model of the hollow structure. To do so, there are currently many ways to fold a 2D pattern to obtain a corresponding 3D shape [160] like tree methods [161]. However, there are few ways to decompose a 3D object into a corresponding 2D origami pattern. This stage aims at extracting the feature of prescribed target 3D shapes by generating 2D projections or nets.

Folding a 3D object requires knowing the original 2D plane and the necessary creases to obtain the desired form without ineffective overlap. Contrarily, unfolding a 3D object requires cutting them along the edges or the creases and then flatten them to a 2D plane [160]. Although cuts can be made anywhere on the 3D structure's surface, it is needed to retain each surface complete of the structure as much as possible.

In order to decompose the 3D mesh M to obtain its corresponding unfolding graph, the dual graph $D(M) = (V_d, E_d)$ of the mesh M is introduced. The latter is used with the Prim's algorithm [162] so as to find the minimum spanning tree. It is worth noting that, without considering the subsequent folding sequence, it is not possible to determine the weighted value distribution of the algorithm, so they are all set to the same value. This leads to different results which can be represented as spanning path P_n, where n represents the nth spanning tree. Then by cutting all edges that have no dual in the spanning tree of $D(M)$, M can be unfold into the alternative unfolding graph $U(M)_n = (V_u, E_u)$, where V_u ={vertices of $U(M)$}, E_u={edges of $U(M)$)} and *n* stands for the *n*th unfolding graph type. The proposed fold-and-cut algorithm is described below.

Algorithm 1: Determine origami Fold-and-cut tessellation

Input: Meshed structure graph $G(M) = (V, E)$
Output: Alternative unfolding graph $U(M)_n$

for 3D mesh $G(M)$, generate $D(M)$.

1. Priority_Queue minQ={all vertices in $D(M)$};
   for each vertex $u \in$ minQ
   u. key =∞;
   u. predecessor = NIL;
   Randomly select a vertex r in $D(M)$ as root;
   r. key =0;
   r. predecessor = NIL;
   while (min Q≠ ∅) **do**
      vertex u = ExtractMin (minQ) ;
      for (each vertex v such that (u,v) $\in E$) **do**
         if ($v \in minQ$ and $w(u, v) < v$.key) **do**
            v.predecessor = u;
            v.key = $w(u, v)$;
         end if
      end for
   end while
2. Cutting all edges that have no dual in the spanning tree, generate the unfolding graph $U(M)_n$.

end for

By applying such an algorithm, it is then possible to determine corresponding unfolding graphs to any 3D meshed structures. As an illustration case, Figure. 39 presents a meshed 3D cube, on which the proposed algorithm has been applied, therefore showing the dual graph and spanning tree with 3D representation to get the unfolding tree.

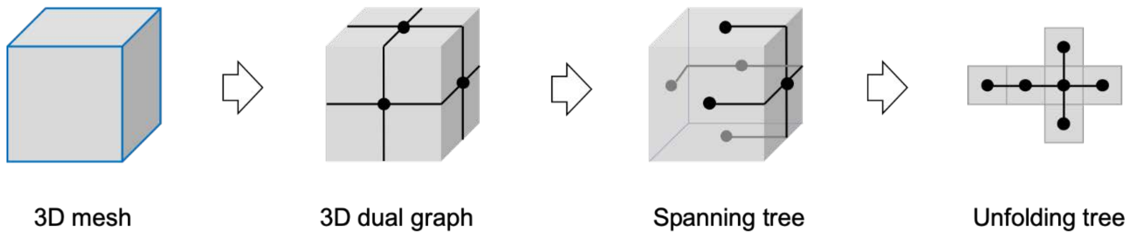


Figure. 39 Example of 3D mesh cube with its dual graph, one admissible spanning tree and corresponding unfolding tree

3.2 2D origami precursor design

The objective of this part is to provide requirements and guidance to define hinges geometry. Since the unfolding graphs are already available in the previous step, here two parallels steps are processed to achieve the final goal. On the one hand, the two-dimensional thickness panels are defined from the unfolding tree to adapt to the specific AM process and technique. On the other hand, the best layout of the alternative unfolded trees and their folding sequence are computed. Such information is crucial for ensuring the hinge design step. The spanning tree only provides the topological layout of the 2D origami precursor. To achieve subsequent operations, all faces of the unfolding tree have to be transformed into panels with a specific defined thickness, leaving room for later hinge design steps.

By applying Prim's algorithm on a given 3D mesh structure, several spanning trees and related unfolding trees can be obtained. In order to define the folding sequence of the 3D hollow structure, it is needed to firstly select one optimal topological layout. For n possible unfolding trees, an algorithm is proposed to search the possible spanning trees, and then compare them to select the best one according to specific criteria. To do so, two objectives have been defined: (1) minimize the number of hinge types and (2) minimize the total sum of torques required to activate the hinges. The latter is important in order to reduce smart materials consumption and/or stimulus intensity.

In order to define the folding sequence from an unfolding tree, the first step consists in identifying the base (reference) face, which refers to the fixed element of the folding structure during actuation phase. The determination of the reference face should be done accordingly with the aforementioned criteria. More the reference face will be far from the center of the unfolding tree, more the needed torques will be important. This means that the identification of the reference face is closely related the search of the unfolding tree center. The center of the tree actually can be considered as a vertex with minimal eccentricity. For an unfolding tree $U(M)_n = (V_u, E_u)$ where V_u = {vertices of M} and E_u = {edges of M)} and n represents the nth unfolding tree type, its corresponding tree is $T(M) = (V_t, E_t)$. To find center or bi-centers of this tree $T(M)$, let denote an endvertex u in the tree $T(M)$ is a vertex of degree one, a vertex v adjacent to an endvertex u is called a remote vertex. A pendant edge (u, v) is an edge between an endvertex u and a remove vertex v [162]. First, remove all the vertices of degree 1 from the given tree and also remove their incident edges. Then repeat the first step until either a single vertex or two vertices joined by an edge is left. If a single vertex i is left, then it is the center of the tree and if two vertices joined by an edge is left then it is the bi-centers of the tree [163]. Here the center of this tree represents the reference face R_i of $U(M)_n$, the vertex in which can be regarded as the start vertex of the spanning tree. The vertices on the face sharing the edges with the reference face of the unfolding tree are called the first type vertices, and the vertices on the face sharing the edges with the first type vertices face are called the second type vertices, and so on, until all the vertices on the faces of $U(M)_n$ are covered, and the vertices farthest from the starting vertex is called the j_{th}-type vertices. Using the vertex of the reference face R as the starting point, the folding sequence can be generated by the corresponding spanning tree.

At this time, the folding paths for different reference faces R_i of the unfolding tree $U(M)_n$ have been determined. In order to select the most optimal one for the 4D printing steps (i.e. stimulation and actuation steps), the torque required for each case need to be calculated. Torque means "turning effect", which is the product of the magnitude of the force and the perpendicular distance of the line of action of force from the axis of rotation. Here, the torque $\boldsymbol{\tau}$ of each hinge depends on the mass of the linked panels to overcome and the distance from the center of gravity to the hinge (see Equation 1).

$$\boldsymbol{\tau} = \boldsymbol{r} \times \boldsymbol{F} \quad (1)$$

Where $\boldsymbol{r}$ is the particle's position vector relative to the fulcrum, and $\boldsymbol{F}$ is the force acting on the particle. The magnitude τ of the torque is given by

$$\tau = rFsin\theta \quad (2)$$

Where r represents the distance from the axis of rotation to the particle here is the distance from the center of gravity of each panel to the crease, F is the magnitude of the force applied, here $F = G = mg$ where m is the mass of the panel and g is the local acceleration of free fall, and θ is the angle between the position and force vectors, as shown in Figure. 40. Assuming that the change of θ can be ignored during the entire folding process, such as defined as follows:

$$\tau_0 = r \times mg \quad (3)$$

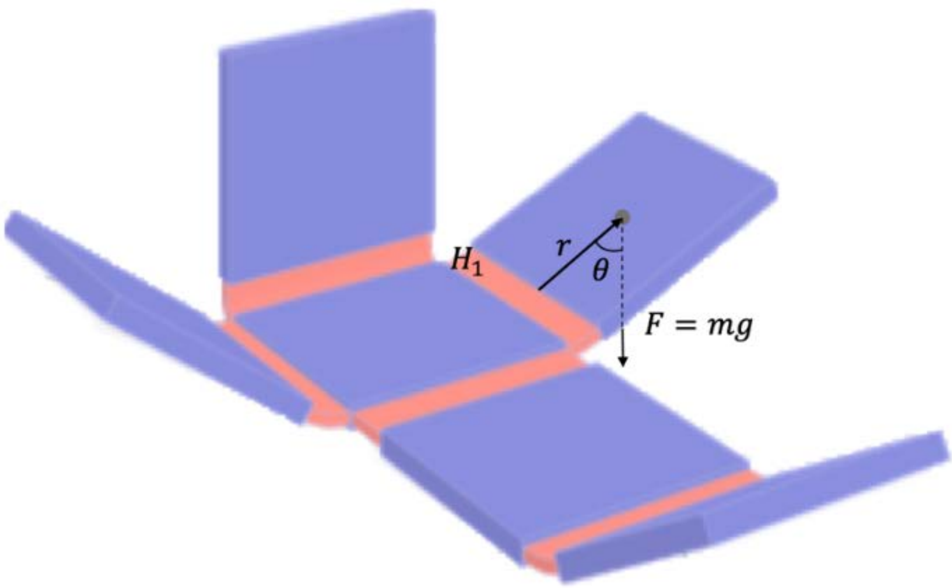


Figure. 40 Diagram of the relationship between torque τ, force F, position vector relative to the fulcrum r, and angle between the position and force vectors θ for the hinge H_1.

The sum of the required torque τ_i corresponding to each unfolding tree $U(M)_n$ with the reference face R_i is:

$$\tau_i = \tau_{i1} + \tau_{i2} + \tau_{i3} + \tau_{i4} + \cdots \tau_{ij} \tag{4}$$

Where τ_{ij} refers to the required torque at the j_{th} crease of the unfolding tree $U(M)_n$ with the reference face R_i, and the total torque is positively related to the quality of the panel to be folded. Here we propose the relationship between the total sum of the torques of the different reference face and the number vertices.

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \cdots \\ \tau_i \end{bmatrix}_{i\times 1} = \begin{bmatrix} N_{11} & N_{12} & N_{13} & \cdots & N_{1j} \\ N_{21} & N_{22} & N_{23} & \cdots & N_{2j} \\ N_{31} & N_{32} & N_{33} & \cdots & N_{3j} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ N_{i1} & N_{i2} & N_{i3} & \cdots & N_{ij} \end{bmatrix}_{i\times j} \times \begin{bmatrix} 1 \\ 2 \\ 3 \\ \cdots \\ j \end{bmatrix}_{j\times 1} \times \tau_0 \tag{5}$$

Where i refers to the face number of the unfolding graph, and τ_i refers to the torque of the reference face R_i. And j means there are j unit paths from here to the reference face, namely the j_{th} types of nodes mentioned in the previous part. And N_{ij} refers the total number of j types of nodes when taking i as the reference face.

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{bmatrix} = \begin{bmatrix} 1 & 3 & 1 \\ 1 & 3 & 1 \\ 2 & 3 & 0 \\ 1 & 3 & 1 \\ 4 & 1 & 0 \\ 1 & 1 & 3 \end{bmatrix} \times \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \times \tau_0 = \begin{bmatrix} 10 \\ 10 \\ 8 \\ 10 \\ 6 \\ 12 \end{bmatrix} \times \tau_0 \tag{6}$$

After obtaining the minimum torque and type through the best reference face of each unfolding tree related to each generated spanning tree in the previous step, the objective is to compare admissible solutions by considering the two aforementioned criteria. To do so, weighted equation is used to evaluate the optimal solution of the unfolded tree, so as to obtain the minimum spanning tree. The optimal unfolding tree here is the one with the smallest torque τ and the smallest number of node type j. To achieve this goal, the proposed algorithm is described below.

Algorithm 2: Generate folding sequence

Input: Alternative unfolding graph $U(M)_n$
Output: Optimal unfolding tree

1. Find the reference face of the unfolding tree $U(M)_n = (V_u, E_u)$
   for Tree $T(M) = (V_t, E_t)$ corresponding unfolding tree $U(M)_n$
      Endvertex u = endvertex of T
      Remove vertex v = adjacent vertex to endvertex u
      pendant edge (u, v) = an edge between u, v
      for (Endvertex u);
         degree $[u]$ = 1
         if degree $[i]$ == 1;
            remove vertex i and remove incident edge
         while only one or two vertices left;
         end if
      end for
   end for
   the left one or two vertices i corresponding the reference face R_i, the vertex in which can be regarded as the start node of the spanning tree, and then number the vertex in sequence until the j_{th}-type vertex.
2. Calculate the torque between each adjacent vertex with the Breadth First Search algorithm, let $\tau_i = \tau_{i1} + \tau_{i2} + \tau_{i3} + \tau_{i4} + \cdots \tau_{ij}$.
3. Compare all the τ_i to get the minimum value and search the minimum value of j to determine the best reference surface R_i of $U(M)_n$.
4. Calculate all the torque of unfolding trees with best reference face, compare the T and j to get the optimal unfolding tree.
5. For random unfolding tree $U(M)$, the first folding sequence occurs between the reference face and the first type vertex, the second folding sequence occurs between the first type vertex and the second type vertex, and so on until the j_{th}-type vertex.

With this second algorithm, the optimal unfolding tree and its folding sequence can be set up. To illustrate its applicability, Table. 4 presents, for a given unfolding tree of a cube, the required torques and the types of nodes are different according to the position of the reference face R. From this table, defining the 5th face as the reference seems to be the best choice. Then the folding sequence can be generated as first folding the face where the first type of vertex is located, and then folding the face where the second type of vertex is located in the same time. After selecting the optimal reference face for each unfolding tree $U(M)_n$, the next step is to compare them so as to select the optimal unfolding tree, as shown in Table. 5. So far, the two objective functions defined in the previous section can all get their specific values.

The final optimal spanning tree can be determined by considering different requirements or objectives, here the two objective functions – denoted $f_1(x)$ and $f_2(x)$ as described in equations 7 and 8 – aims to (1) minimize the number of hinge types, and (2) minimize the total sum of torques required for hinges actuation. In order to make optimal decisions in the presence of trade-offs between two or more conflicting objectives, like involving these two objectives into a comprehensive indicator to determine the final spanning tree, a multi-objective optimization has been introduced.

$$f_1(x) = minimize\ j \tag{7}$$

$$f_2(x) = minimize\ \tau \tag{8}$$

To transform a multi-objective optimization problem into a single objective, we can often use the method of weighted sum [164]. So the object function minimize $F(x)$ is described below:

$$Minimize\ F(x) = \{f_1(x), f_2(x)\} \tag{9}$$

$$\text{Subject to } x \in X$$

Where x is the unfolding tree, $f_1(x), f_2(x)$ and X is the feasible set of decision vectors. Since these two objective functions are non-homogeneous, a normalization method is used to transform the dimensional quantity into a dimensionless quantity. If the population mean and population standard deviation are known, a raw score $f_1(x)$ is converted into a standard score by:

$$Z_1(x) = \frac{f_1(x) - \mu_1}{\sigma_1} \tag{10}$$

And a raw score $f_2(x)$ is converted into the standard score by:

$$Z_2(x) = \frac{f_2(x) - \mu_2}{\sigma_2} \tag{11}$$

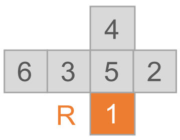
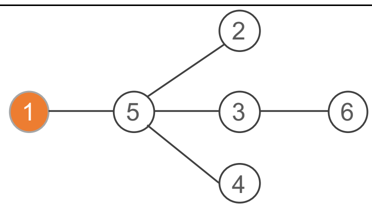
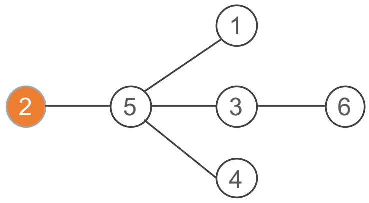
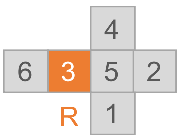
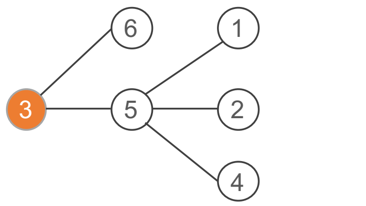
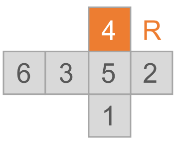
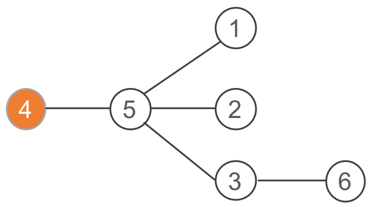
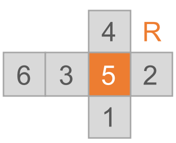
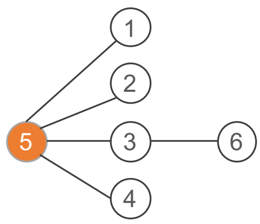
Where μ is the mean of the population and σ is the standard deviation of the population. Then $Z_1(x)$ and $Z_2(x)$ have no physical dimension right now. Scalarize a set of objectives into a single objective by adding each objective pre-multiplied by a user-supplied weight. Weight is a relative concept, which represents the importance of the object being evaluated, different weights can be quantitatively assigned to different objective functions. The weighted sum S is defined as follows:

$$S = \sum Z(x)w(x) \tag{12}$$

Where $w(x)$ is the weight function and $\sum w(x) = 1$. In the cube case, since these two objective functions are equally important, the weights are equally distributed at 0.5 for each of them. If there are other factors and considerations, the weight function can be adjusted at any time. Then the equation (9) can be transformed into:

$$Minimize\ F(x) = \sum Z(x)w(x) \tag{13}$$

Table. 4 Torque and node types corresponding to different reference faces

i	**Reference face**	**Folding sequence** (**R**, **1st**, **2nd**, **3rd**)	***j***	τ_i
1			3	$10\tau_0$
2			3	$10\tau_0$
3			2	$8\tau_0$
4			3	$10\tau_0$
5			2	$6\tau_0$

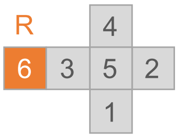
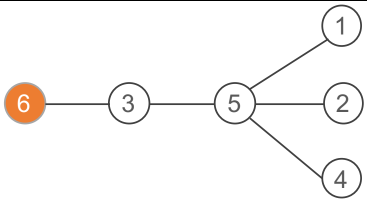
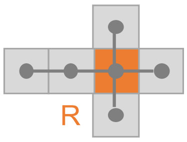
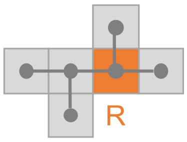
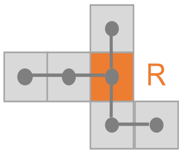
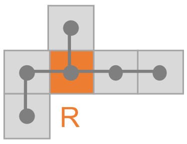
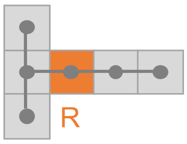
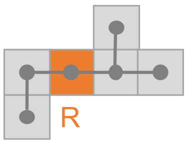
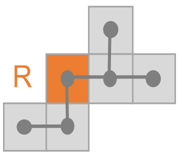
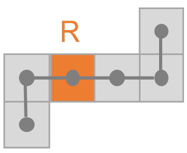
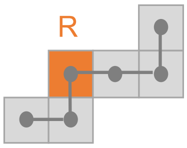
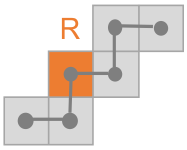
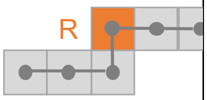
6			3	$12\tau_0$

Table. 5 Torque and node types corresponding to different unfolding graph

n	**Unfolding tree**	f_1	Z_1	w_1	f_2	Z_2	w_2	$F(x)$
1		$6\tau_0$	-1.83	0.5	2	-0.72	0.5	-2.55
2		$7\tau_0$	-0.87	0.5	2	-0.72	0.5	-1.59
3		$7\tau_0$	-0.87	0.5	2	-0.72	0.5	-1.59
4		$7\tau_0$	-0.87	0.5	2	-0.72	0.5	-1.59
5		$8\tau_0$	0.09	0.5	2	-0.72	0.5	-0.63
6		$8\tau_0$	0.09	0.5	2	-0.72	05	-0.63
7		$8\tau_0$	0.09	0.5	2	-0.72	0.5	-0.63
8		$9\tau_0$	1.04	0.5	3	1.26	0.5	2.31

9		$9\tau_0$	1.04	0.5	3	1.26	0.5	2.31
10		$9\tau_0$	1.04	0.5	3	1.26	0.5	2.31
11		$9\tau_0$	1.04	0.5	3	1.26	0.5	2.31

The symbolic example in Table. 4 shows the alternative sequences and their evaluation. For complex cases with more connected 2D panels, the number of alternative unfolding sequences may greatly increase due to the combination operation. Hence, screening method to rank alternatives may not work for costly computation, but optimization tools, e.g., combinatorial optimization algorithms, should be used.

4. Sequential folding planning: Actuator design

After obtaining the crease pattern of state A, it can be clarified where the folding behavior is required for the entire unfolded layout. To be more precise, it can be defined where the actuators are located to fulfil the folding function. Therefore, it is necessary to design/choose a suitable interaction mechanism for these active creases to meet the folding requirements at the actuator design level. Besides, in actual situations, not all actuators in each position/location have to be activated at the same time or reach the final state at the same time. For example, some self-locking devices need to be folded in different phases to prevent collisions [165]. And some devices need to respond to different states in different environments, deforming gradually instead of in one step, such as the finger devices [166]. Therefore, for the actuator design, addressing the folding sequence planning is also a significant objective. In Figure. 41, a flow diagram of proposing sequential folding strategy is shown.

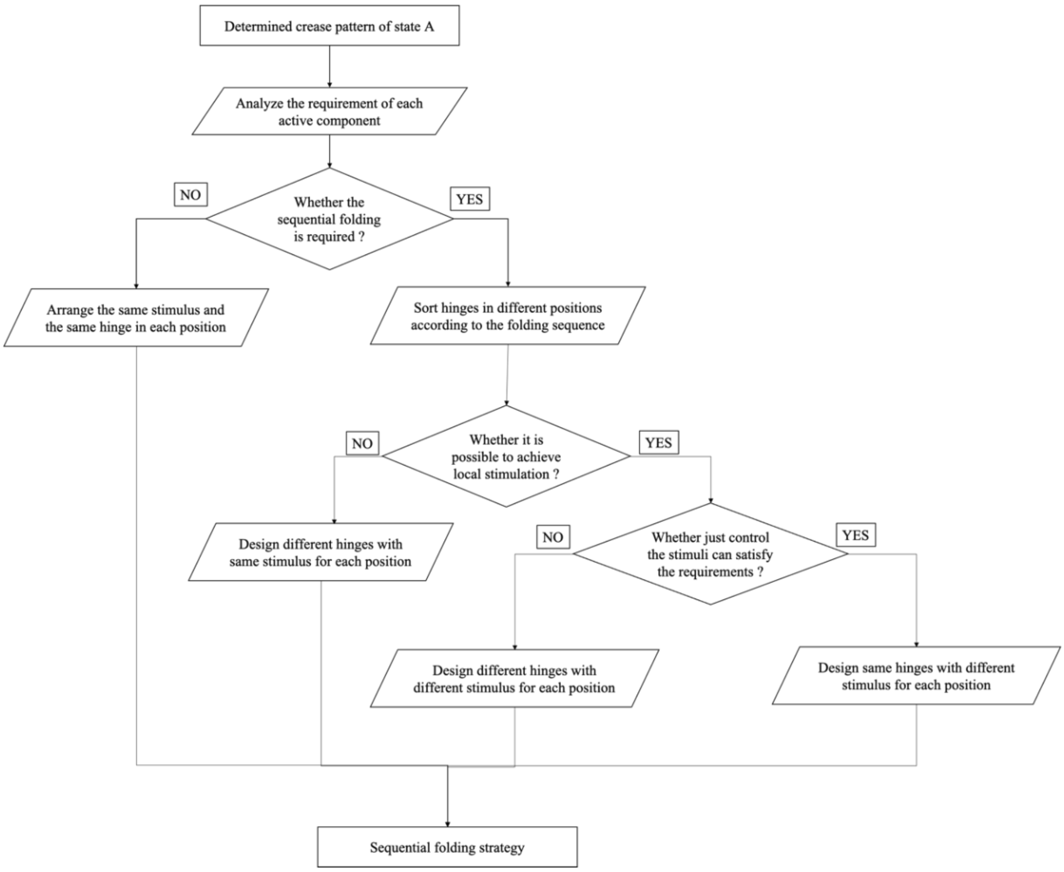


Figure. 41 Flowchart of designing sequential folding strategy

4.1 Related works on sequential folding

At present, the research on sequential folding by 4D printing has attracted more and more attention, mostly by controlling the two aspects of interaction: stimulus and hinge. According to different controls aspects, the common sequential folding method can be divided into three different types, (1) different stimuli with the same hinges, (2) same stimulus with different hinges, and (3) Different stimuli with different hinges. The following will specifically introduce the characteristics of these three types in detail and summarize the relevant research in Table. 6.

Different stimuli with same hinges

This type of sequential folding is to design the same hinge (same geometry and material type) in the different active creases' positions. Different responses can be achieved by controlling the stimulus type or the application time of different positions' hinges. For example, as shown in Figure. 42, Deng et al. [166] used the interaction mechanism of polystyrene film to be folded after the heat stimulation and through the Joule effect to control each hinge's on-current time in parallel to control the folding response of each position. The advantage of this sequential folding control type is that only one type of hinge needs to be designed. However, the disadvantage is that some stimulation types are difficult to achieve only for local applications.

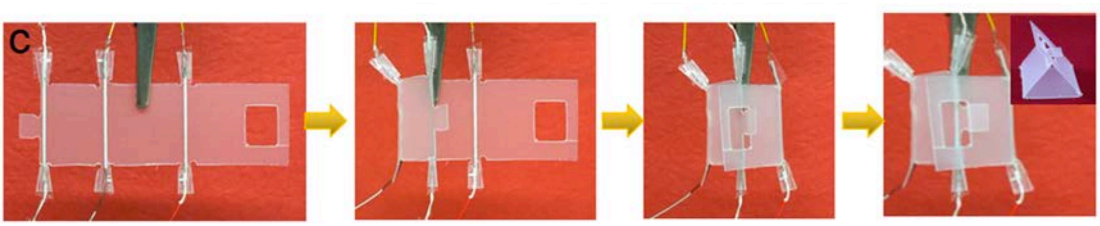


Figure. 42 Example of sequential folding by different stimuli with same hinges [166]

Same stimulus with different hinges

This type of sequential folding is to design different hinges at different positions to produce a graded response when the same stimulus is applied simultaneously. As shown in Figure. 43, the hinge can be designed into uniform hinges with different response intensity (Figure. 43 (a)) [166], the hinges with different content of smart materials (Figure. 43 (b)) [165], and hinges with different materials types (Figure. 43 (c)) [167]. The advantage of this type of design is that it can avoid the use of complex local actuation systems and can initiate sequential folding under a spatially uniform stimulation field. The disadvantage is that different hinges (structure/material) need to be designed.

Different stimuli with different hinges

This type of sequential folding is to set different stimuli and design different hinges at different positions. As shown in Figure. 44, Liu et al. [167] used the mechanism of pre-stretched polystyrene film to absorb light to produce folding. Using the feature of different colored polystyrene film absorb light of different wavelengths to control different light as different stimuli and control the coating's color on the PS board as different hinges, to achieve the sequential response of hinges at different positions. The advantages and disadvantages of this type are undeniable. By controlling the different stimuli and hinge types to control different positions' folding behavior, achieving high-order accuracy and multi-level complex sequence control is possible. Simultaneously, a very obvious shortcoming is that it is needed to design different hinges and match stimulus drives for different positions, which undoubtedly increases the workload and complexity of the design.

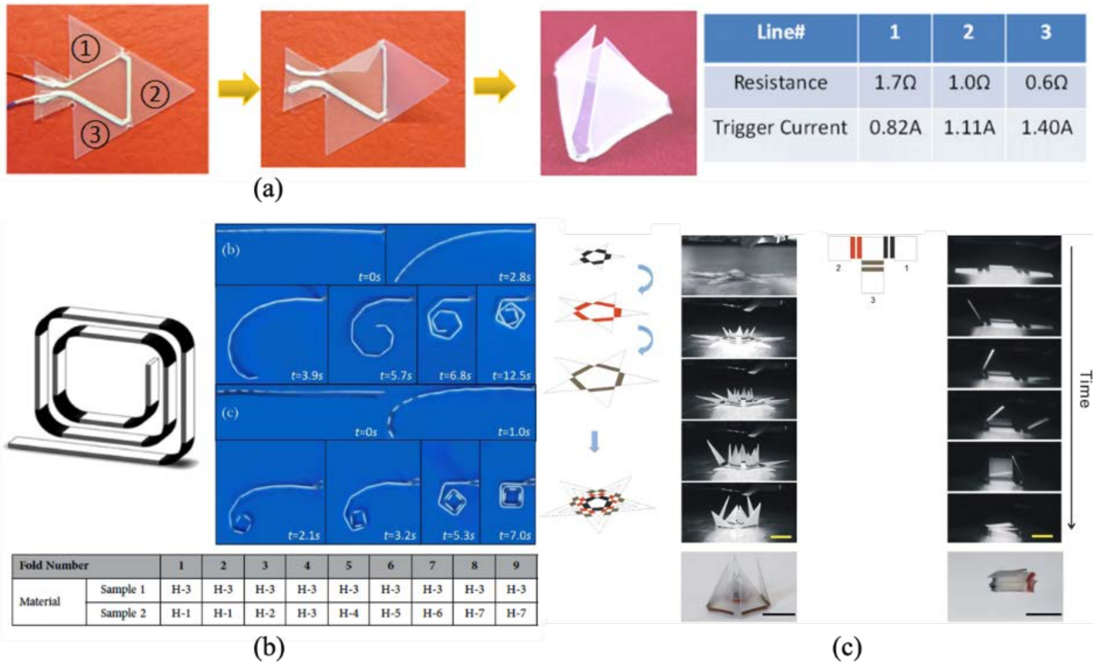


Figure. 43 Example of sequential folding by same stimulus with different hinges (a) the uniform hinges with the different response intensity [166] (b) the hinges with different materials grads [165] (c) hinges with different materials types[167]

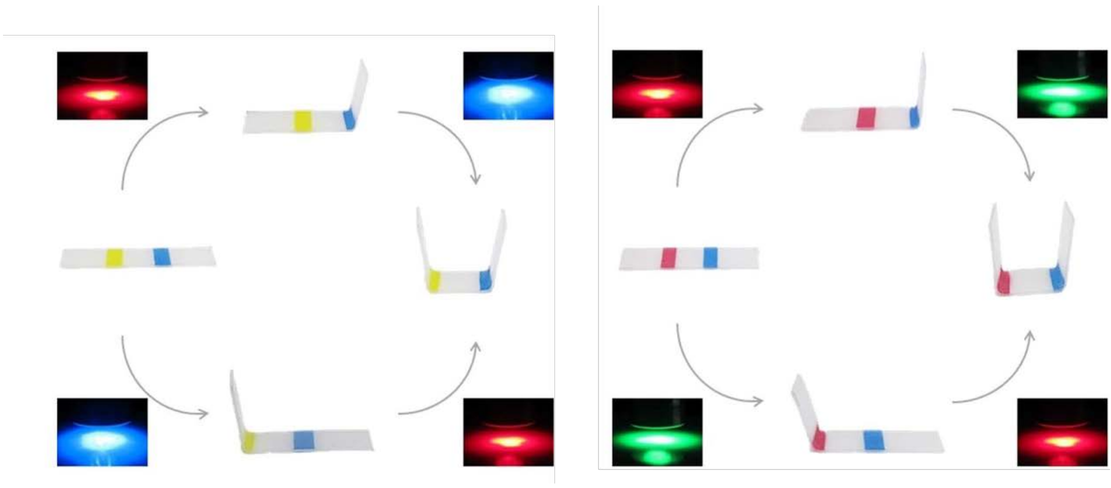


Figure. 44 Example of sequential folding by different stimuli with different hinges [167]

4.2 Sequential folding planning

The interaction mechanism needs to be determined so that the printed smart structure can respond to stimulus in an appropriate manner. As mentioned in the review section, various mechanisms have been developed to realize the 4D printing process such as hydro-mechanics [165], thermo-mechanics [167], etc., The various smart structure geometry with shape-memory materials like bi-layer structures, sandwich structures, and fiber structures. The complexity of designing and manufacturing varies among these mechanisms and corresponding active hinge geometry. The specific solution can be selected based on the specific requirements. For ensuring a folding sequence, two control mechanisms can be applied whether by using (1) different smart materials or materials with different responsivities, and/or (2) different stimuli or different stimulus intensities. Figure 45 shows the selection of the sequential folding method by different stimuli or by different hinges.

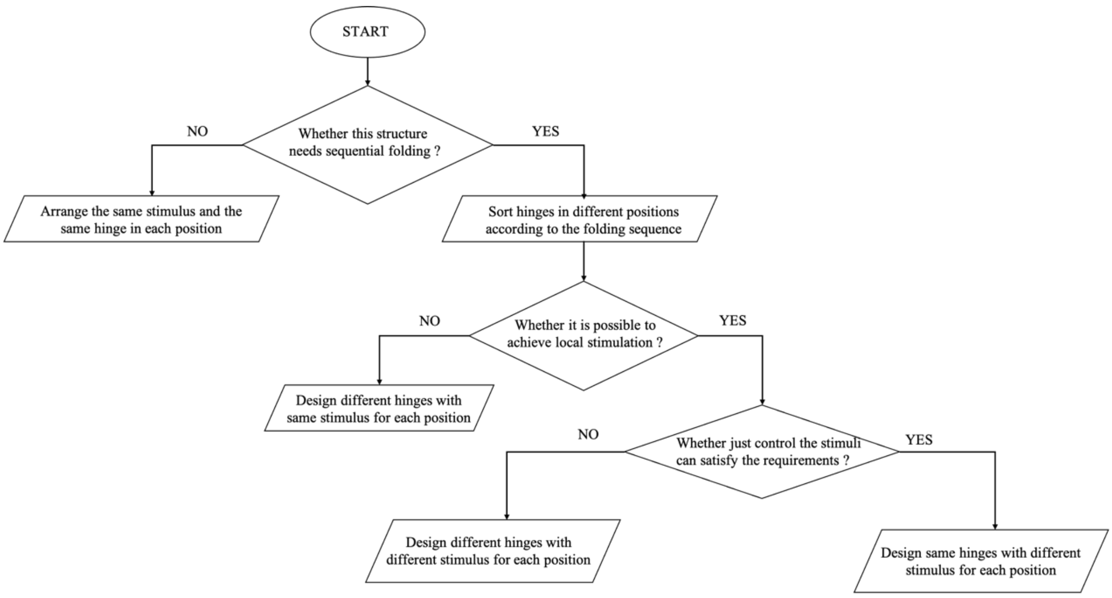


Figure. 45 Example of the selection of the sequential folding method by different stimuli or by different hinges.

Table. 6 Summary of different types of sequential folding

	Activation method	**Smart materials**	**Sequence design type**	**Difference**	**Sequence control**
Deng et al. [166]	Current activation	Silver-coated pre-strained polystyrene	Different stimuli with same hinges	The time of applying current is different	Control the time of applying current
Deng et al. [166]	Current activation	Silver-coated pre-strained polystyrene	Same stimulus with different hinges	Different resistances take different time to reach Tgs	Control the layout of different hinges
Mao et al. [165]	Thermal activation	Digital Shape Memory Polymers	Same stimulus with different hinges	Different digital SMPs have different Tgs	Control the layout of different hinges
Lee et al.[168][169]	Light activation	Inked Polystyrene Sheet	Same stimulus with different hinges	Different inked PS have different transparency	Control the layout of different hinges
Liu et al. [167]	Light activation	Colored Polystyrene Sheet	Same stimulus with different hinges	Different colors have different degree of light absorption	Control the layout of different hinges
Liu et al. [167]	Light activation	Colored Polystyrene Sheet	Different stimuli with different hinges	Different colored PS absorb light of different wavelengths	Control the hinge colors & Control the light wavelengths

5. Sequential folding control: Hinge design

Once the optimal layout and the folding sequence defined, hinges can be allocated to the creases of the 2D origami layout. Contrary to the active/passive hinge determination step proposed in [168][169], all hinges here are assumed to be active and then to be composed of smart materials. To do so, the geometric design stage needs to meet two requirements: (1) be able to deform under external stimuli to achieve folding, and (2) be able to fold accordingly with the predefined folding sequence. The former should consider the interaction mechanism of 4D printing and the specific hinge geometry. The latter should consider the temporal responsivity of the hinges in consistency with the folding.

5.1 The principle of folding sequence control

The process of deforming the printed structure through the 4D printing method can be regarded as a hinge response made of smart materials driven by external stimuli. By analyzing the existing research on sequential folding, we reasoned that the principle/essence of sequential folding is to make the deformation of the active hinge at different positions to have a "response time difference". The time difference depends on setting different gradients for the control conditions, which can be achieved by controlling the response time (start time of response) and the time required to reach the final state. Specifically, 4D printing folding sequence control can be realized by controlling the applying time of stimulus (early or late) or controlling the required folding time (fast or slow). As a result of this, Figure. 46 is given in order to explain the design procedure of determining state A printing strategy more clearly.

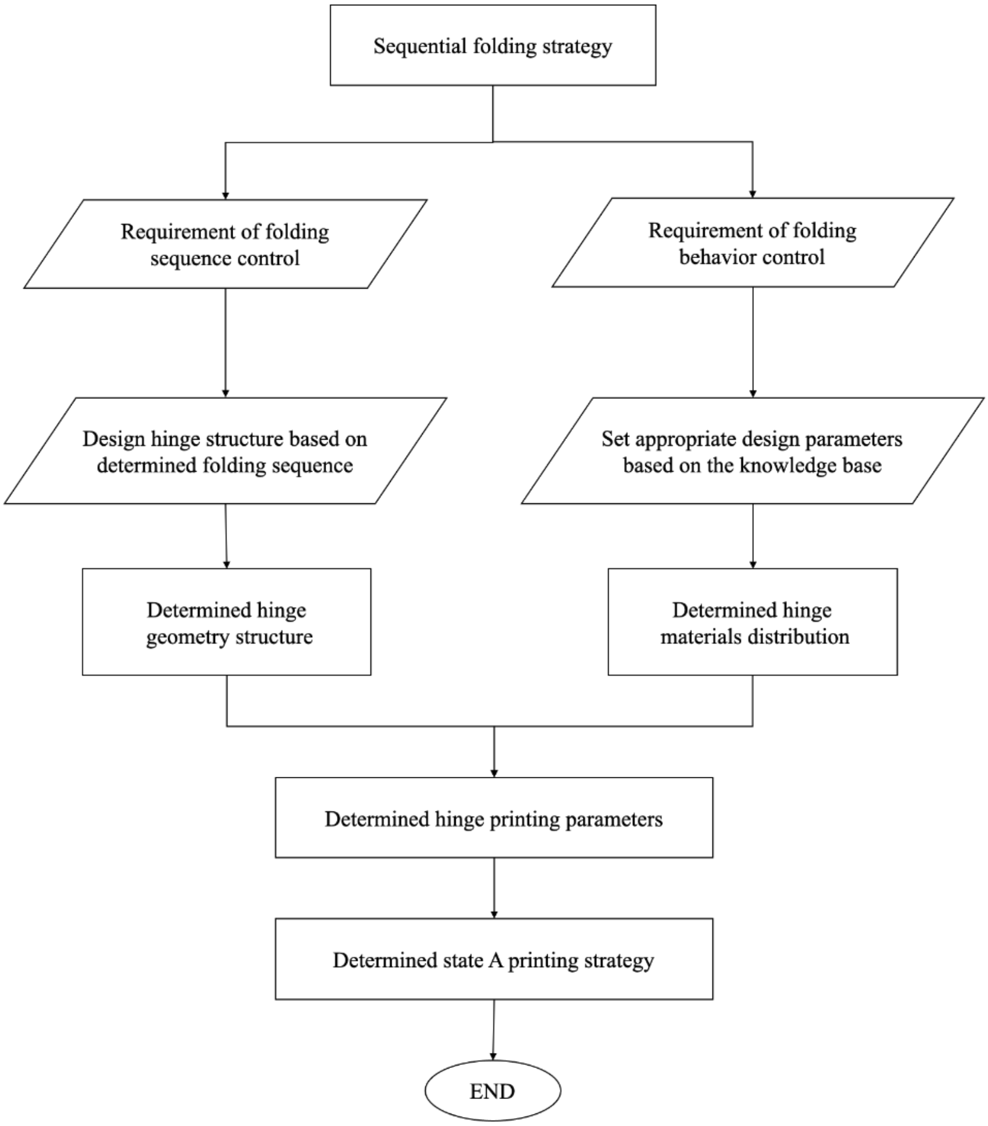


Figure. 46 A flow diagram: from proposed sequential folding strategy to determined state A printing strategy

In this process, the stimulus can be regarded as the condition to trigger the response, and the smart/ active hinge can be regarded as the reactant. These two elements are the two necessary elements to realize the response. Therefore, the response speed can be controlled by selecting different response speeds. The mechanism and control of the concentration/intensity of both sides are realized. It can be seen from the previous section that a specific smart material will react in its corresponding stimulus environment to produce folding deformation. In order to realize the sequential folding, sequential control is required, which depends on setting different gradients for the control conditions. Therefore, the alternative methods for implementing sequential folding can be divided into five categories, including (1) control the different start time of reaction, (2) control the different stimulus's types, (3) control the different SM types, (4) control the different stimulus's intensities, (5) control the different SM contents, as shown in the Figure. 47.

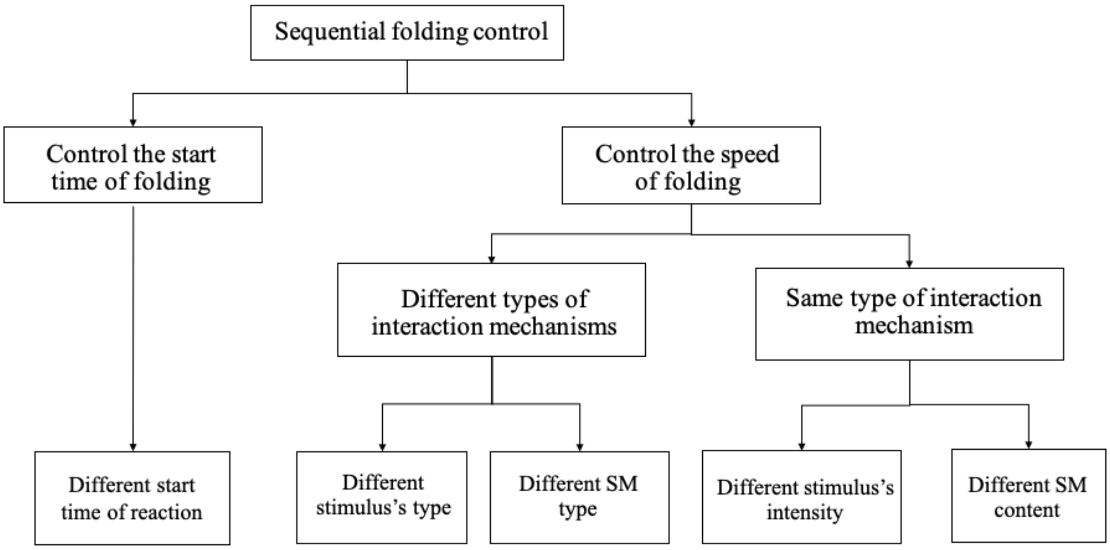


Figure. 47 Example of sequential folding by different stimuli with different hinges

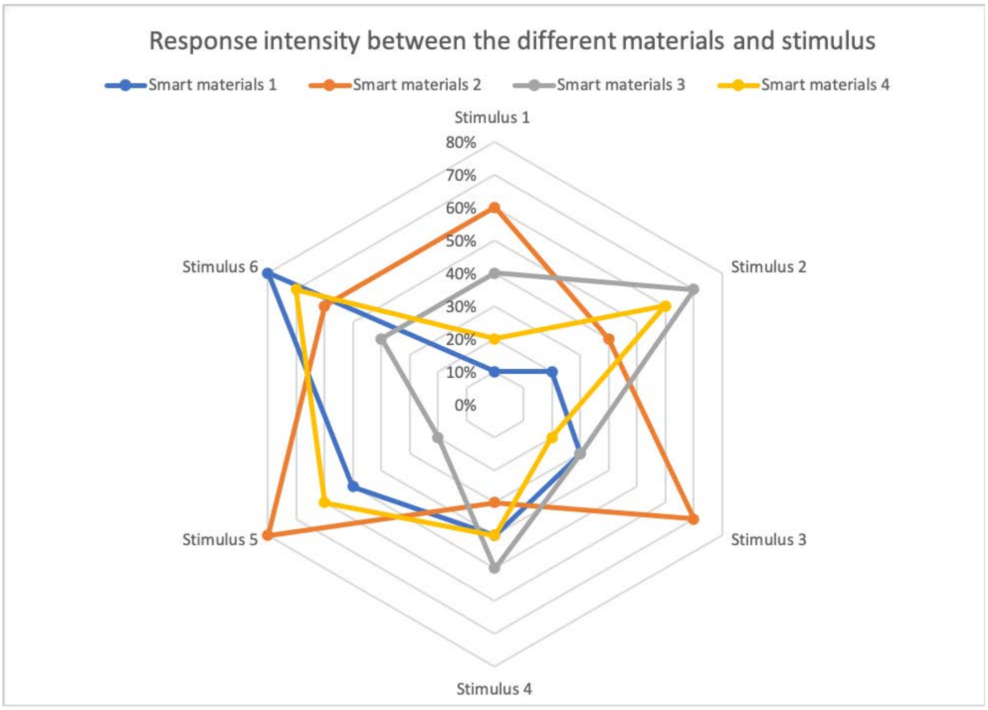


Figure. 48 Example of sequential folding by different stimuli with different hinges

5.2 Hinge structure design

The hinge design is mainly based on material composition and structure geometry, while the role of the hinge is mainly reflected in two aspects: to achieve a specific folding angle and folding in a programmed way. Since the folding sequence of the cube case is already generated based on Table. 6, it can be known that to achieve the final structure, two folding operations are needed, the corresponding hinges are noted as the first type hinges and the second type hinges. As illustrated in Figure. 49, both of these hinge types need to fulfil 90° folding requirement. However, they need to have different temporal responses. This information can be defined as the basic requirements of selecting interaction mechanisms and designing hinge geometry.

To fulfil these requirements, there are many materials and structural options that can be chosen. In order to further determine the specific hinge design, other additional conditions can be used to make the right decisions. By still using the cube as an example, one may assume that there is no restriction on the selection of the materials and processes. Since temperature seems to be the easiest physical property to implement and control, this stimulus has then been used as the triggering mechanism here. Printed active composites (PACs) consist of different digital materials, which have the shape memory effect can be used to realize the shape shifting behavior. This advanced study provides the technical support for the proposed hinge design. In principle, the hinge geometry can be regarded as the fiber-reinforced structure. The folding angle can be controlled by adjusting the thermomechanical loading program and the printing parameters. The folding sequence can be controlled by varying the number of fibers of different hinges. Based on this information and the assumption of considering the same stimulus intensity, the specific geometry can be defined for each hinge. As shown in Figure. 49, the temporal delay of the green hinge actuation is based on the fewer fibers than red hinges ones. There is no doubt that there are still many other methods to meet the basic requirements, like some two-way shape memory materials have the reversibility which brings the innovative effect for geometry and stimulation design, designers can adapt them according to their specific actual situation.

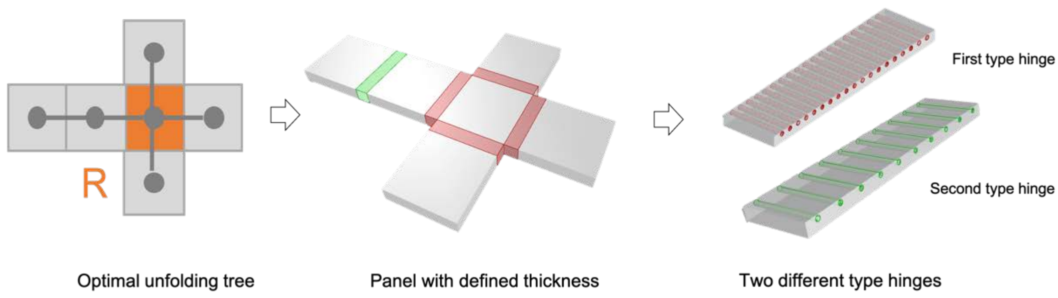


Figure. 49 Specific hinge design based on the optimal unfolding tree

6. Specific 3D/4D printing strategy

As mentioned beforehand, the specific hinge geometry design for 3D/4D printing strategy has been addressed to tackle hollow structure design and fabrication issues. After finishing the 2D origami precursor design process, a suitable 4D printing technology is indeed the key to achieving the final structure fabrication. Furthermore, there is another way to realize the sequence folding by controlling the external stimulus, which also needs to be discussed. Therefore, this step's main goal is to determine the final 4D printing technique – achieving the fabrication process through multi-material printing – enabling the 3D printed structure actuation by the external or internal stimulus to obtain the final target hollow support-free structure.

6.1 Specific 3D/4D printing strategy definition and realization

A complete 3D/4D printing strategy includes specific geometry, material distribution, reaction mechanism, and AM technology. These factors are not entirely independent but affect each other. In the previous steps, we have designed the hinge geometry according to the selected mechanism and smart materials so that a suitable AM method can be matched for that. Since the PACs are built as the fiber-reinforced structure, including the matrix to be an elastomer and the fibers to be a glassy polymer, the PolyJet technique can be selected for the multi-material polymers printing and parameters adjustment.

As shown in Figure. 50 (a), the hinge parts are fabricated with matrix and fibers, each hinge has two layers of equal thickness, one of them have the fiber-reinforced and the other is the pure matrix. Since the panels do not need to change the form during the folding process, it will be fabricated in rigid materials. The materials related to fiber, matrix and rigid parts are digital material (FLX9860 also termed Gray 60), Agilus30Black and VeroWhite, respectively. The process planning setting of the whole structure is shown in Figure. 50.A corresponding multi-material printer (Objet Connex 260, Stratasys®) is required to achieve the structure fabrication, the printed structure is shown in Figure. 50.

6.2 3D printed structure actuation strategy

The last important step is to add external stimuli to achieve the final deformation according to the generated folding sequence. It was discussed previously that the control of sequential folding could be achieved by designing different geometric structures for different hinges. In this case, the printed structure will be deformed in response to the same external stimuli. After heating and stretching the printed structure as shown in Figure. 50 biaxially, the hinge part will be folded when release of the loads in the low temperature thus achieving the final hollow structure as shown in Figure. 50 Due to the fibers number of the two types of hinges are different, in the same external environment, the required folding time is different.

Another situation worth discussing here is to achieve sequential folding by controlling stimuli. When all the hinges have the same geometry, different stimuli intensities can be applied to the hinges at different positions to achieve a temporally programmed response. External stimuli can be applied at different times for the hinges in different positions. Each method has its advantages and disadvantages, and designers can design and select them according to the specific situation.

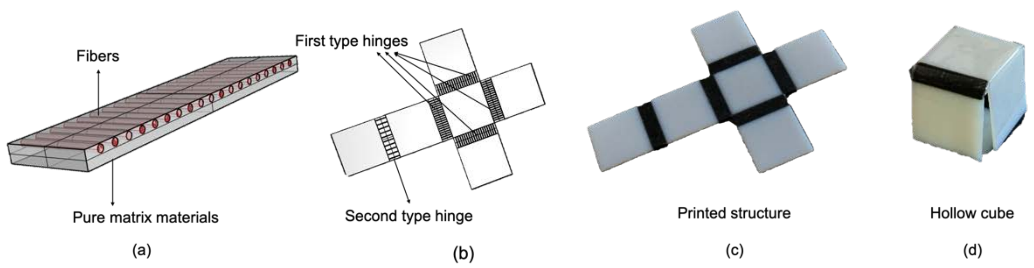


Figure. 50 Hollow cube implementation with (a) hinge composition, (b) process planning setting, (c) its 2D printed origami precursor and (d) its 3D structure once stimulated.

Chapter 5. Implementation and case studies

The previous chapters have proposed the systematic design framework based on origami for 4D printing of the deployable structure and their specific design method of each step. Since this design process's objective is to guide the active structure design by 4D printing, it covers as many situations as possible, and the steps required in most situations. However, it is unnecessary to traverse all the proposed steps in practical applications, and it can be adjusted according to specific design issues. This chapter will present how the proposed systematic design framework of 4D printing deployable structure is applicable in specific applications in the form of case studies. Moreover, it will illustrate how to use the proposed framework to design 4D printing active structures through specific design examples from three different types of structures-deployable structures, hollow structures, and reconfigurable structures.

1. Deployable structure design

The deployable structure shows great potential in many engineering applications. The deployable structure's application process including three stages: initial stage, deployment stage, and final stage. The goal here is to design the origami-inspired initial state with the arranged smart components to be deployed automatically under external stimuli to achieve the final stage through 4D printing. The first case study here is to design a deployable solar panel.

The assumption made here is that a deployable solar panel needs to be designed to show different states according to different external changes without conventional switch control. Without limiting the structure before and after the transformation. Through the analysis of the functional requirements of the structure, it can be known that deployable means that the volume or surface area needs to be changed greatly during the transition between both states. The simplest way is to find the structure type that fulfils this conversion condition in the knowledge base of structure conversion (see

Chapters 1 & 2), and then make an adjustment according to the actual situation.

Based on the classification of the deployable structure (Figure. 25), it is first necessary to determine the type of movement in the deployable process. The three types of sliding, folding, and rotating can meet the design requirements of the deployable structure. Without further clear requirements, folding is the easiest to obtain a larger volume conversion ratio and easier to design. The next task is to determine the direction of movement or deployment. Since in parallel, central, circular and peripheral, the central symmetry of central can be used to simplify the design, so circular is relatively the best choice. In the overall structure analysis step, we can always match the general design type driven by the functional requirements.

In the crease pattern level, the design "central folding type" can be used as the input design concept. The goal of this step is to design the location of the active element. Therefore, it is necessary to find a specific crease pattern that meets the design type. In the unfolded origami inlay knowledge base, common twist types include triangle, cube, hexagon and rhombus to meet the requirements of central folding, as shown in Figure. 51. Therefore, we can select a type as the overall profile configuration of the deployable solar panel. In this case, we temporarily select the most representative sexual square twist for subsequent design instructions. After determining the crease pattern, the specific area expansion ratio can be determined by the relevant size of the origami, and specific parameter values can be set according to the specific situation. As shown in Figure. 52, the expanded area ratio of both states A and B is:

$$S_A : S_B = (a_1 + b_1 + c_1)^2 : (a_2 + b_2 + c_2)^2 \tag{14}$$

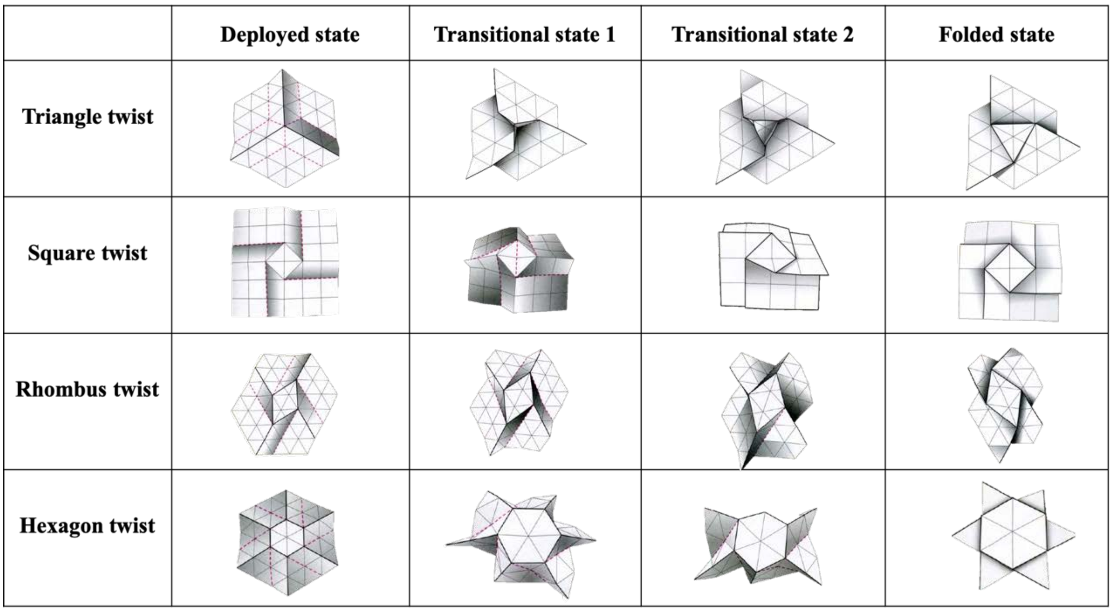


Figure. 51 Existing transition states of origami twist types

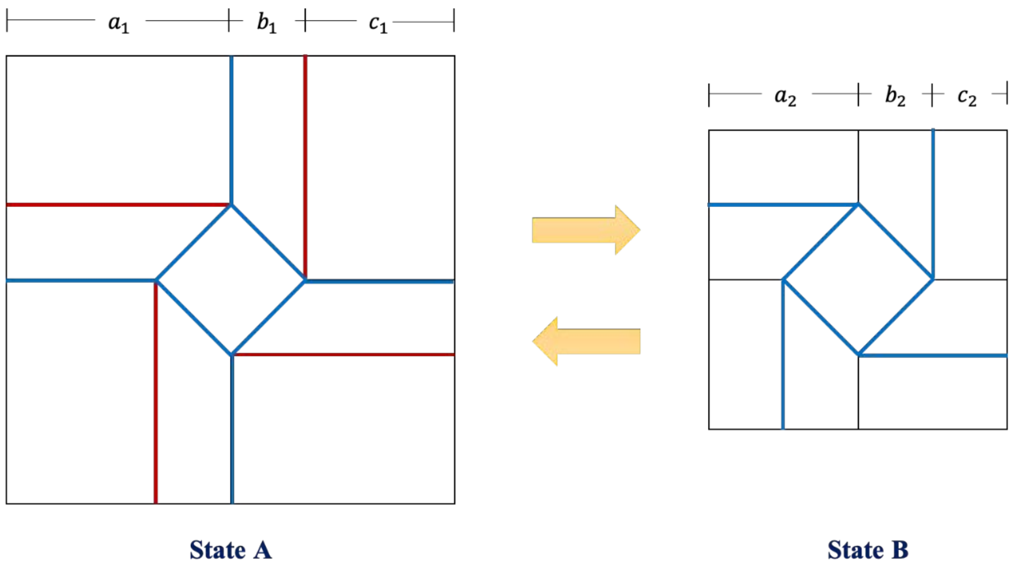
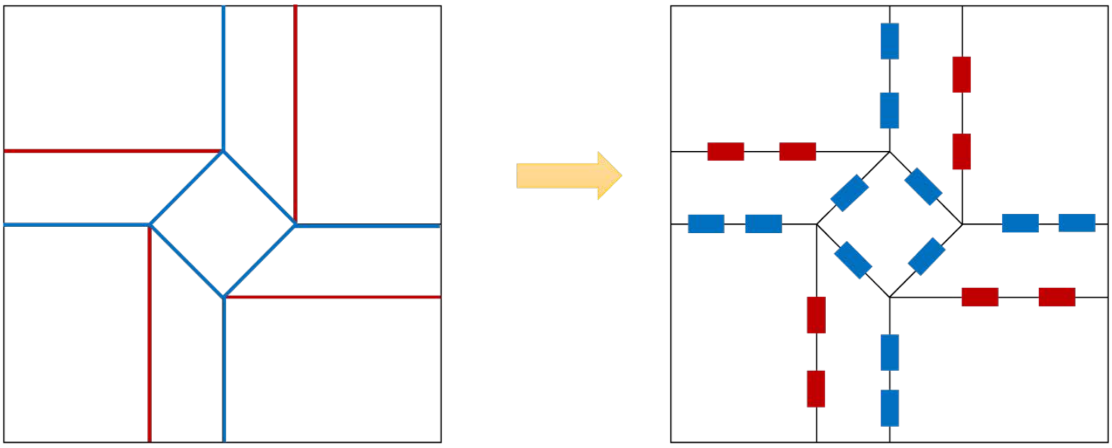


Figure. 52 The deployment ratio is affected by different dimensions

After determining the crease pattern, the design type and folding order of the active hinge need to be considered. As shown in Figure. 53 (a), the red line represents the valley crease during folding, and the blue part denotes the mountain crease. Since different folding directions require different types of hinges to achieve, it is necessary to distinguish the corresponding hinges on the creases of the mountains and valleys in the hinge design. As shown in Figure. 53 (b), different active hinges are designed on the creases of the mountain peaks and valleys, and the different hinge design types are distinguished by different colors, which are determined by the different folding directions. The hinge type here is not fixed and can be selected according to the specific situation. At this time, the two hinge types need to be subdivided. According to the simulation of each part of the folding, it can be seen that there will be no collision during the folding process. Therefore, for each position of the hinge, there is no need to consider and design its folding sequence. The hinges in all positions can be designed into a uniform type and applied to all types of interaction mechanisms.



(a) (b)

Figure. 53 (a) State A with crease pattern representation (b) State A with hinge layout representation

According to the comparison of the structures (before and after the transformation), it can be seen that the folding angle of each crease needs to achieve the 360-degreet. In order to accomplish this goal, the corresponding hinge needs to be able to achieve large angle folding under external stimuli. Most reaction mechanisms cannot satisfy such a large folding angle requirement when the parameters are adjusted as much as possible. Therefore, the best solution is to use the shape memory effect to realize the folding function through autonomous thermomechanical programming steps. Therefore, SMP can be selected as the smart materials and the simplest hinge structure is the uniform type. At this point, the geometry design and the materials distribution of state A can be confirmed.

2. Hollow structures

With the rapid growth of interest in micro-robotics and wearable electronics, smart structures, embedded sensors, and other electronic components have attracted significant attention. Many research issues have also emerged, such as embedding electronic components in a hollow structure without damaging the surface. The proposed method can solve this problem. In order to illustrate the generalization of the proposed design process to more general structures, an application to the Platonic solids is proposed. Here, the second case study will illustrate how to design the active structure according to the design requirements when the target structure is known. The purpose here is to reversely design state A based on state B and the conversion relationship between both structures, mainly highlighting the design of crease patterns through the unfolding or decomposition step. Here, tetrahedron and octahedron have been identified as the target structures and the LED lights as the electronic components to be embedded.

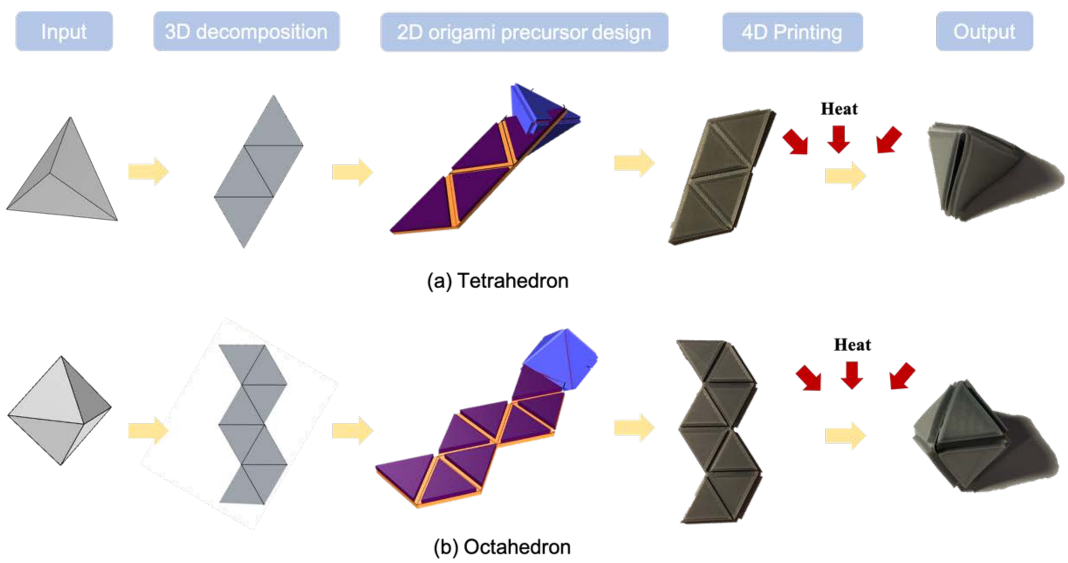


Figure. 54 Fabrication of the two hollow platonic solids.

As shown in Figure. 54, in the 3D decomposition step, as the geometric characteristics of the Platonic solids themselves are undeniable, the edges can be directly considered as the 'mountain fold' in the 2D origami precursor and use one of them as the cutting line. As for the selection of specific unfolding trees, the 2D planes with axial symmetry and center symmetry respectively for these two special structures have been determined. In the 2D origami precursor design step, a certain thickness based on the previously determined unfolding tree has been specified to minimize the total folding number. Secondly, since there is no requirement like "minimize the consumption of smart materials" here, the determination of the folding sequence only needs to consider embedding LED lights. In order to simplify the overall design, the middle hinge is identified as the second type hinge, and all the other hinges are identified as the first type hinge, which folds at the same time. The LED lights are embedded during the time difference between the two types of hinge folding. In order to control the folding time more accurately, all the hinges are designed in the same geometric, and the deformation is controlled by the application time of the stimulation. Since the proposed method has no restrictions on the AM process, to show more possibilities, in the 4D printing step, here we selected thermo-mechanics as the mechanism and PLA as the printed material, all the hinges are designed in the same bi-layer structure. 3D printers (Ultimaker® Extended,) working on the basis of FFF and PLA filaments (Ultimaker, filament diameter = 2.85 mm, T_g = 60-65°C) were used for fabrication of all design solutions presented in this work. Since the 2D structure has been printed, first apply thermal stimulation to the first type of hinges. After these hinges are folded, place the LED lights in this structure that is not completely closed, then apply thermal stimulation to the second type of hinges to fully fold the central hinge until the overall structure is closed. After going through these steps, the internal hollow tetrahedron and octahedron embedded LED lights were successfully obtained, as shown in Figure. 55.

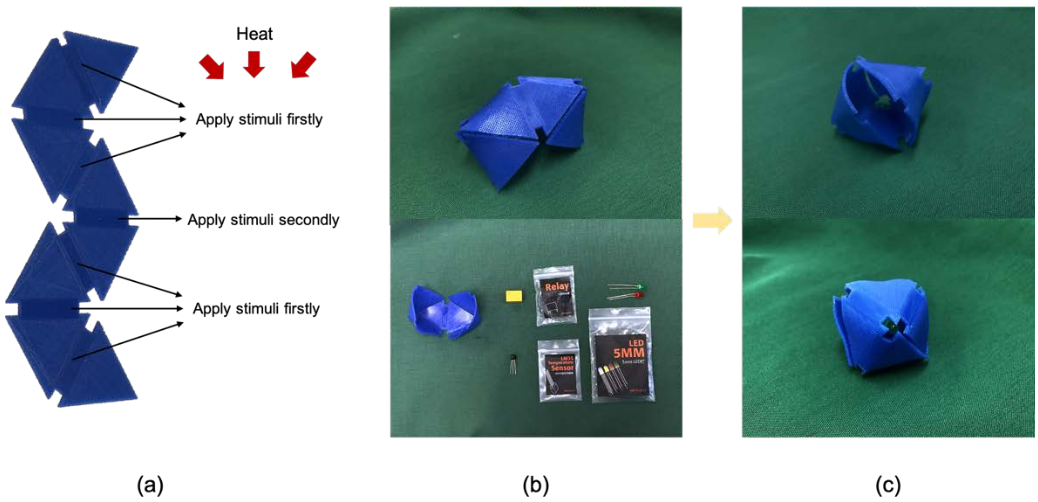


Figure. 55 Process of embedding LED lights in hollow octahedron. (a) printed structure with same hinges (b) structure with the first stimulation and embedded LED lights (c) structure with the second stimulation

3. Reconfigurable structures

Reconfigurable structures attract more and more attention due to their specific properties of switching their own shape structure once manufactured and assembled into multiple functional states over its lifecycle. Such structures usually need to consider the components' position and geometric relationships about the states before and after transformation, which is rather complicated and time-consuming for the designer. Therefore, they need to be assisted in the logical, geometric and material development to fully address self-reconfiguration issues.

In this part, an origami-based design approach to self-reconfigurable structures considering stimulus-responsive materials is proposed. The 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 makes it 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 the proactive design.

The cuboid is 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. Figure. 56 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.

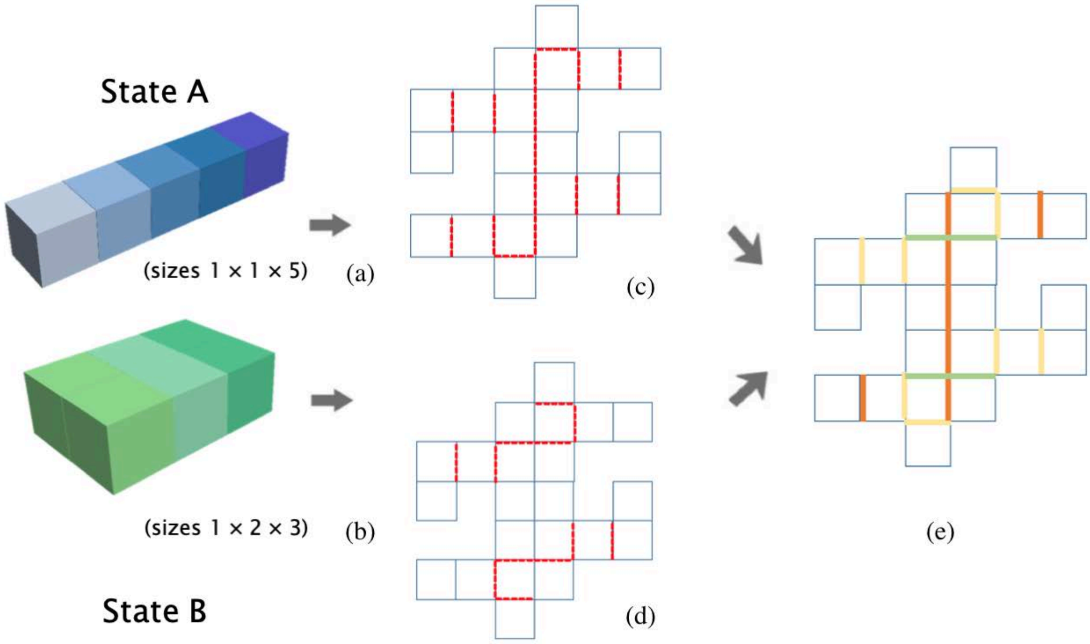
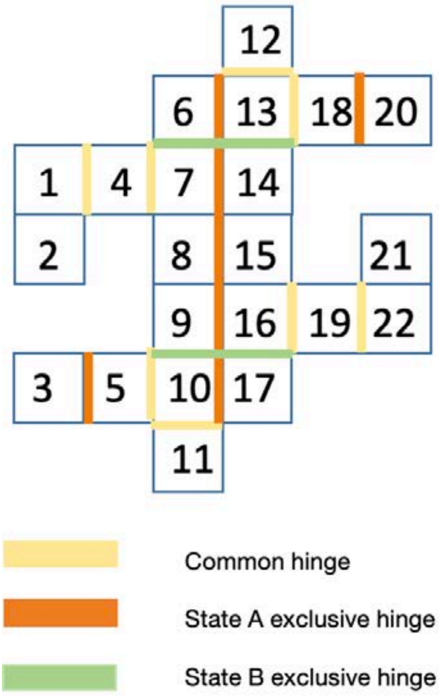


Figure. 56 Two types of cube group (a) state A, (b) state B and related (c,d,e) unfolded structures

As shown in Figure. 56 (a) and (b), the first state is spliced by five cube unites into a 1 by 1 by 5 cube group (defined as state 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, we can get the expanded view of state A as shown in Figure. 56 (c), with the red dashed line above representing the mountain fold, and Figure. 56 (d) corresponding to State B. After combining Figure. 56 (c) and (d), we can analyze Figure. 56 (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.

According to Figure. 56 (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 every two adjacent panels, as illustrated in Figure. 57, the whole structure can be directly classified into state A exclusive hinge, state B exclusive hinges, state A-B common hinges, normal hinges (inter parts), 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 A-B common hinges, inter hinges, and square faces.



Linkages	Inert hinges	Common hinges	A exclusive hinges	B exclusive hinges
1----2	✓			
1----4		✓		
3----5			✓	
6----7				✓
4----7		✓		
7----8	✓			
8----9	✓			
9----10				✓
5----10		✓		
10----11		✓		
6----13			✓	
12----13		✓		
7----14			✓	
13----14				✓
8----15			✓	
14----15	✓			
9----16			✓	
15----16	✓			
10----17			✓	
16----17				✓
13----18		✓		
16----19		✓		
18----20			✓	
19----22		✓		
21----22	✓			

Figure. 57 Classifications of the mechanical hinges

Since this case study aims 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.

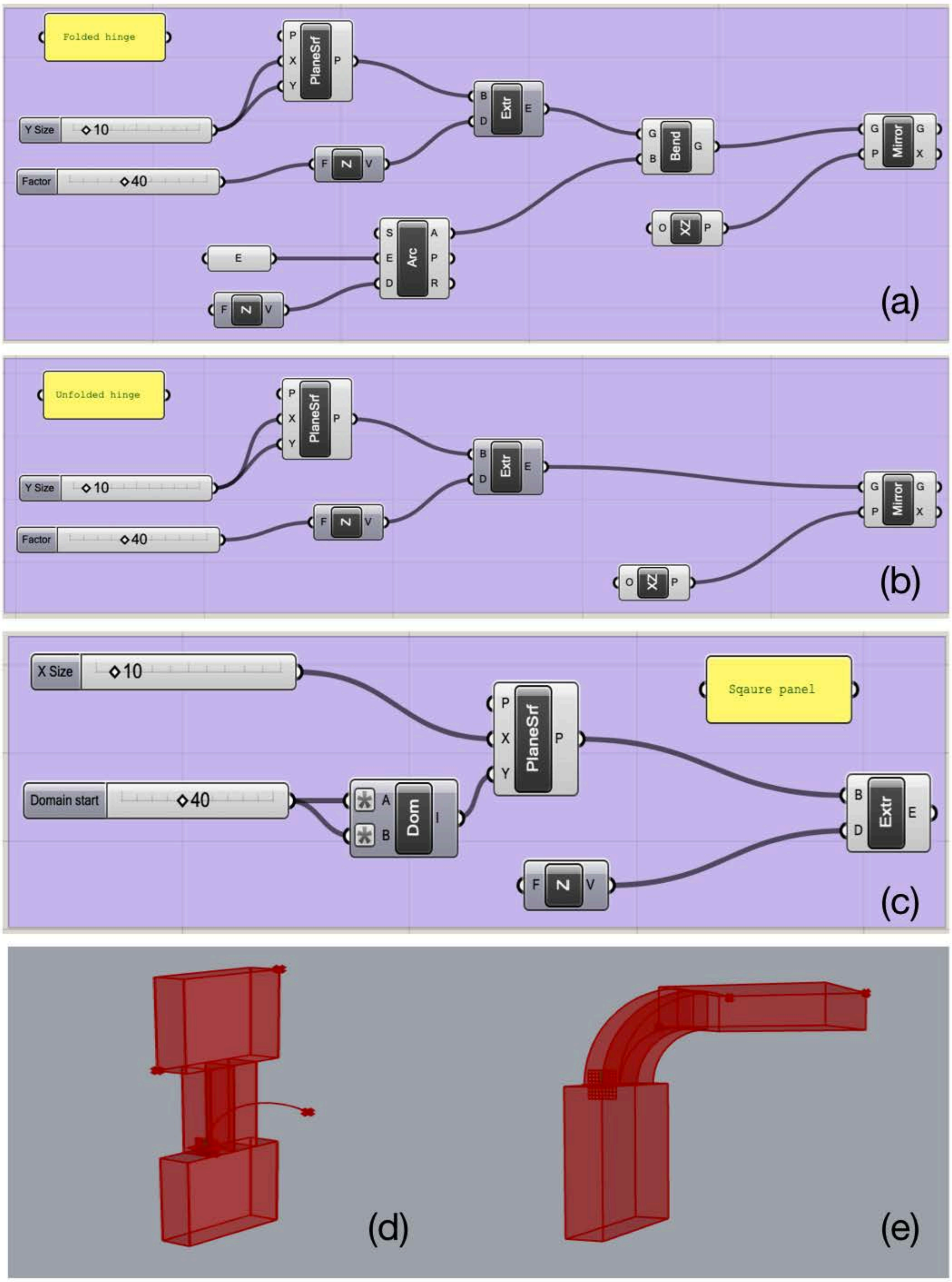


Figure. 58 Design flow and parameter setting in Grasshopper of (a) folded hinge, (b) unfolded hinge, (c) square panel. And the simulation result of (d) non-active and (e) active hinges

For our case study, a preliminary design has been defined through a CAD model in Rhinoceros as shown in Figure. 58 (a,b,c). In addition, VoxSmart has been used to simulate the behavior of the active hinge part [149][150]. Based on the Joule effect, we integrate SMP and resistive wires in order to stimulate with temperature the SME to activate the folding/unfolding primitive of the active hinges with a stimulus (Figure. 58 (d)(e)). PLA materials has been used as the inter materials to the inter parts. Once the behavior is checked from a qualitative point of view, the distribution and geometry are saved in G-code format to be printed with our customized 4D printer, which combines FDM with Direct Ink Writing (DiW) techniques a CNC chassis.

According to the proposed approach and the way the manufacturing is processing, we obtained similar results as simulated. When state A is exposed to the stimulus, in this case, is electricity and heat, the original shape will change to state B. Conversely, we can get a similar transformation from state B to state A. Nevertheless, as seen in Figure. 59, 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 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.

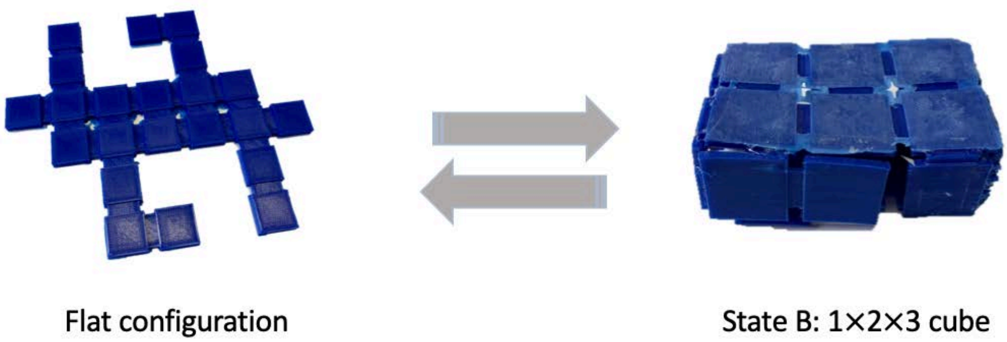


Figure. 59 Reconfigurable structure through its “as printed state” to “final desired state”

4. Conclusions

This chapter demonstrates three case studies to prove that our proposed systematic design process can be used as a guideline for designing the active structure by 4D printing. By illustrating three representative active structures, deployable structure, hollow structure, and reconfigurable structure design, respectively, the effectiveness of our proposed method is proved. According to the different characteristics of different active structures, there are different emphasis when applying our design process. The steps required for each structure are within the entire process's coverage, and the corresponding steps can be omitted or added according to suit the actual situation. These case studies illustrate the systematic and instructional of our proposed method.

Chapter 6. Conclusions and perspectives

The objective of this last chapter is to synthesize our scientific contribution and to bring research perspectives, allowing us to concretize and validate our proposals, and finally, to widen the fields approached in the thesis. Therefore, the first part provides a general conclusion on all the propositions developed in the thesis. The second part describes the prospects for work in the field of what we have proposed.

1. General conclusion

This paper proposed a systematic design process to design deployable structures through origami-based design using 4D printing to solve the problems of driving difficulties and complicated mechanisms and provided a guideline for designing active deployable structures. This research focused on exploring the internal connections between the multiple abstraction levels over the overall product structure to the specific material allocation and geometric design to make the right design strategy aligned to a specific 4D printing technique.

To demonstrate this design process, we first introduced the basic information of 4D printing, origami-based design, and deployable structures. Then we analyzed and summarized their research status and existing difficulties. Secondly, we propose a systematic design framework for active structure design by 4D printing. Each step in the entire design process is then introduced in detail, especially the origami pattern design based on the "3D-2D-3D" strategy and the folding sequence planning and control. Finally, based on the existing knowledge, we apply this design process to the active deployable structure and provide some illustrative case studies.

2. Research perspectives

Although there are many applications of 4D printing active structures, there is still a long way to go before 4D printing is fully applied in real life. Like the insufficient exploration of intricate structural design and manufacturing, few specific tools for 4D printing design, these problems hinder the 4D printing development. Therefore, our objective is to make 4D printed active structures more accurately designed and controlled to get more real-life applications. To do this, we propose three research perspectives closely tied to the mentioned above. First, the short-term perspective intends to concretize and improve our proposed approaches. The other two perspectives, including the mid-term and long-term, intend to adapt our contribution of the "origami-based design for 4D printing of active structure" contexts. We describe these perspectives through the three sections below.

2.1.Short-term perspectives

In this section, we first put forward three short-term perspectives to improve and improve our proposed methodology, which will be elaborated from three aspects: knowledge base augment, simulation improvement, and software development.

As for future work, it is necessary to further develop and augment the relevant knowledge base of 4D printing origami design to meet the design of more functional requirements. The more crease pattern models and more structural transformation types need to be collected and organized to simplify and adapt more complex structural designs. In addition, new interaction mechanisms (including new smart materials and stimulus types) need to be paid attention to better apply and serve the active structural design.

Secondly, the simulation part needs to be paid attention to, especially the real-time dynamic simulation of the overall structure transformation. The simultaneous local deformation simulation at different positions can be used to realize the control and dynamic simulation of the overall structure deformation.

Furthermore, it will be great to make related programs and software to make designers who can independently choose suitable 4D printing principles, hinge structure, material distribution, and printing parameters according to the desired deformation type. The goal is to develop a plug-in within Rhinoceros3D and Grasshopper environment so that designers can create active structures, assign smart materials to them, and visualize the entire deformation process from the initial shape to the final shape. The geometric structure and material distribution of the initial active hinge can be adjusted iteratively according to the intermediate simulation results to obtain the optimal design strategy through this workflow.

2.2.Mid-term perspectives

After ensuring that the origami-based 4D printing active structure design method's effectiveness, it is necessary to consider obtaining a better structure. Therefore, as the medium-term perspective, more optimization methods need to be involved in dealing with the problems encountered in the design of complex structures. For example, how to ensure that better results can still be obtained when there are conflicts in different design aspects. What criteria should be used to confirm the design plan? How to improve the strength of the structure while meeting the folding deformation needs? These all need to be resolved further.

2.3. Long-term perspectives

As for the last long-term perspective, we hope to design more hinge types with different geometric and material structures. Furthermore, apply more types of interaction mechanisms in 4D printing, especially to explore the indirect stimuli which can be precisely controlled by adjusting the variables. The relationship between the folding behavior and hinge parameters can be found to establish parameter equations for precise control of the overall structure through experimental testing and calibrating the deformability and material properties of the new hinge.

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Personal Publications

Journal Article

1 Jian, B., Demoly, F., Zhang, Y., & Gomes, S. 3D-2D-3D: 4D Printing 3D support-free hollow structures via origami-based design, Engineering, 2020. (Under review)

International Conferences

1 Jian, B., Demoly, F., Zhang, Y., & Gomes, S. (2018, September). Towards a Design Framework for Multifunctional Shape Memory Polymer Based Product in the Era of 4D Printing. In Smart Materials, Adaptive Structures and Intelligent Systems (Vol. 51951, p. V002T08A002). American Society of Mechanical Engineers.

2 Jian, B., Demoly, F., Zhang, Y., & Gomes, S. (2019). An origami-based design approach to self-reconfigurable structures using 4D printing technology. Procedia CIRP, 84, 159-164.

National Conference

1 Jian, B., Demoly, F., Zhang, Y., & Gomes, S. (2019,). A preliminary investigation for origami-inspired reconfigurable structure design by 4D printing. 16ème Colloque National S-mart. Les Karellis – Vallée de la Maurienne.

Titre: Conception basée sur les origamis pour l'impression 4D de structures déployables

Mots clés: Impression 4D, Conception à base d'origami, Structure déployable, Fabrication additive, Matériaux intelligents, Conception des produits.

Résumé: Les structures déployables peuvent être déformées entre les différentes configurations par des mécanismes prédéterminés, ce qui montre le grand potentiel de nombreuses applications d'ingénierie. Cependant, leurs mécanismes complexes rendent également très difficile la conception de leur structure. Avec les développements croissants en impression 4D, ses caractéristiques d'auto-transformation sous des stimuli externes offrent de nouvelles possibilités pour le déploiement de structures actives, complexes et difficiles. En outre, l'ingénierie basée sur les origamis a fourni un soutien technique considérable pour la transformation des structures, en particulier en passant par les états 2D à 3D, ce qui a conduit à de nombreuses études de conception basées sur des structures déployables inspirées de l'origami. Toutefois, la relation complexe entre la géométrie de la structure déployable et les matériaux et paramètres techniques connexes de l'impression 4D n'a pas été étudiée en profondeur. Actuellement, le manque de méthodologie de conception basée sur les origamis pour l'impression 4D fait toujours défaut. Dans ce travail de recherche, nous nous concentrons sur l'exploration des connexions internes entre les multiples niveaux d'abstraction allant de la structure globale du produit et l'affectation spécifique des matériaux et la conception géométrique afin d'aligner la bonne stratégie de conception sur une technique d'impression 4D spécifique. En bref, ce travail se veut être une ligne directrice pour la conception de structures actives déployables. Pour démontrer cet objectif, nous avons d'abord introduit les informations de base de l'impression 4D, de la conception basée sur les origamis et des structures déployables. Ensuite, nous avons analysé et résumé l'état d'avancement de leurs recherches et les difficultés existantes. Ensuite, nous proposons un cadre de conception systématique pour la conception de structures actives par impression 4D. Chaque étape de l'ensemble du processus de conception est présentée en détail, en particulier la conception de modèles d'origami basée sur la stratégie "3D-2D-3D" et la planification et le contrôle de la séquence de pliage. Enfin, sur la base des connaissances existantes, nous appliquons ce processus de conception à la structure active déployable et fournissons quelques études de cas illustratives.

Title: Origami-based design for 4D printing of deployable structure

Keywords: 4D printing, Origami-based design, Deployable structure, Additive manufacturing, Smart materials, Product design.

Abstract: Deployable structures can be deformed between the different configurations through predetermined mechanisms, showing the great potential in many engineering applications. However, their exquisite and intricate mechanisms also bring a great difficulty to the design of its structure. With the growing 4D printing efforts, its self-transforming characteristics under external stimuli provide new possibilities for deploying complex and challenging driving structures. Furthermore, origami-based engineering has provided tremendous technical support for structural conversion, especially from 2D to 3D states, leading to many design studies based on origami-inspired deployable structures. However, the complicated relationship between the deployable structure's geometry and the related materials and engineering parameters of 4D printing has not been thoroughly explored. Currently, the origami-based design methodology for 4D printing is still missing. In this research work, we focus on exploring the internal connections between the multiple abstraction levels over the overall product structure to the specific material allocation and geometric design to make the right design strategy aligned to a specific 4D printing technique. In short, this work intends to be a guideline for designing active deployable structures. To demonstrate this objective, we first introduced the basic information of 4D printing, origami-based design, and deployable structures. Then we analyzed and summarized their research status and existing difficulties. Secondly, we propose a systematic design framework for active structure design by 4D printing. Each step in the entire design process is then introduced in detail, especially the origami pattern design based on the "3D-2D-3D" strategy and the folding sequence planning and control. Finally, based on the existing knowledge, we apply this design process to the active deployable structure and provide some illustrative case studies.

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