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Design for multi-material 4D printing: Development of an algorithm for interlocking blocks assembly generation

Kheira Benyahia[a], Hichem Seriket[a], Romaric Prod'hon[a], Samuel Gomes[a], Jean-Claude André[b], H.Jerry Qi[c], Frédéric Demoly[a]*

[a] ICB UMR 6303 CNRS, Univ. Bourgogne Franche-Comté, UTBM, Belfort, France
[b] LRGP UMR 7274 CNRS, University of Lorraine, Nancy, France
[c] G.W.W. School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

* Corresponding author.: Frederic.demoly@utbm.fr

Abstract

4D printing involves smart materials (SMs) that can respond to stimulation energy by changing their shape/property. Current advances in digital materials require addressing heterogeneous (multi-material deposition) 4D printing to attain targeted shape-changes. However, innovative structures embedding inert and SMs simultaneously are yet difficult to build. To overcome this challenge, we propose a genuine computational design approach addressed to heterogeneous additive manufacturing (AM). The main idea is to resort to an efficient algorithm capable of converting a computed digital multi-material distribution in a voxel-based 3D/4D structure to interlocking blocks intended to be printed separately with different AM techniques and then assembled.

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1. Introduction

For as long as anyone can remember, design approaches and manufacturing technologies have continuously known evolution to deliver innovative devices. AM is a perfect example to illustrate this evolution. The latter technology received exponential interest from several domains leading to disruptive and incremental innovations. 4D printing is one of the AM-related innovations aiming at combining AM techniques and smart materials (SMs) [1-3]. 4D printing makes building smart devices with shape-, functionality- or property-changing capabilities, possible in the presence of stimulation energy such as moisture, heat, light, pH, etc [1-4]. Seen as an interdisciplinary research field, 4D printing is gathering numerous perspectives and attracting interest from both academia and industry [2,3,5]. Among the numerous existing studies in the literature, one can notice that 4D printing can be achieved through either single-material deposition (homogeneous) or multi-material deposition (heterogeneous) manufacturing [4,6,7]. Although both directions warrant full attention to raise knowledge in 4D printing, it is important to meet industrial needs concerning physical behaviors, reversibility, and responsiveness, to name a few. In that regard, multi-material 4D printing offers more freedom in design engineering of active composites that exhibit both structural and soft properties. Recent research studies in 4D multi-material printing have laid out the possibility to compute material distributions in a 3D structure using AI-based technologies, digital materials, and voxel-based modeling [1,8]. The objective of these computations is to allocate the right material (passive or active) at the right place and the right stimulus or actuator at the right time, in order to achieve the desired shape-changing behavior and optimum mechanical performances [1,8]. However, structures with digital material

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distributions resulting from the computations are complicated to print with the available AM techniques, thus, development of new multi-material AM strategies is required. An authentic approach aiming to overcome the limitations of digital multi-material AM – regarding AM techniques and smart materials compatibility – is to consider interlocking assemblies of blocks of different materials printed with different AM techniques [1,9,10]. Few interlocking assembly methods are explored in the literature, including mechanical interlocking methods, bio-inspired interlocking methods, and computational interlocking methods [1]. Among the aforementioned methods, mechanical interlocking with computational support offers more freedom in terms of material and AM processes combination. It is a matter of partitioning three-dimensional structures into interlocking elements like 3D puzzle-like blocks, in order to bypass large parts printing limitations and/or multi-material AM [1,5]. Although numerous studies have been carried out regarding computational 3D interlocking assembly generation, very little is known about multi-material 4D printing in terms of digital material distributions – resulting from genetic algorithms and AI-based techniques –.

In that regard, the main purpose of this paper is to propose a computational design approach dedicated to multi-material (heterogeneous) 4D printing using the interlocking assembly of discrete three-dimensional puzzle-like blocks. The starting point here is a digital material distribution within a 3D/4D structure, to which a subset of interlocking blocks – intended to be printed individually and then assembled – are determined as a means to build any voxel-based structure including either solid and/or lattice elements [1,11,12]. Hereby, an algorithm is developed to determine judicious interlocking arrangements of blocks ensuring the maintenance of the assembly without relying on assembly features – such as adhesives or nails –. In this manner, the proposed approach provides an efficient interlocking assembly method that is not achieved yet in the literature. A voxel-based representation and a dedicated computer-aided design (CAD) plugin appropriate to multi-material 4D printing, are adopted in our research study, to adequately control the geometry of the part in terms of properties, active and inert regions occupations.

2. Development of an algorithm for interlocking blocks assembly generation

As highlighted in Fig. 1, the generation of the interlocking blocks assembly takes place over four main steps:

- Partitioning of a voxel-based multi-material structure into homogeneous (same material) set of voxels after analyzing the digital material distribution in the given structure
- Determining the degree(s) of freedom (DOF) and the blocking relations of the set of voxels identified in the first stage (by involving mathematical models)
- Computation of the interlocking blocks assembly by determining keys interlocking blocks first (last parts to insert in the assembly), then the fixed interlocking
- Sequence planning of the interlocking assembly

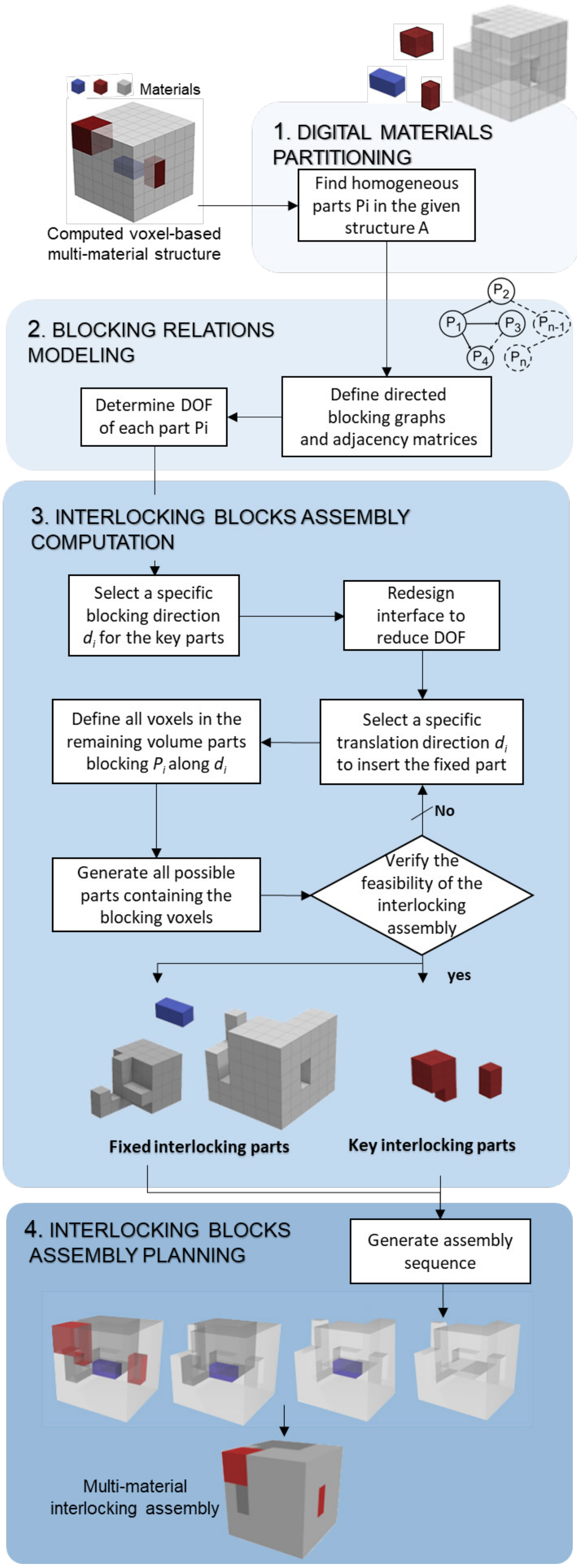

Fig. 1. Flowchart of the proposed computational design approach [1]

2.1. Step 1: Digital material partition

The main objective of a computed voxel-based multi-material structure is that inert and active materials are spatially allocated in a 3D voxel grid, in order to achieve the desired shape-changing. The first step is to section the structure A according to its digital material distribution after identifying homogeneous blocks P_i (set of voxels) in such voxel-based representation, see Fig. 1.

2.2. Step 2: Blocking relations identification through mathematical models

This step consists in adopting mathematical models such as directed graphs and adjacency matrices, in order to describe blocking relations toward all directions ($\pm x$, $\pm y$, $\pm z$) between the identified blocks P_i in the previous step. First, the directed graphs are set, then translated to related adjacency matrices for degree(s) of freedom (DOF) calculation and interlocking algorithm development purposes. A two-dimensional assembly configuration example is illustrated in Fig. 2, to interpret blocking relations between parts P_i in an Assembly. Let a $DBG_d = (P_i, R_i)$, a directed blocking graph where P_i are homogeneous parts (blocks) of the assembly A, and R_i are ordered pairs (arrows) of nodes to define blocking relations between P_i along the direction d ($\pm x$, $\pm y$, $\pm z$). For instance, an ordered pair between P_1 and P_2 indicates that P_1 is blocked by P_2 along d_i.

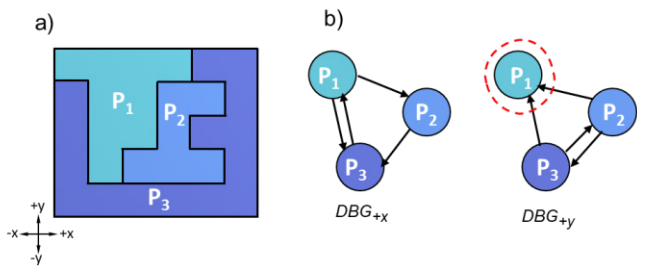

Fig. 2. An example of an assembly of three interlocked parts. (a) part arrangements (b) related DBGs along the directions +x and +y. The key part toward +y is highlighted in the dashed red circle [1]

An assembly A is considered as interlocking when each of its parts is completely immobilized once positioned (inserted in the assembly). Key part(s) are the only parts that have the freedom of moving to ensure the mechanical fastening of the assembly (for repeatable assembly and disassembly purposes), see P_1 in Fig.2.

2.3. Step 3: Interlocking blocks assembly computation

In this section, the computation of interlocking blocks assembly generation will be discussed. The developed algorithm aims at sectioning a multi-material 3D/4D structure into interlocking homogeneous blocks (parts) and defining their interlocking arrangement. Once the blocks are assembled, the desired 3D/4D shape is obtained. The computation is two-fold. First, all parts with (DOF>1) are redesigned to decrease their DOF to 1 degree and classified as key parts. Next, embedded parts or voxels with (DOF=0) are liberated to ease their insertion in the assembly, by allowing additional sectioning in the remaining volume. Thus, new interlocking parts are generated (fixed parts). The remaining parts have (DOF=1) and they are set to be key parts automatically.

Since the digital multi-material distribution is imposed by voxel-based modeling, the iterative interlocking generation can be significantly complex and time-consuming. Thus, a few actions and conditions are set, in order to guarantee the interlocking of the generated parts, and they are as follows

- Narrow modifications in the digital multi-material distribution are allowed when needed to overcome the computation limitations without violating the physical properties of the structure
- Each part is allowed to be inserted along one and only one translation direction
- Once the key part(s) is(are) inserted into the assembly, the latter is entirely secured and maintained.

In order to further explain this essential step, a simple example of a 3D assembly containing four homogeneous blocks is provided in Fig. 3. It displays a voxel-based representation (6×6×6 voxels) with a random digital material distribution. Each of the four blocks composing the initial structure P_1, P_2, P_3, and P_4 respectfully, represents a specific material or property. First, the key parts are generated, then the remaining interlocking parts generation follows.

2.3.1. Key interlocking parts generation

As illustrated in Fig. 3a, P_1 has DOF>1 (mobile part), in other words, P_1 is able to move along more than one translation direction ($-x$, $-y$, $+z$) in Fig. 3a. In this case, a slight modification in the initial material distribution is required to ensure the interlocking assembly of P_1. Suppose that we want to block P_1 along both $-x$ and $-y$ directions, and keep it mobile only along $+z$. For this purpose, we select all the neighboring voxels to P_1 (see Fig. 3b), then pick randomly one candidate that fulfills the blocking condition (see Fig. 3c). The picked candidate will then be added to the key part P_1 (see Fig. 3d). In such a way, the key part P_1 will remain mobile along one single translation direction $+z$. P_3 in Fig. 3a has DOF = 1. This part will be automatically set as a second key part.

2.3.2. Fixed parts generation

As illustrated in Fig. 3a, P_2 is entirely embedded in P_4, thus impossible to be inserted or disassembled. To bypass this dilemma, the algorithm development considers successive reasoning. First, a random direction is picked to inset the desired part (for example, +y in Fig. 3e). Then, a selection of all blocking voxels in the picked direction follows (voxels in green in Fig. 3e). Next, the algorithm will generate all possible interlocking parts containing the blocking voxels. Finally, only parts that guarantee the insertion toward one direction and the blocking conditions, are kept as options (see Fig. 3f for an example of a valid interlocking generation).

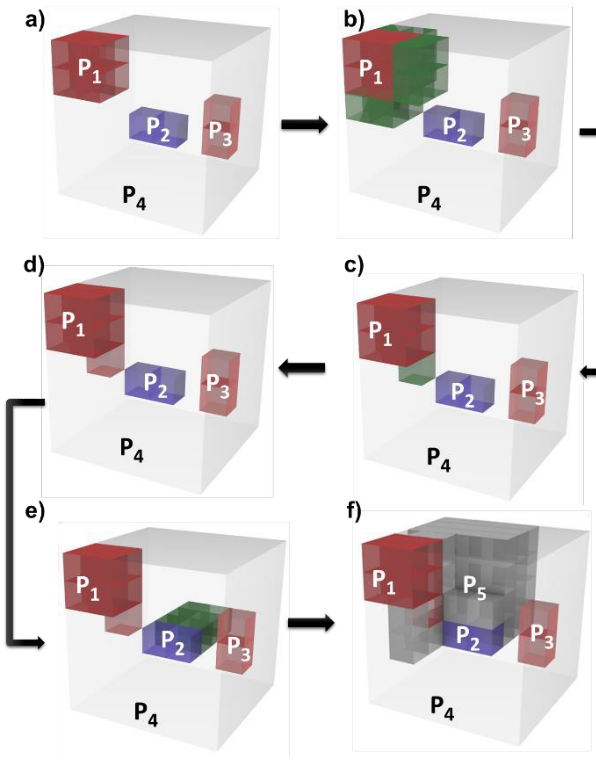

Fig. 3. 6 × 6 × 6 digital voxelized multi-material cube, (a) input structure, each voxel color refers to a type of material/property, (b) to (d) key part generation, (e) and (f) refer to fixed interlocking parts generation [1]

2.4. Interlocking blocks assembly planning

This step is considered as critical. It takes place to determine the order of the assembly of each generated interlocking part in order to finally build the desired multi-material 3D/4D structure. For this purpose, the algorithm will rank the generation order of the interlocking parts by using the blocking relations and the aforementioned reasoning layers. The assembly sequence is then obtained by reversing the order of the generation of the interlocking parts. That is to say, the last generated parts will be the first to be inserted in the assembly and vice versa, which is appropriate since the first generated parts are key parts (the last to be inserted to fasten the assembly). See Fig. 4 where the assembly sequence of the cube example is provided.

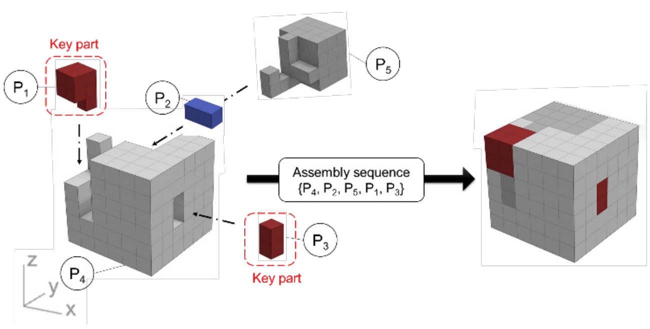

Fig. 4. Assembly sequence planning of a 6 × 6 × 6 voxelized cube, with random digital multi-material distribution [1]

3. Results and discussion

In this section, a case study is implemented to illustrate the relevance and applicability of the approach that converts a 4D voxelized structure with digital multi-material distribution to a set of homogeneous blocks, intended to be printed individually using different AM processes and then assembled to the desired shape. The proposed case study is a beam measuring 18×18×126 mm^3, composed of 1512 voxels (33 mm^3 per each voxel). A soft material (Agilus30) printed with Objet260 Connex3 machine (Stratasys Ltd., USA) and a temperature-sensitive hydrogel (prepared according to the work of [13] —this hydrogel shrinks when exposed to heat—), were used to build a shape-changing 4D structure.

3.1. Interlocking blocks assembly generation results

Hereby, we illustrate an implementation of the proposed computational design approach through newly developed plugins within VoxSmart and Rhinoceros3D/Grasshopper environment. It includes three main components:

- The voxelyzer: converts a 3D structure to a detailed voxel-based model of materials distribution.
- Material distribution partitioning: decomposes the voxel-based representation to homogeneous subsets of voxels.
- Interlocking generation: generates the interlocking set of both key parts and fixed parts, as well as the assembly pla-

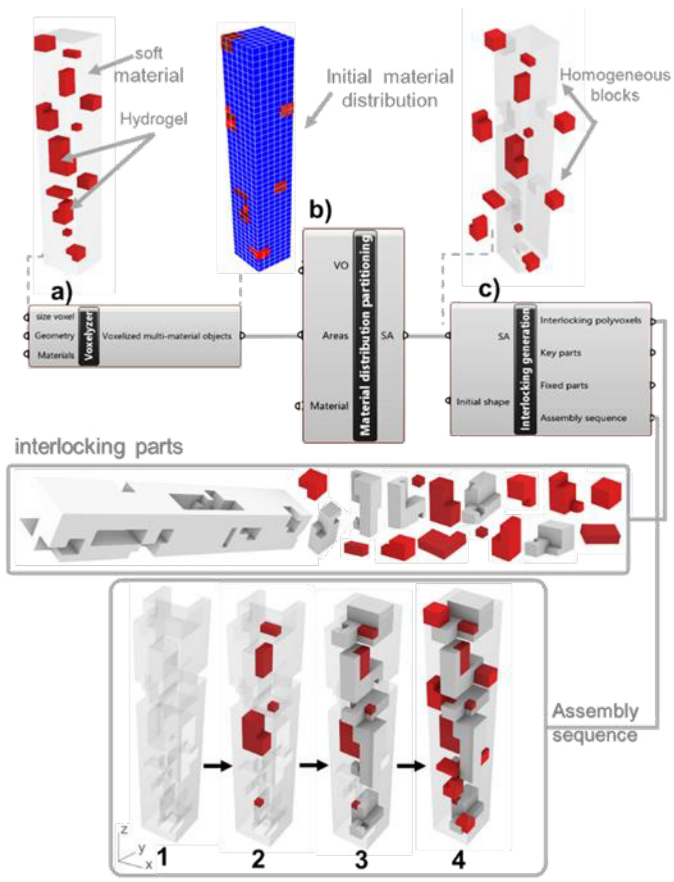

Fig. 5. Illustration of a 18 x 18 x 126 mm^3 multi-material structure interlocking assembly generation steps and plugins within the VoxSmart add-on in Grasshopper for the interlocking computation: (a) Voxelyzer, (b) material partition, (c) interlocking generation [1]

nning sequence. One should note that it exists more than one possible interlocking set, that can be generated. An example of an interlocking blocks assembly generation is provided in Fig. 5.

3.2. Stimulation

As discussed in section 2.2, computation complications may occur due to the imposed digital material distribution. For that very reason, narrow modifications were allowed when necessary in order to ensure the assembly of all present parts in the structure. However, even a small modification in materials distribution may cause considerable consequences in the structure's physical properties. Therefore, a simulation phase is required to investigate whether the physical properties of the structure were negatively impacted or not. A minor shape-changing difference between the initial material distribution and the adjusted one is targeted. Figure 6 illustrates simulations of both the original distribution and the adjusted one, at different temperatures (25°C, 30°C, 40°C, and 80°C). Table 1 on the other hand provides displacement calculations to quantitatively compare both presented distributions.

Table 1. Maximum distances between voxels' positions in the original distribution and adjusted one at 25°C, 30°C, 40°C, and 80°C.

	25°C	30°C	40°C	80°C
Maximum distance (10^{-2} mm ±0.0001)	0	7.74	24.22	24.61

Considering the simulation results in Fig. 6 and distances measurements in Tab. 1, one may notice that the differences in terms of shape-changing and physical properties are very small if non-existent at different temperatures. Therefore, the slight modifications applied in the digital material distribution to generate the interlocking assembly did not offend the physical behavior of the structure. Thus, we demonstrated the relevance of the proposed approach. To illustrate the physical shape-changing, the assembly blocks (active and passive) were printed and then manually assembled to build a multi-material structure with a digital material distribution. Figure 7 shows the case study shape changing as expected in the simulation phase. The shape-change is obtained after 3 min exposure to 40°C hot water. The structure recovers its initial shape when water is cooled down to room temperature after 5-10 min. This figure also demonstrates that the blocks remained interlocked even after deformation due to heat and water immersion. This adds more value to the proposed computed interlocking approach.

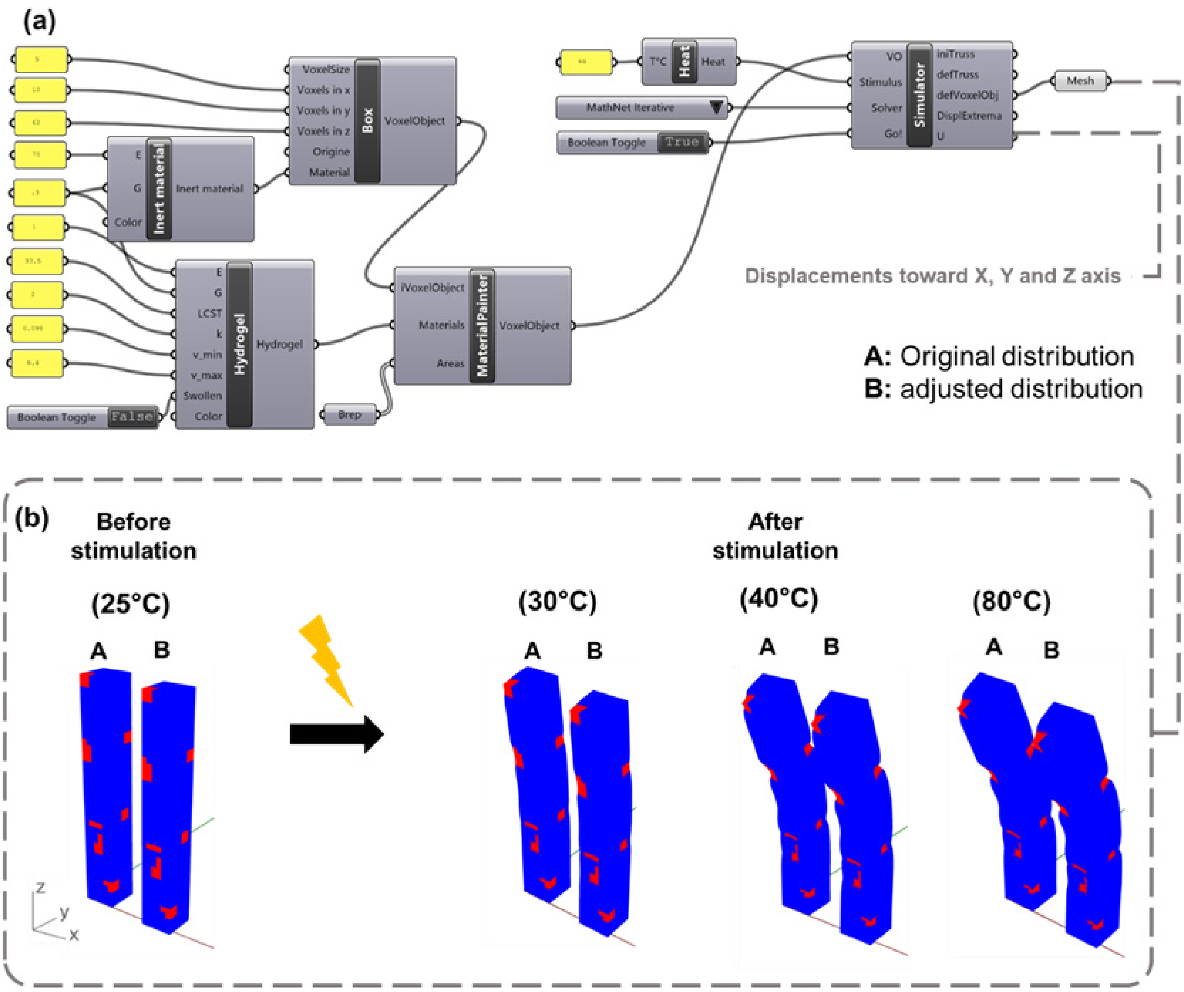

Fig. 6. Simulation of the original distribution deformation (A) and the adjusted distribution (B): (a) VoxSmart dedicated plugins. Materials assignment: soft material in blue: Agilus30; active material in red: hydrogel), and SM simulation, (b) A and B distributions before thermal stimulation (at 25°C) and after stimulation (at 30°C, 40°C, and 80°C) [1]

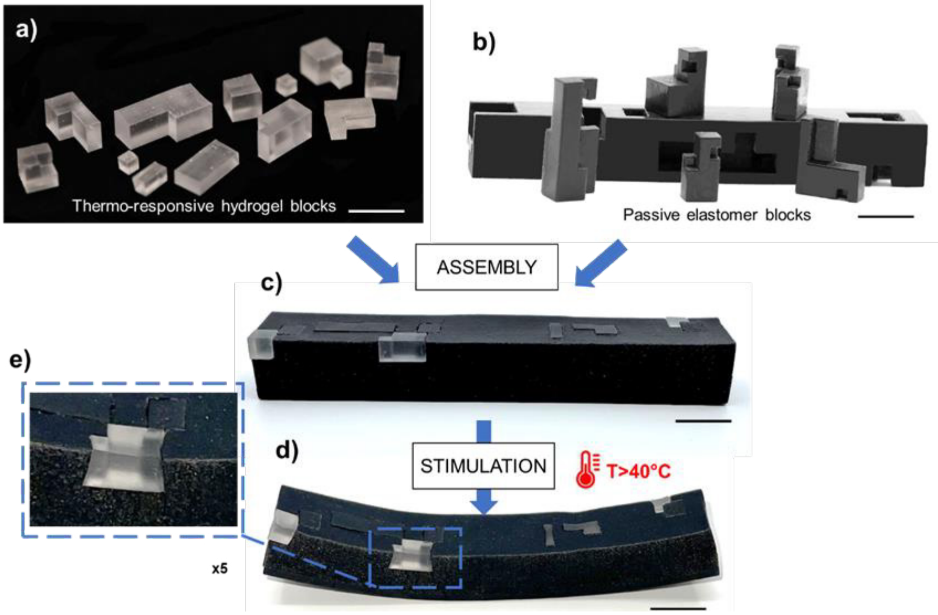

Fig. 7. Printed interlocking blocks: (a) thermo-responsive hydrogel, (b) Agilus30 blocks, (c) assembly of the interlocking blocks, (d) deformed structure after stimulation with 40°C hot water, (e) deformation magnification in (Focus x5) [1]

4. Conclusion

In this paper, we propose a computational design approach dedicated for multi-material 4D assemblies. Starting from a digital multi-material distribution that fulfills a specific shape- or property- changing behavior, the developed algorithm coverts the voxel-based representation to a set of interlocking homogeneous blocks capable of building the desired structure once assembled without relying on additional assembly features that may be structural decreasing or labor- and time-consuming. The study demonstrates an efficient way to overcome some of AM limitations such as building complex assemblies that cannot be printed through a unique AM process in a single printing run, due to printing volume or the compatibility of the materials. Under these conditions, one can notice that our case study was meant to execute one limited shape-changing configuration. Relaxation of these limitations should be attempted in future work, in order to generalize the present approach. It would be also significant to consider in future work geometric deviations and tolerancing related to AM processes. AM inaccuracies can cause modifications in geometries, therefore leading to assembly issues that can be magnified in the case of multiple-parts assembly. Besides, as a means to better control the multi-material distribution interlocking when adjustments are required, a complementary algorithm that considers multi-scale interlocking blocks generation will be developed.

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