Mechanical analysis of Shape changing behavior of 4D Printed Parts

SEOKWOO NAM [1] and Eujin Pei [2]
[1,2] Institute of Materials and Manufacturing
Department of Design, Brunel University London, United Kingdom
email_ Seokwoo.Nam@brunel.ac.uk [1]
email_ eujin.pei@brunel.ac.uk [2]

Abstract
4D printing (4DP) uses Additive Manufacturing (AM) to create freeform components using smart materials to allow print parts to deform during calculated times. This paper provides a comprehensive review of the transformational behavior of 4D printed parts that can be achieved using the Shape Memory Polymer (SMP). With the process of 4DP, a flat-packing structure can be printed and activated by external stimuli to switch to a fully deployed functional structure. This paper gives designers and engineers an understanding of the potential for formative behavior that can be realized using 4DP. This knowledge allows designers and engineers to implement appropriate design strategies to better control configuration change behavior through mechanical analysis. This research summarize of shape-changing behaviors that can be categorized according to basic, complex and combined behaviors.

Keywords
4D Printing, Shape Memory Polymers, Shape-change, AM, Mechanical analysis

1. Introduction

Additive manufacturing (AM) has been recognized as a disruptive manufacturing process that has made significant progress in the use of new materials and machines. In recent years, 4D printing (4DP) has become a new technology that can transform, shape, assemble, or transform components into new forms (Teoh, 2017). With the development of 4DP technology, a wide range of applications such as medical, construction, and robots are expected to be developed. Although 4D printing requires use of smart materials including Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs), organic materials such as wood and paper can be used as bio-reactive materials. Statistics show that the size of the market for Shape Memory Polymers (SMPs) is expected to grow from US$1billion in 2021 to US$3.4billion in 2025. This paper focuses on SMPs because it is lighter than SMA, more cost-effective and more resilient than SMAs due to existing technology (Hornat et al, 2017). In addition, widespread adoption of SMPs usage is expected to be achieved, compared to SMAs, which typically involves more complex processes. This document provides a comprehensive review of changes in 4D printed parts that can be achieved using Shape Memory Polymers (SMPs).

2. 4D Printing (4DP)

2.1. An Overview of Additive Manufacturing

Additive Manufacturing (AM) is a process of building layer by layer directly from 3D CAD data and uses minimal material without the need for complex and costly tools. It is a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies (ISO/ASTM 52900, 2015). Additive Manufacturing (AM) uses methods such as material extrusion, material jetting, binder dispensing and sheet lamination to build a rigid three-dimensional structure through controlled deposition of materials. Today, most AM processes enable the production of mechanically stable parts and achieve their intended form as mechanically sound and static parts. As a result, most of these parts are not designed to be operated or modified. Moving parts, such as hinges or actuators, include assembling several parts together after production. Post-processing of individual components requires specific tolerances and takes time to assemble. One answer to this is to use materials that can be modified in a controlled manner over time when it is exposed to an external stimuli.

2.2. 4DP Technology

4DP technology is a free-form digital manufacturing process that is utilized for rapid development of smart materials such as SMA and SMP. AM created a self-changing structure called 4D printed parts that changed the response to external triggers such as heat, light, electricity, or other stimuli. 4D printing is a four-dimensional process, in the sense that the object can change over a duration, dependent on environmental stimuli (Nkomo, 2018). The biggest advantage of using 4DP is to reduce the size due to computer folding. In AM parts, most machine build sizes should accommodate the surface area and volume of the part. However, 4D printing does not have such constraints because it can "fold" or "compress" large parts to meet the constraints of the machine bed. Farhang et al. (2017) emphasized that the basic elements of 4DP include AM processes, stimuli, stimulus materials, interaction mechanisms and mathematical modeling. Figure 1 shows that the AM process is necessary for the production of free-form parts, and the stimulus stimulates a new form of stimulant-response material. An interaction mechanism is a programming process in which materials transform into temporary shapes. Finally, the mathematical modeling process defines the material distribution and its structure needed to achieve the desired change in its shape (Farhang et al, 2017).

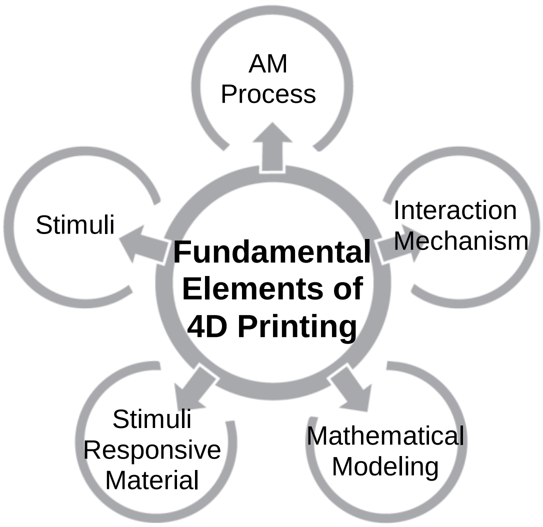

Figure 1. Fundamental elements of 4DP (Farhang, Seyed, Xun and Jun, 2017)

2.3. Current application of 4D printing

4D printing is still in its early stages of development. Below are recent examples of 4D printing applications showing the potential to reorganize the development of new products in several ways. Figure 2 shows a 4D printed Smart Valve. The team at the ARC Centre of Excellence for electro-materials science described that the use of shape memory materials can be changed from one form to another and could be used for use in medical soft robotics. This combination of technology and materials was used to create valves that operate in response to the temperature of the water surrounding the valves.

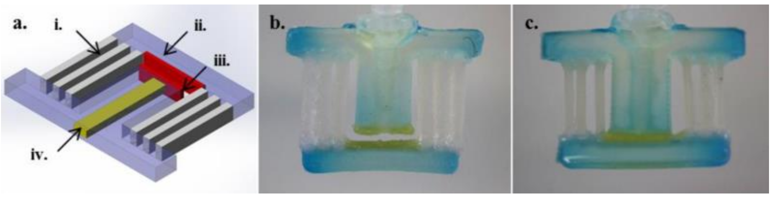

Figure 2. A smart valve is created by 4D printing (Bakarich et al, 2015)

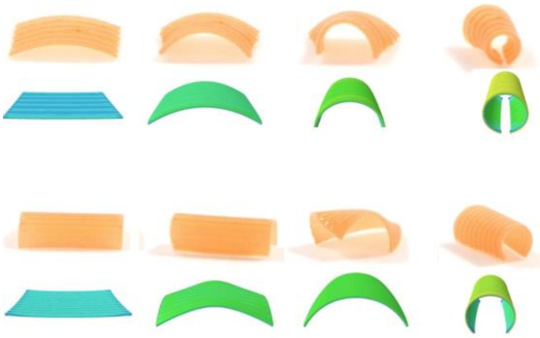

Figure 3 illustrates that MIT's Tangible Media Group has developed a novel “pasta” that can respond in a variety of ways that fold when in contact with heat and water. The printed Pasta is flat, and when boiled, it can achieve different shape deformations such as bending, folding and rolling. To achieve this effect, Wang and Yao (2017) 3D printed a piece of edible cellulose over the top layer of the gelatin.

Figure 3. Shape-Shifting Pasta (Wang et al, 2017)

According to Frost & Sullivan's (2014) market research report, 4D technology and equipment are expected to grow rapidly in the medical, aerospace, defense and automotive industries. 4D printing can produce a variety of products that support parts for human organs from automotive parts. Benefits of 4D printing include improved functionality of mechanical products, new uses of adaptive materials, additional manufacturing efficiency, and reduced manufacturing costs and carbon emissions.

3. Overview of Shape Memory Polymers (SMPs)

3.1. Characteristics of SMPs

SMP was developed 30 years ago. SMP studies have evolved over the past few years from a single form to a multi-form feature, and in this short period of time, material scientists have evolved considerably in designing a fully reversible conversion capability. The SMP involves two-stage. The deformation in stage one is the force required to restore the original shape, which is achieved through the penetration networks, chemical crosslinks or crystalline phases of the material (Meng and Li, 2013). The second stage is to temporarily fix the temporary form by the Glass Transition (Tg) or crystallization state between the different liquid crystal stages through a covalent or non-covalent bonds, such as Diels–Alder reactions, which is a thermo-reversible reaction. SMP mechanisms are usually achieved through thermal transitions, thermo-responsiveness and chemo-responsiveness. The thermal transition of the SMP is due to the molecular switches, which are physical and chemical crosslinks. Morphology and formation separated by stages is the foundational mechanism behind the state of change of material (Lee et al., 2017). In the case of thermosets, the network chain between the net points consists of a switch segment of a chemical crosslinks. Shape-memory switches are achieved by thermal transitions in the polymer segments. Thermosets display less creep and therefore shows a less irreversible change during transformation when compared to thermoplastics. Better shape, machinery and thermal memory than thermoplastics (Leng et al., 2011). In the case of heat reactive SMP, dual component systems are used in polymers excited by heat. The matrix maintains elasticity throughout and the fiber changes material stiffness in the reverse direction (Ratna and

Karger-Kocsis, 2008). The heat response SMP uses the glass switching or melting point as the critical temperature. The SMP consists of two stages, the first phase is a temporary form (or programming phase), and the second stage is a recovery phase (Huang et al., 2010). For chemical reactive SMP, water in the chemical stimulates the plastic effect of the polymer (Roos and Karel, 1991). These effects often reduce the temperature of the Glass Transition temperature (Tg), and the material must be heated over Tg. Because of this chemical reactivity, there is an alternative to shape recovery. It can be caused by ionic strength, pH value, or substance concentration (Lu et al., 2013).

3.2. Stimuli and the Shape Memory Effect (SME)

4DP allows the selection and use of materials that respond to environmental conditions and change the composition. Exposure to external changes, such as water and temperature, normally used as activation stimuli may result in overall deformation of the material. Heat-reactive SMP can trigger SME through heat from sources such as heated gas or water. SMPs are characterized by their ability to recover their original shape from a temporary form that they take on. They remain in a temporary form until an external stimulant is used and then return to its original form. This process is called as the Shape Memory Effect (SME). Most existing SMPs are almost limited to one-way memory that requires re-programming after recovery, but the recyclable material usually has two permanent stages, so there is usually two-way memory. The two-way SME has SME that can be changed back and forth from temporary to permanent. Smart or Stimulus Response Materials: Stimulus Response materials are one of the most important components of 4D printing. Stimulation response materials can be classified into several sub-categories as shown in Figure 4 (Sun et al, 2012).

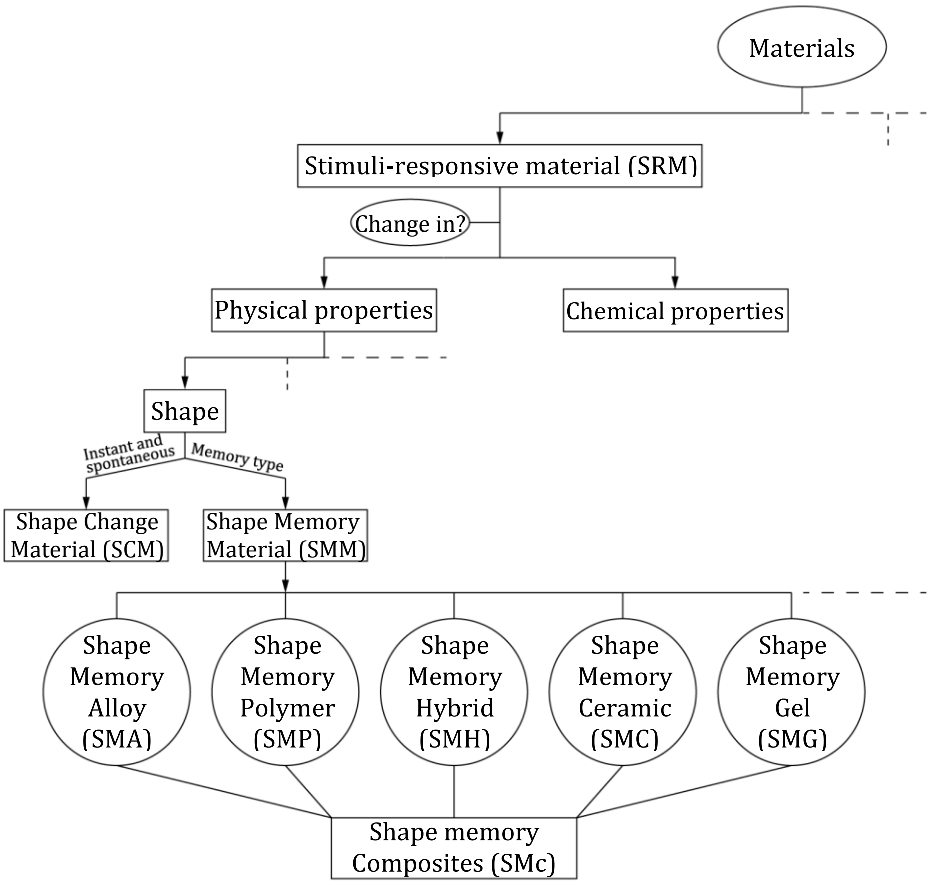

Figure 4. Stimuli-responsive materials (Sun et al, 2012)

4. Shape Changing Behaviors through a mechanical analysis

In terms of mathematical analysis, all shape deformation are the result of different stress along the plane. It is affected by different strains, gradients, and shapes. Elements of shape changing behavior include Folding, Bending, Rolling, Twisting, Helixing, Buckling, Curving, Topographical Change, Expansion / Contraction, Waving and Curling. And each Shape changing behavior have a different mechanical analysis.

4.1. Folding, bending and rolling mechanical analysis

Folding provides improved bending stiffness at the same time as a relatively large global deformations of the sheets. In addition, folding allows the sheets to deform so that it does not form into a regular shells. Folding is a localized deformation with sharp angles within a narrow hinge area, and bending is the overall deformation leading to a smoother curvature (Ryu et al, 2012). When continuous force is applied to the bending effect, the shape deformation of the rolling occurs. The difference between bending and rolling is the variance between gradients and gradients after deformation. Bending has two positive gradients and two negative gradients, the rolling consists of various gradients, and the rolling is a motion in which the shape rotates more than 360 degrees on its axis (Figure 5).

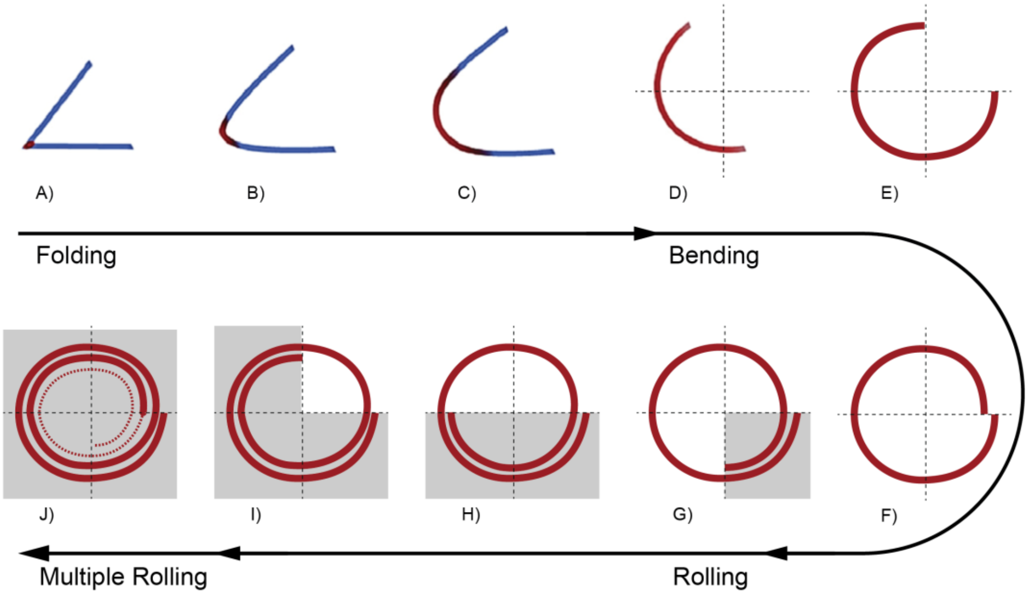

Figure 5. The mechanical analysis of folding, bending, rolling and multiple rolling.

4.2. Twisting and Helixing mechanical analysis

The twisting is dominated by stretching in the plane (Armon et al., 2014), and the helix is a type of smooth space deformation with curves occurring in three-dimensional space. Increasing the width of its own twisted sample increases the stretching energy very quickly, while the bending energy of the spiral structure is only linearly related to the sample width. And there are also have difference axis that the axis of the twist is centered, while the axis of the helixing shape change has various axes (Janbaz et al., 2016) (Figure 6).

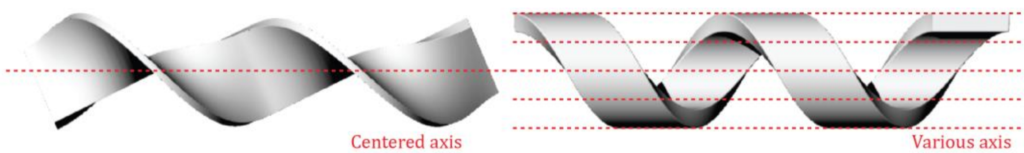

Figure 6. The mechanical analysis of twisting and helixing (Forterre et al, 2011)

4.3. Buckling mechanical analysis

Buckling is characterized by sudden sideways failure of structural members under high compression stress. Programming the flat layout of various active and manual elements can produce the desired compression stresses during operation. The externally generated compression force is also used in passive material layer to induce non-plane buckles (Liu et al., 2016).

4.4. Curving mechanical analysis

Stress gradients can be generated based on the light intensity gradient along the thickness of the material, which results in a voluntary curving of the structure after release from the substrate (Zhao et al., 2017). Curving is the amount of curvature that deviates from a flat surface of a geometric object. This shape-changing behavior is possible by the stress mismatch between the stiffness of different swelling properties and the active substance when in contact with water.

4.5. Topographical Change mechanical analysis

The Topographical changes result in distorted shapes similar to the physical characteristics of a ground terrain. In concentric circles where adequate stimulation exists, mountain and valley features can be generated. Surface topography represents a local deviation of the surface from a flat plane. These features generally occur under compressed load conditions (Wang & Zhao, 2015).

4.6. Expansion / Contraction mechanical analysis

Normally, materials expand when heated and contract when cooled. The shape, volume, and area of the material change as the temperature changes. Expansion and contraction shape changing behaviors are based on a shape memory cycle that includes general programming and recovery steps for thermo-responsive SMPs. This mechanism is driven by various expansion ratios between active and rigid materials, which consist of scalable hydrophobic active materials and rigid materials (Bakarich et al., 2015).

4.7. Waving and Curling mechanical analysis

The waving behavior creates undulating features or wavy up-and-down form. This design of the structure requires the location of the material located in both segments. The wave patterns consist of combinations of SMP and other laminated segments (Wu et al, 2016). Various wave shape changing can be achieved by changing the position and material of each layer. It can use surface curling by creating continuous surfaces as an alternative to curved creases. Larger surfaces provide uniform inflation and typically exhibit much more pronounced curling effects. Curling deformation is activated by stress mismatches between rigid and active materials at various swelling characteristics (Tibbits et al, 2014). Depending on the thickness of the layer and the strain induced, both waving or curling can be effectively programmed. The difference between waving and curling is normal of the curves after deformation. Waving has a more regular curves, while curling is comprised of various irregular curves (Figure 7).

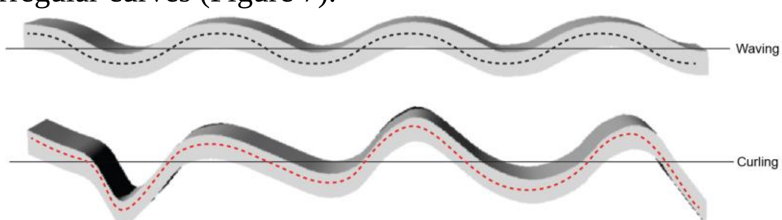

Figure 7. The mechanical analysis of waving and curling

5. A Taxonomy of Shape-Changing Behaviors

As a future-oriented technology, 4D printing has added an additional dimension to the development of additive manufacturing that can be exposed to triggers such as light and heat and thus transform the structure. Manufactured components can cause small, fundamental changes that can result in completely new structures. It categorizes behavior of form change into three categories, including a basic shape change, complex shape change and a combination of shape change. Basic shape changing behaviors include only a single deformation process. The main characteristic is that it is a single step with a completely uniform effect. Basic shape changes include Folding, Bending, Rolling, Twisting, Helixing, Buckling, Curving, Topographical change, Expansion and Contraction. Basic features can be programmed to undergo specified strain sequences over time, sometimes referred to as "sequential" shape variations (Manen et al, 2018). Complex shape changing behavior actions consist of multiple variations that extend the previous format of the basic feature or can be derived entirely from a polyhedron. For example, multiple folds, multiple bends, multiple twists, multiple spirals, multiple buckles, multiple buckles, multiple terrain changes, and curvature changes are basic forms of extended behavior. Other complex structures include shaking and curling. Finally, a combination type of shape changing behavior is a combination of different types of shape changing behaviors that can program more than one component action in a component in a timely or carefully timed sequence. Basically, from a mathematical analysis point of view, all shape variations have different stresses. It affects different strains, gradients, and shapes. The classification table is illustrated in Figure 8.

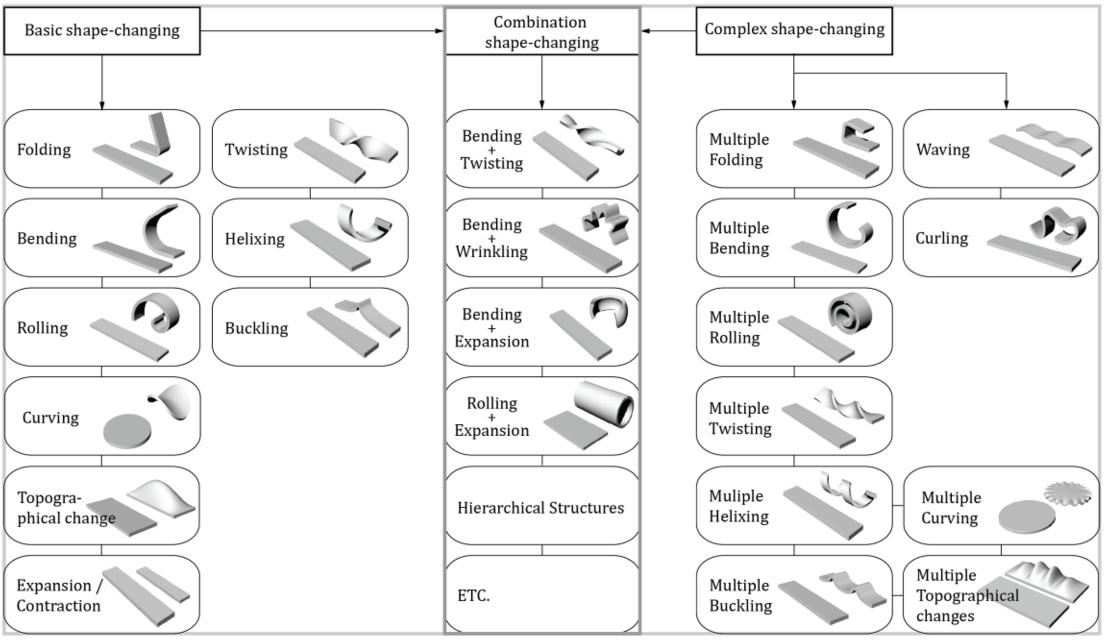

Figure 8. A Taxonomy of Shape-Changing Behaviors of 4D Printed Parts

6. Conclusion

4D printing is gradually drawing attention as a new technology that can overcome limitations of AM and provide new applications. We see the essential elements of 4DP including AM process, stimulation, stimulus response materials, interaction mechanisms, and mathematical modeling. Against this backdrop, this paper provides an overview of shape-memory polymers (SMPs) and various form change behaviors. The design of features within 4DP components allows simple structures to be built before they are activated with complex functional parts and structures. When activated, the 4DP components can be fixed or returned to their original form. One of the most important factors in the 4D printing field is to understand the effects of configuration changes depending on three main factors: stimulation, the type of active material, and computer-assisted design through macanicla anaysis. Therefore, it is important to position the shape changes, understand the different form of shape change behaviors, and understand how they behave over time. Figure 9 shows the conceptual understanding that 4DP constitutes an AM process, stimulus, stimulus materials, interaction mechanisms, and mathematical modeling. 4DP effects themselves focus on location, shape-changing behavior, and behavioral changes over time. Very few tasks covers these studies on the transformation shapes and structures that can be achieved in design modeling of mechanical analysis of shape changing behavior. However, it is necessary to apply effective configuration changes to mechanical analysis modeling. During the programming phase, designers and engineers need to understand and implement strategies that use mechanical considerations shape changing behaviors to control the effects of changes in shapes of 4D printed parts. The study could close the existing knowledge gap in this field. The key direction of future work is to strengthen the validation of this classification system for more thorough empirical research and experimentation through the mechanical considerations. It will also apply direct applications to investigate the effects of design modeling through mechanical analysis. Analyze the design direction in which shape changes can be predicted through an appropriate mechanical analysis.

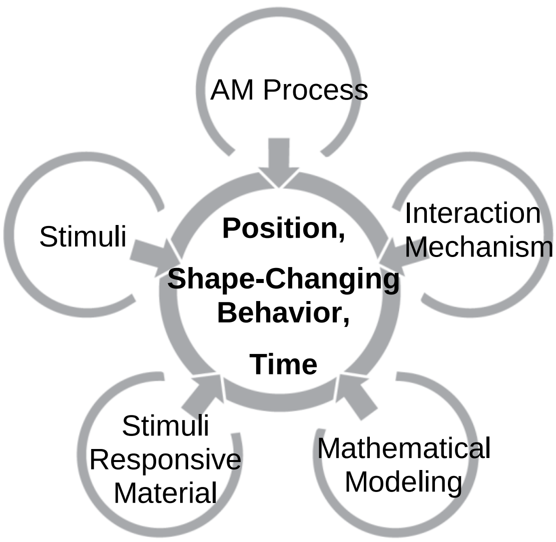

Figure 9. A Conceptual Framework of 4D Printing

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