Towards a multi-view and multi-representation CAD models system for computational design of multi-material 4D printed structures

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Abstract. The emerging technology of 4D printing combines additive manufacturing and active materials under energy stimulation to create objects with shape and/or property-changing capacities. Designing such structures requires careful consideration of the transformation's specifications, shape and structure, stimulation strategy, and materials selection, thereby integrating multiple perspectives constraints and knowledge. The long-term objective aims to develop a computational design synthesis for 4D printing framework that comprises generative, evaluation, and recommendation procedures. To do so, these procedures require a suitable information backbone aligned with the involved stakeholders and the design process. Therefore, we propose a multi-view and multi-representation system in a computer-aided design (CAD) environment to support generation and synthesis while streamlining design intents. An implementation is made through an CAD add-on and a case study is introduced to demonstrate its applicability.

Keywords: CAD representation, 4D Printing, Computational design

1 Introduction

4D printing is an emerging technology that combines additive manufacturing and active materials under energy stimulation, such as heat, light, electric/magnetic fields, moisture, solvent, pH, and mechanical energy, leading to adaptive, transformable, deployable, or self-assembling objects and structures. Consequently, 4D printing opens the door to innovative applications in architecture, automotive, space, and biomedical domains, among others [1]. Beyond rapid progress in single-active material 4D printing, multi-material 4D printing has gained growing attention over the last five years. This strategy involves combining active and passive materials to achieve a desired shape change, providing additional freedom in the design stage to build objects with enhanced mechanical and actuation performance [2]. However, working with active and passive materials induces new challenges for spatial arrangement of materials in accordance with the stimulation strategy [3]. For example, Roudbarian et al. [4] integrate a shape memory polymer (SMP) inside an elastomeric matrix to change the deflection profile of the structure when exposed to specific temperatures. Similarly, hydrogels are used to control the shape change due to their swelling/deswelling effect when exposed to multiple stimuli such as water, solvent, light, etc. [5]. By controlling the internal structure and combining multiple active and passive materials together, possibly being hard and soft, it is possible to program a wide range of shape-change behaviors called transformations, such as folding, bending, twisting, or contraction/expansion. In addition, the meta-structure of a 4D printed part, namely the spatial arrangement of void, active and passive material in the structure that behave like a metamaterial, also has a significant impact on the object's behavior [6].

This new way of thinking and designing objects leads to a tremendous number of design solutions specifically during the embodiment design phase. For instance, the geometry definition, transformations specifications, materials selection and space arrangement, meta-structure selection and fabrication techniques involves multiple actors with different expertise, concerns, knowledge, and viewpoint [7]. These stakeholders involve diverse levels of perspective and abstract representations of the 4D-printed object. Among the stakeholders involved, the product/system architect specifies transformation functions and needs a suitable computer-aided design (CAD) representation. One current intuitive representation manipulated by both architects and designers introduces skeleton modeling. This representation allows to quickly define kinematics of an object and support mechanical design. Other CAD representations can also be found in the literature such as tree-based representations, graph-based representations, boundary-representation (B-rep), 3D meshes, or CSG representation. Feature-based representation [8] are notably suited at capturing design intents but can be complex to implement and use. Since skeletons are efficient for data manipulation and automatic generation and intuitive for mechanical experts, skeleton has been used as a backbone in this article for representing both kinematics of the object and mechanical design space.

The geometric definition of the object is rather a matter of concern of designer. The mechanical engineer, with the support of the material expert, brings more attention to the spatial arrangement of mechanical properties and materials, and requires a dedicated representation supporting advanced simulation. Finally, the process planner or maker in the context of 3D printing must select the suitable or more viable fabrication technique to be used in function of the shape, requirements in terms of quality and materials used in the overall structure.

While interconnected, these multiple perspectives or views, may sometimes conflict with each other as a change within one representation may impact others. For instance, a change of the product architect's model can exert influence on the geometric definition, consequently leading to the need for adjustments in other interconnected aspects of the design. Providing such an interdisciplinary multi-view and multi-representation tool for the actors involved in the computational design synthesis for 4D printing is challenging and strategic in the context of finding the right material and distribution of materials to realize a targeted transformation, usually named inverse design problem. This representation backbone must encompass concurrent knowledge integration as well as multi-scale representation and relies on computational design synthesis (CDS) [9], which is the fact of creating, generating and optimizing design by algorithm mean. The latter is a design methodology that leverages computational methods and algorithms to explore, generate, and optimize design solutions [10]. It involves the use of digital tools and techniques to generate and analyze large number of potential design solutions in an efficient and systematic manner, with the goal of finding the optimal solution for a given design problem. CDS encompasses a wide range of techniques, including optimization algorithms, generative design, simulation, and parametric modeling. It allows designers to quickly and easily test and evaluate numerous potential design solutions, and to make informed decisions based on data-driven insights and analysis.

Considering the wide design space involved and the high complexity arising from 4D printing, CDS seeks to speed up the design process. In the context of 4D printing, CDS has been successfully applied to the locomotion of soft robots as enhanced by van Diepen and Shea [11]. More specifically, generative mechanisms for 4D printing may include automatic generation of materials distribution at the voxel level based on artificial intelligence (AI) [12], automatic generation of meta-structures, and automatic skeleton extraction. Non-exhaustive evaluation mechanisms may include AI-based driven simulations, process suitability evaluation, skeleton or geometry analysis, and toolpath optimization. Recommendation mechanisms may consist of automatic material or process recommendation based on formal ontology [13], materials distribution, or meta-structure recommendation.

2 Multi-View and Multi-representation Model

The proposed multi-view and multi-representation model aim to capture the diverse abstraction levels of 4D printed objects and structures in the embodiment design phase is composed of four distinct views, namely as specified, as designed, as structured, and as manufactured (or printed). These views are related to the concerns of the actors involved and introduce specific representations, such as skeleton-based, geometry-based, voxel-based, and layer-based respectively. The subsequent sections provide description of the representations used and their usefulness in the design of 4D-printed structures.

2.1 Skeleton-Based Representation

The skeleton-based-representation supports the specifications of the transformation functions with a rough design structure. The object is represented by bones and joints. A joint is a connection between multiple bones and can be represented by a point, whereas a bone is a structural element linking two joints. The model of the skeleton is shown in **Fig. 1**.

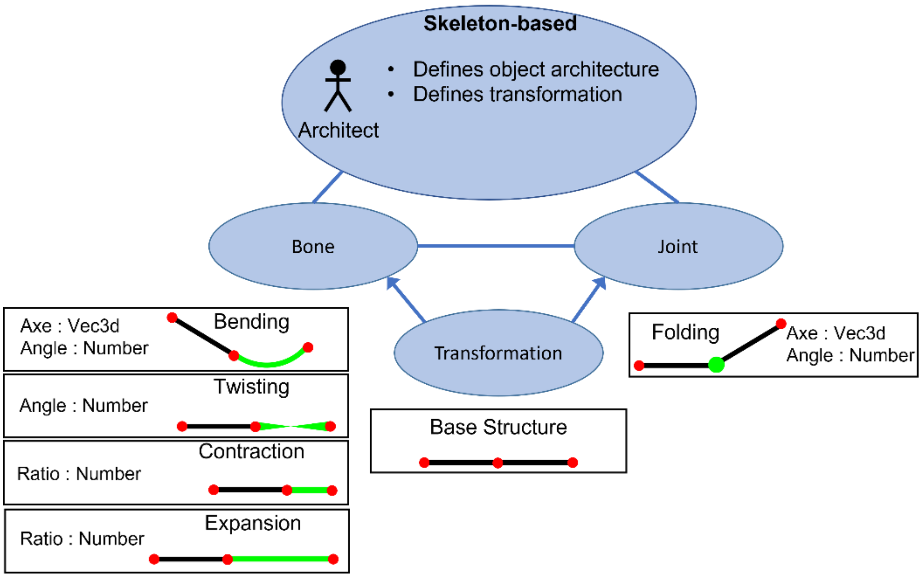

Fig. 1. Model of a skeleton-based representation for different transformations, their parameters and where they are applied.

To simulate 4D printing-induced motion, specified transformations can be applied at the skeleton level. Different types of transformations are available for the product architect and can be allocated either to the bone (i.e., bending, twisting, stretching, expansion, and contraction primitives) or the joint (i.e., folding primitive). The transformation primitives and their related high-level parameters are illustrated in **Fig. 1**. For instance, the twisting transformation is defined by one angle parameter which is the twisting angle. The appropriate rotation is applied along the bone axis and will impact the overall skeleton, thus the geometry by successive kinematics. The bending transformation can be specified by a bending angle and a bending axis which is defined as a 3D vector starting from the joint. At this stage, this representation does not consider the object's geometry but rather focuses on capturing the main behavior or intended transformation to achieve. Using skeleton-based representation, the architect defines transformation requirements for each bone or joint creating a target scenario for the overall behavior of the 4D printed object. This simple and abstract representation serves as a basic core structure for other subsequent representations.

2.2 Geometry-based representation

Then the geometric representation is introduced to support the designer activity, which consists of the definition of a design space built upon/with the design skeletons. The design space is progressively built by introducing the boundary and the rough shape of the object. It can be defined using common CAD geometry volume like B-rep or mesh. These elements are defined by vertices (3D points) and connecting faces (triangles or square) in the framework as illustrated in **Fig. 2**, and allow the designer to create functional surfaces and envelopes-volumes. Each bone and joint of the skeleton-based representation is tied with a part or volume of this representation. With this representation, the designer can also specify locally or globally abstract design intent or properties. For instance, the designer may specify a region of the object/structure to be transparent, rough, colored specifically or prehensible, another region to be a functional surface that need to keep a certain shape and with specifics feature to permit future assembly. Various abstract properties are available and may also come from existing knowledge captured in ontologies [13].

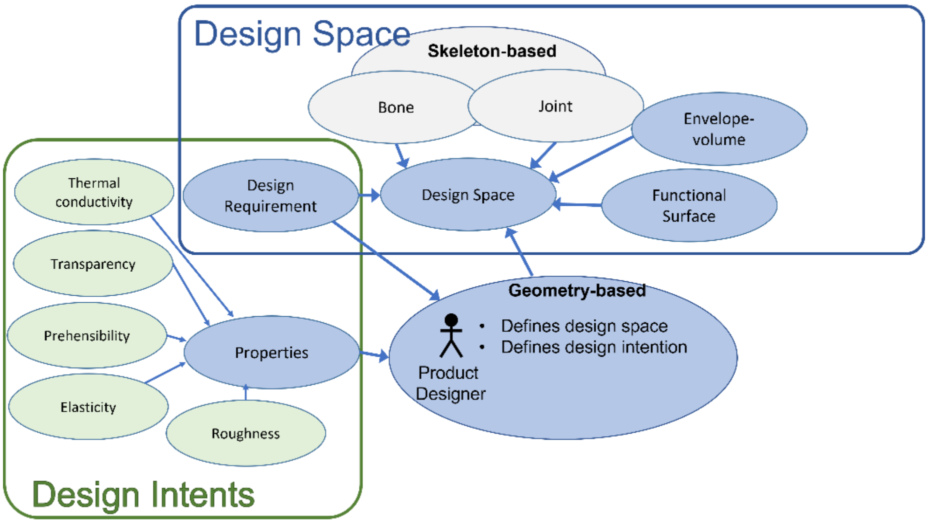

Fig. 2. Geometry-based representation with connection to the skeleton-based representation, design space elements and design intention elements

The geometry-based representation also serves as a foundation for animating the overall geometry of the structure with specified transformations represented by the skeletons[14]. Realistic mechanical rendering and body collision are not handled at this stage as it only provides insight to the designer into how the rough geometry will behave, and which design requirements must be met and where. This close connection between the skeleton- and geometry-based representations induces streamline communication between the product architect and the designer, as the skeleton model control the transformation of the part shape.

2.3 Voxel-Based Representation

The voxel-based representation is intended to be used by both material experts and mechanical engineers. Together, they must choose appropriate distribution of active and passive materials and where to apply them to the 4D printed structure. Another concern about topological optimization is also addressed here by choosing region where no matter will be placed.

The meta-structure defines the regular or irregular arrangement of matter or voids inside a 3D design space. Incorporating voids in the structure may result in weakening the object's mechanical structure but is also widely discussed in the literature as the basic idea behind topology optimization. If performed correctly, topology optimization delivers a lightweight part with a similar mechanical resistance than a massive part. More specifically in the context of 4D printing, such void meta-structures may render the actuation easier by providing multiple entry points for the stimulus to penetrate deep inside the structure. Also, thinner structures may result in increased deformations which could be suitable for 4D printing.

To ease dynamic material tuning on the voxel-based representation, the object is broken down into volume elements called voxels. Each voxel can be either void, active, passive, or even a meta-structure as illustrated in **Fig. 3**. Moreover, this kind of representation allow the possibilities to switch between an "abstract" representation where a single voxel is in fact a more complex distribution, and a more "concrete" view where each voxel is rendered as existing inside the structure.

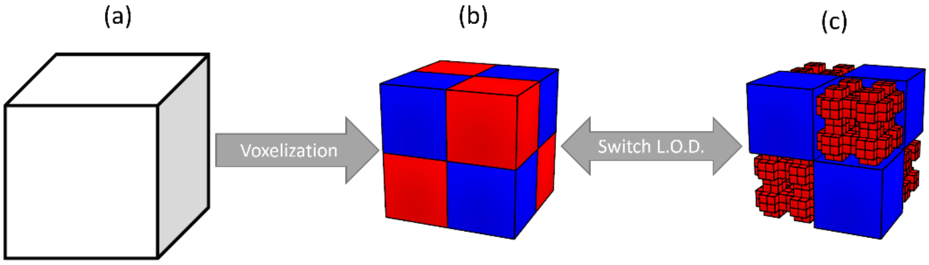

Fig. 3. Example of voxelization and matter distribution with several levels of detail (L.O.D). (a) Initial design space to voxelate. (b) Abstract distribution of active (red) and passive (blue) matter, where red voxels are defined as meta-structure. (c) Resulting distribution of the previous representation showing all the details of the meta-structure.

The global allocation of voxels and void regions defines the material distribution. Each material has a specific color allowing the material expert and the mechanical engineer to easily tune and display the material distribution. The object decomposition into voxels is based on a recursive hierarchical data structure called octree. The octree data structure provides the flexibility to choose between a simple, high-level representation or a more detailed, finer representation, depending on the needs of the current design phase. Decomposing a 3D design space into voxels of a given size is called the voxelization. Moreover, with this representation, partial or adaptive voxelization can be applied only to regions of interest where specified transformations must be fulfilled. Such regions are clearly defined inside both skeleton and geometry-based representations using the transformation location and the properties applied onto the design space.

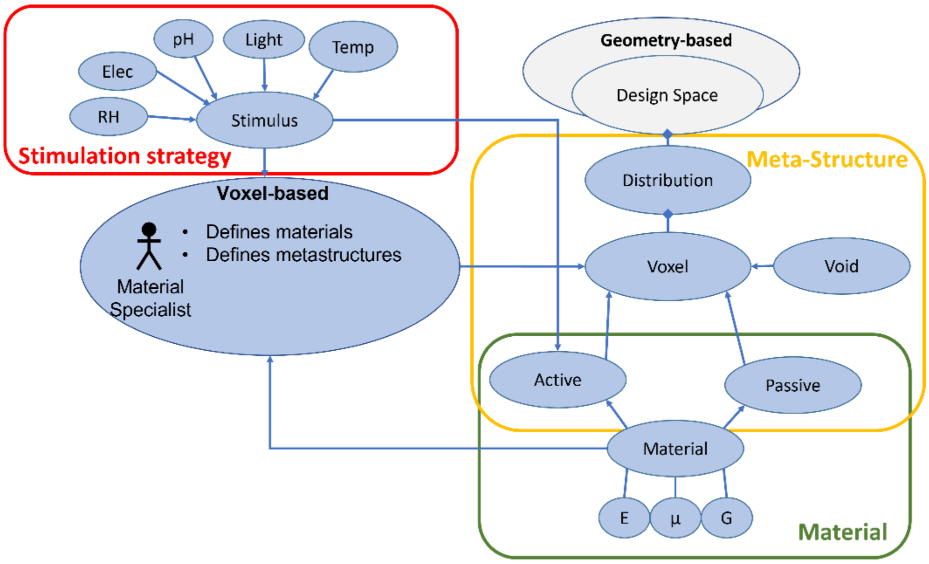

Fig. 4. Voxel-based representation with connection to previous representation, stimulation elements, meta-structure elements and material elements (E: Young's modulus, υ: Poisson's ratio, G: Shear modulus)

With a such a representation, it becomes easier to simulate and analyze different scenarios, such as the deformation of the object to different loading conditions or to environmental stimuli. Realistic mechanical rendering of the structure in 4D printing has been widely studied and voxel-based representation is particularly suitable for mechanical computation and simulation of 4D printed object's behavior using direct stiffness method [6, 15]. Fast mechanical simulation of the 4D printed structure is available for the mechanical engineer and material expert. An adaptation of VoxSmart [16], a fast behavior simulator of smart material has been adapted and used to allow its connection and usage directly on the voxel-based representation of this framework.

Moreover, the simulation helps to analyze, compare, and confront the simulation with the required prescribed transformation at the skeleton level to check if the requirements are fulfilled showing an intricated relationship between multiple stakeholders as shown in **Fig. 4**.

2.4 Layer-Based Representation

So far, the multiple representations presented above do not consider the additive manufacturing technique, which can be seen as the final step in the design for 4D printing process. This is where the process planner or maker must provide its expertise and select the appropriate printing technology. Indeed, as pointed out above, the materials selection inherently impacts the technical processes usable, generating potential design conflicts between designer, the process planner, and the material expert.

Moreover, not all materials can be printed with all existing additive manufacturing technologies. Among the available AM processes, on can use direct ink writing, fused filament fabrication, digital light processing, or material jetting to print 4D objects/structures. Some technologies require a printing path as they are based on material extrusion, some others work directly on 3D files like STL file format. The first benefit of the layer-based representation consists of proposing different outputs depending on the technique used. As 4D printing is inherently a layer-by-layer process, it is logical and intuitive for the process planner to provide a layer-by-layer representation for the 4D-printed structure. A layer-by-layer representation is much more convenient to analyze and customize toolpath with extrusion-based processes or analyze support creation or requirement. The layer-by-layer approach can also be efficiently combined with voxel-based modeling as shown in Bader et al. [17], therefore connecting again the process planner with material expert and mechanical engineer.

3 Case Study

The digital chain of the proposed representations in the context of computational design synthesis for 4D printing is illustrated through a case study: a little man which makes a step by raising and lowering opposite arm/shoulder and bending opposite legs/hips backward and forward.

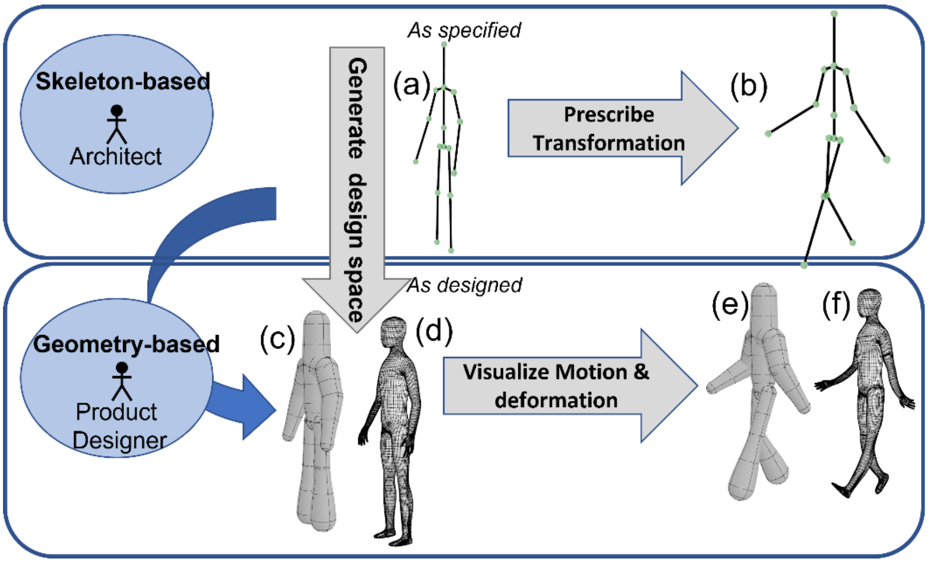

Fig. 5. Skeleton- and geometry-based representations of the little man. (a) The initial skeleton and its joints. (b) Skeleton with motion prescribed. (c) Generated design space from skeleton. (d) Complex mesh associated with the design space. (e) Generated activated design space driven by skeleton motion. (f) Complex mesh deformed by activated design space.

First, the skeleton-based representation of the model is created, then, the different transformations are created and applied as shown in **Fig. 5** (a) and (b). For instance, a first transformation of bending of -20° is applied on the left hips toward its V-axis, which lead to the raise of the leg. Then a bending of 30° is also applied to the right knee on its V-axis to make the foot of the little man going back. Finally, two bending of -45 and 45° are applied on right elbow and left shoulder respectively, forming the as specified view. Then, the product designer can generate the design space by assigning spheres of different radius on each joint to create an initial volume for working illustrated in **Fig. 5** (c) and (e). The designer can also refine the shape of the model by adding or creating a more detailed body inside the initial design space as shown in **Fig. 5** (d) and (f), forming the as designed view.

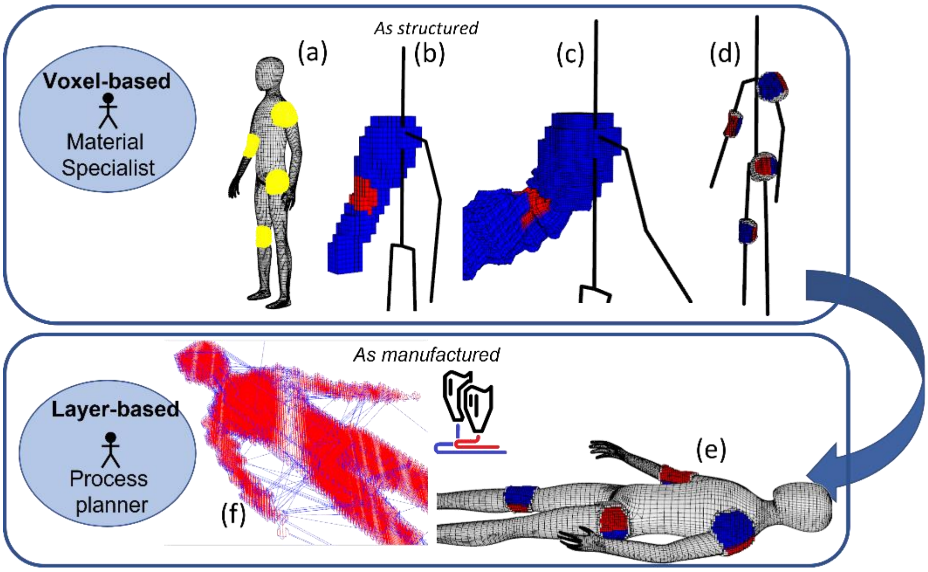

Fig. 6. Voxel and layer-based representations of the little man. (a) Regions of interest are in yellow. (b) Distribution of materials in the subpart (elbow) of the little man. (c) Resulting motion when simulated in VoxSmart. (d) Visualization of the four distributions. (e) Material jetting configuration with separated part for each material. (f) FFF Toolpath for printing

Starting from the previous view, the material specialist can easily select region to voxelize and applying a materials distribution and associated meta-structure to the model to achieve the desired transformation as illustrated in **Fig. 6** (a). To realize bending transformation, different distribution of material using a hydrogel as active material and polylactic acid (PLA) as passive material are defined as depicted in **Fig. 6** (b). With the help of the first two views, the material specialist can simulate the deformation behavior of a subpart of the object inside VoxSmart [16] as visualized in **Fig. 6** (c) to validate the transformation thus forming the as structured view. Finally, the as structured view is exploited to generate the as manufactured view to provide the printing files which can be STL files for each material for a material jetting printer or G-Code path for a FFF printer as described in **Fig. 6** (e) and (f) respectively.

4 Conclusion

The proposed approach of a multi-view and multi-representation system for 4D printing design has shown the potential to synthetize and centralize different stakeholder viewpoints with their own concerns and outlook into the same digital workflow. It also shows the possibility to extend and connect existing work into the workflow, allowing further development and extension of this work. Moreover, CDS serves as the foundation for future developments of a more complete framework, where additional sources of intelligence, such as knowledge database or machine learning can be integrated to provide generative, evaluation and recommendation mechanisms adapted to 4D printing. At different levels, these mechanisms can assist the stakeholders in the rapid determination of a complex design solution. Currently, the stakeholder needs to know how active materials behave and where to assign them, but in the future, a more complete CDS framework will automatically match stakeholder needs resolving conflicts automatically between prescribed transformations, design intents, material selection and arrangement, and additive manufacturing technique selection. As a perspective, machine learning can be used to generating counter-intuitive material distributions or meta-structures, improving mechanical computation for 4D printing simulation or prescribing a material distribution to achieve a target transformation. This work opens exciting possibilities and demonstrates the great potential of future works joining 4D printing design with artificial intelligence to unlock full potential of technology.

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