

CHAPTER 1

INTRODUCTION

Due to the fast development in the domain of communication and an ongoing trend of digitization and digitalization, manufacturing enterprises are facing important challenges in today's market environments: a continuing tendency towards reduction of product development times and shortened product lifecycles. In addition, there is an increasing demand of customization, being at the same time in a global competition with competitors all over the world. This trend, which is inducing the development from macro to micro markets, results in diminished lot sizes due to augmenting product varieties (high-volume to low-volume production).

To cope with this augmenting variety as well as to be able to identify possible optimization potentials in the existing production system, it is important to have a precise knowledge of the product range and characteristics manufactured and/or assembled in this system. In this context, the main challenge in modelling and analysis is now not only to cope with single products, a limited product range or existing product families, but also to be able to analyze and to compare products to define new product families. It can be observed that classical existing product families are regrouped in function of clients or features.

However, assembly oriented product families are hardly to find. On the product family level, products differ mainly in two main characteristics: (i) the number of components and (ii) the type of components (e.g. mechanical, electrical, electronical). Classical methodologies considering mainly single products or solitary, already existing product families analyze the product structure on a physical level (components level) which causes difficulties regarding an efficient definition and comparison of different product families.

4D printing (4DP) entails the use of an AM technique to process SMs, and possibly others conventional materials to build an object. In others words 4DP can be seen as the interaction between smart materials (SMs) and AM (4D printing = 3D printing + SMs). ASTM International classifies AM processes in 7 families, each characterized by the principle according to which matter is formed. They include: material extrusion (whose typical technique is fused deposition modeling), powder

bed fusion, vat photo polymerization (whose most commercialized technique is SLA – stereo lithography apparatus), material jetting (e.g. PolyJet), sheet lamination, directed energy deposition, and binder jetting. Besides there is about thirty types of SMs [2] which differ depending on what they are sensitive to and how they respond to the stimuli. The whole spectra of AM processes and SMs can therefore potentially yield more than 270 ways of exploring 4DP. Despite still being in its infancy, the 4DP technology has already been the subject of many review papers.

CHAPTER 2

SYSTEM ARCHITECTURE

The desire to make structures more efficient is the main driving force behind research in the field of materials. The performance sought is almost always the optimization of one or more structural properties (strength, density, etc.) of materials, which has led, for example, to the emergence of composite materials or functionally graded materials. However, with the discovery of piezoelectricity in 1880 and the shape memory effect, the desired materials' performance is no longer solely structural but also functional. Thus, the need to provide materials with functional capacities has led to the emergence of the so-called smart materials (SMs). Different definitions of SMs are found, but all agree that they are materials that are sensitive to a stimulus (or several stimuli and able to alter their states as response to the stimuli. Bogue identifies the following repertoire of SMs functionality: shape changing, self-actuating, self-healing, self-diagnostic and self-sensing. The smartness of these materials can be classified according to whether they exhibit an active functionality (i.e. generating stress or deformation) or passive one (i.e. producing no stress or displacement such as optical fibers or photovoltaic materials).

Despite their interesting properties, there are relatively few products made of SMs that make their way out of laboratories. Even for shape memory alloys (SMA), many applications do not pass the stage of real industrialization; this is for instance the case of the Boeing Variable Geometry Chevron using SMA pads, which has not yet flown. Various reasons may explain this situation. SMs exhibit non-linear behavior and time-dependent properties. Properties such as Young's modulus, yield strength and conductivity can change significantly during product use or as a consequence of changes in the environment (temperature, humidity, etc.); this makes their uses more complex by a non-expert. Moreover, the technological maturity of these materials also hinders their adoption. Conventional materials are completely characterized and standardized: their behaviors and lifetimes can be predicted accurately. Such a level of reliability is, however, not (yet) reached in the case of SMs in general. This gap often leads to conduct several validation tests and possibly to carry out many design iterations to develop a SM based product. Furthermore, research efforts in SMs are mainly

targeted at understanding their physical fundamentals (syntheses, characterization, constitutive behavior modeling, etc.).

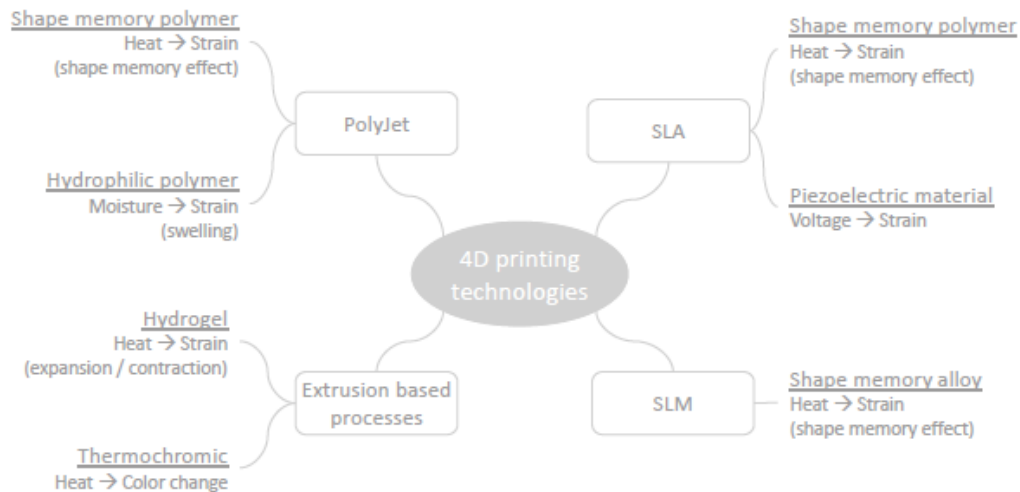


Fig. 2.1. Existing 4D printing technologies.

Apart from some applications-specific research areas such as structural health monitoring or energy harvesting, a very few has been done to allow the designers – that is, those more likely to find original industrial applications of SMs – to consider them with-out reliance on experts’ knowledge. This need to empower de-signers to use SMs in their applications without requiring them to be experts, has been highlighted as early as in 1997 for the case from shape memory alloys. However, from then this call to action has been barely heard. There have been databases describing the SMs in term of responsiveness (stimulus, response), but these data are purely informative and do not help in testing rapidly and realistically the SMs behaviors. While a field’s expert is not necessarily a good designer, it cannot be asserted neither that a good designer can effectively design a product considering a field he or she barely knows. There is therefore a need to bridge the gap between SMs experts and designers, so that the latter’s creativity can leverage SMs’ properties to generate more applications. Besides with the emergent technology of 4D printing, the aforementioned need is more and more urgent. Broadly speaking, this paper is intended to contribute to the 4D printing revolution, on the design methodology side. Particularly it provides the first research efforts for a pipeline for designers to rapidly design and simulate SMs based items, in a way relevant to the AM characteristics of 4DP, that is, through voxel-based modeling.

CHAPTER 3

TECHNOLOGY USED

Designing for 4D printing

A holistic approach to the problem

Inherent to a 4D printed product are three main characteristics: its ability to change in a way consistent to the desired functionality, its material distribution which is partially or totally made of SMs, and its structure which is to be additively manufactural. These make the design process of a 4D printed product more complex than the one for a conventional product. Tackling a 4DP design problem holistically could be through an approach consisting in answering these questions:

- How to produce objects' designs that are efficiently suited for AM processes?
- How a product is well designed to assume various states and potentially to fulfil various functionalities?
- How is the knowledge about the smartness of smart materials, made effectively available to designers? And how can these designers – which are likely to be non-experts easily model and simulate their SMs-based designs?

A design for transformation scheme methodology is first used to design a context – or a backbone – that is consistent with the desired change and that directs (and somehow constrains) downstream stages of the design process. This change oriented context is then used to design the active and inert parts of the product using a Design with SMs (DwSM) approach and a Design for AM (DFAM) scheme. As mentioned in the introduction section, this paper is mainly intended to contribute to the DwSM aspect of the overall Design for 4D printing research project.

Exploring the design space around smart materials

Within the DwSM toolbox, of high importance is understanding or grasping the basic behaviors of the SMs. Indeed, a designer cannot successfully handle a design problem in a field he or she barely knows. As such, the endeavor to ease the design process for any project involving SMs, entails making the knowledge on SMs available in a way accessible and understandable by designers. Such knowledge would serve the

purpose of instilling the basic behaviors and capabilities of SMs. Though the purpose of this paper is not to review all the SMs it is worth outlining the capabilities of SMs at first. Therefore, and for the sake of comprehensiveness, this subsection is intended to fulfill that goal.

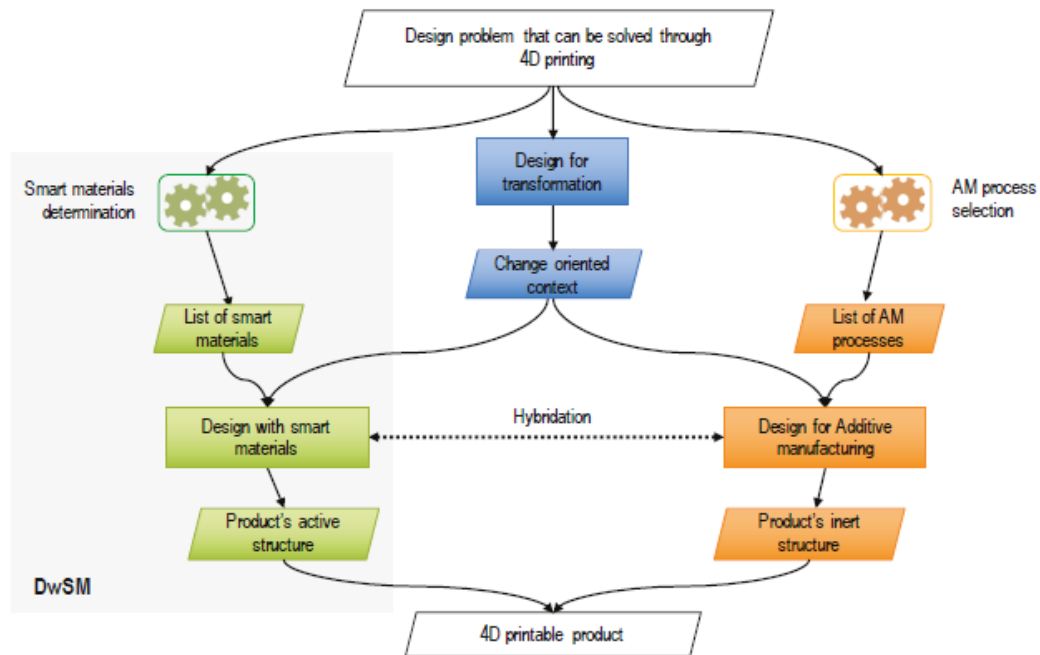


Fig. 3.1. Design for 4D printing framework including DwSM part.

Since the discovery of piezoelectricity and the shape memory effect, the range of SMs properties has significantly expanded, in terms both of stimuli and responses. Many definitions of SMs are found in the literature, however all of them are in agreement with the fact that these are materials whose properties (be them physical or chemical) are altered as a response to a specific change – a stimulus – in their environment. Behind such properties, can be seen the research endeavor to incorporate intelligence in the matter so it behaves autonomously by sensing, reacting and adapting to the environment, as does any biological system. Many matters possessing such capabilities are termed as smart materials; however, for the purpose of study and to provide other characteristics which define the scope of the investigation. Consider as SMs:

- Materials which sense and react to stimuli at their own, that is, which do not need another material to perform such functions. This excludes for instance dielectric elastomers, because for these materials to work they must be sandwiched between two electrodes.
- Materials whose response is not encountered, as a physical phenomenon in a conventional material. Thus are excluded, materials such as electro caloric materials which – like any resistive materials exhibiting the Joule effect – show a reversible temperature change as a response to an electrical current.
- Materials whose response to a stimulus is different from the stimulus itself. Depending on how they respond to a stimulus, SMs fall in any of the following groups:
 - Shape changers: these are those which respond to stimuli by strain or stress. While some of them simply exhibit change in size (e.g. hydrogel, piezoelectric material, etc.) other, such as shape memory material, react by changing shape.
 - Optical sensors: within this group are materials whose response is optically perceivable; this includes for instance thermochromics materials, triboluminescent materials or switchable mirrors.
 - Converters: these materials are those whose response is typically, a signal that can be used as a stimulus for another SM or to provide information about a medium's state. Examples of such materials include piezoelectric material, thermoelectric material or photovoltaic material. This group is not totally mutually exclusive with the sensory materials group.
 - State changers: SMs usually have a single condition, state changers are those whose conditions change in response to the right stimulus. Examples of these are electro-/magneto-rheological fluids or shear thickening fluids.

CHAPTER 4

IMPLEMENTATION AND RESULT

The importance of understanding or grasping the basic behaviors of the involved SM has been highlighted. A further stage towards empowering designers to consider SMs applications, entails letting them to realistically model and simulate their designs. Indeed, at a time of the design process when the designer has an idea of a material distribution, how can he or she know that it actually behaves the way it is intended to under the right stimulus? To help designers in this regard, the design process should be, as early as possible, informed on the actual behavior. This could be done by providing a framework where material distributions (including both inert materials and SMs) can be modeled and simulated. This requires modeling the behaviors of SMs. For such model to be as realistic as possible, it must:

- Reproduce actual behavior of matter, i.e. any deformation must be physically plausible and accurate.
- Be volumetric, as shape is involved.
- Be sensitive: its behavior should be driven by changes in the environment. It must depend on variable measuring how much stimulus is sensed, so that behaviors are triggered accordingly.
- Capture the actual behavior of the modeled SM.

Furthermore, in order to let designers rapidly explore the design space around SMs in the conceptual design phase, running qualitative simulation based on these models should be easy and fast enough (not too much computationally costly). Users should be able to pattern these materials in any arrangement in order to test their distributions' behaviors.

Modelling matter

A scheme for modelling matter or conventional material is first needed, and then the model will be altered accordingly to model the stimulus responsive behavior of the SMs. In such a way, the accuracy and relevancy of finite element method (FEM) in modelling material behavior make it a good candidate for the needs. However, this modelling method does have some limitations that may hinder the exploration of what

is possible in the early design phase. SMs (even the metallic ones) can exhibit large deformation: hydrogel can shrink by up to 400%, and SMPs can recover from strain more than 200%. Traditional FEM is not very appropriate at handling such large deformations. Linear elastic theory is used to derive the FEM equations, and therefore objects' deformations are assumed to be small (typically around 1%, what is true for materials such as metals).

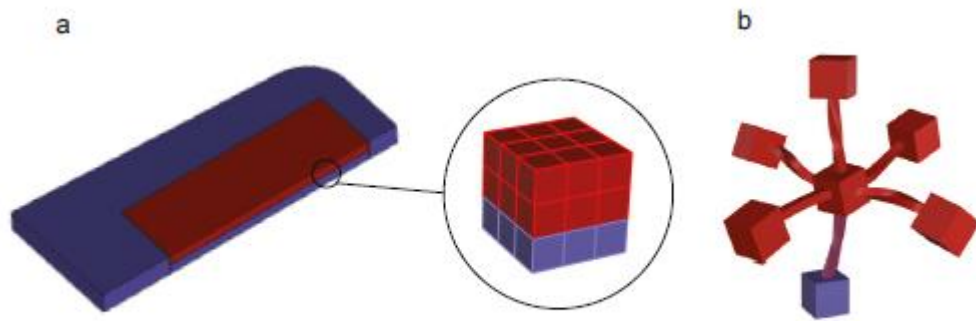


Fig. 4. (a) Modeling scheme and (b) Exploded view of a voxel with its neighboring voxels.

A 4D printed item does fully leverage SMs capabilities when these can be combined with other conventional (or smart) materials, in other words while taken alone SMs do exhibit interesting capabilities, but taken in combination with other materials either, what is achievable is expanded or less SM is required to achieve the same result. Depending on how two (or more) materials are combined, the overall response to a stimulus may not be the same. As such a well-balanced 4D printed item is inherently multi-material. Simulating the behavior of a heterogeneous object through FEM reveals quite cumbersome, and may be too computationally costly, which makes it not worth particularly at the beginning of the design process. The computer graphics industry has flourished, over the course of computers' power evolution, with number of methods (including FEM) for realistically modelling matter dynamics (especially deformation) and on a physics basis. Simulation with these methods can be at an interactive rate. De-spite the obviousness and the relevancy of these modelling techniques to 4D printing modelling, design and simulation issues, almost none of them has hitherto been harnessed to 4D printing. Elected to use mass-spring systems (MSS) to model matter. Rationale behind this decision includes the fact that MSS allow rapid simulation, indeed this modelling scheme can rapidly yield a true qualitative response to the behavior of a given material distribution under a specific stimulus.

Instead of using points as the matter constituents, voxels (considered as volumetric pixels) are used, as depicted in Figure 4. (a).

Using voxel eases the cognitive aspect of the design activity, in that as it inherently involves shape, spatial reasoning (which is inherent to the decision of a material distribution) is better processed. In place of springs between adjacent voxels beams are used, as shown in Figure 4. (b). These beams resist stretching, biaxial bending and twisting. Voxels at both ends of a beam can move spatially, actually each node of the beam has 6 degrees of freedom. Beams extend from center to center, half of their length being inside either of the voxels, and so depend their material properties. For instance, in case of a beam connecting two voxels made of dissimilar materials, the beam elastic modulus (E) and shear modulus (G) are calculated with the following formula:

$$E = 2E_1E_2 / (E_1 + E_2)$$

$$G = 2G_1G_2 / (G_1 + G_2)$$

Here a standard Bernoulli-Euler beam theory is used to model the behavior of the beam. The interaction between voxels is made more physically realistic by adding other forces and moments to the beam, these account for damping, collision and self-penetration avoidance. In addition to variables measuring their spatial position, each of the voxels has a variable measuring a stimulus in the environment. Depending on the modelled material, this variable triggers a specific change in the voxel, or equivalently in the beams extending from this one.

Implementation and use case

A new add-on – which is called VoxSmart – has been developed within the Grasshopper™ (GH) plugin environment to embody the proposed representation and simulation scheme. GH is a graphical algorithm editor using generative algorithms that is related to the CAD tool Rhinoceros R_. The representation and simulation of an active part consist of four main steps:

1. Voxelyzed geometry definition: the part to be simulated is described on a voxel basis. GH components that allow for 3D voxels array generation, voxels removal and voxels addition have been developed to provide assistance in the geometry definition. In future versions of VoxSmart, a component for voxelyzing a predefined geometry will be available.

2. Material distribution definition: each voxel is assigned a material. First the materials are created using GH components. A generic component for an inert (or conventional) elastic material is implemented. In addition, components for other stimulus responsive SMs have been also developed.

3. Stimulus definition: the environment stimulus that is triggering the SM response is specified. Components for various kinds of stimuli have been implemented, and can be tuned through a set of specific parameters.

4. Simulation: once geometry, materials and stimulus have been set, the model can be simulated. The output of all the previously mentioned components are all collected in another component that runs the simulation.

The proposed simulation scheme has been tested with a use case that has been 3D printed: the smart valve. The valve is made out of an inert polymeric material and hydrogel, which in aqueous medium shrink as the temperature is rising. Water flows from the top through the central part, sections on the sides are made out of hydrogel and are also immersed in the water. As the water temperature increases, the hydrogel sections shrink, causing the bottom part to block the valve. This behavior has seamlessly been reproduced with developed GH add-on VoxSmart.

CHAPTER 5

APPLICATIONS

4D Printing: Solar cells

Complex 3D structures are printed with light in a proprietary process that programs them to return to their original forms in a matter of seconds as soon as their temperature reaches a certain “sweet spot.” The research has been published in the online journal Scientific Reports under the title, “Multimaterial 4D Printing with Tailorable Shape Memory Polymers”. The workflow for fabricating a multi-material structure based on a photo-curable shape memory polymer network.



Fig 5.1:4D Printing solar cells

4D Bio-printing

The success rate of organ transplantation increases, the demand for transplantable organs increases as well. However, the supply of these organs is much lower than the demand for them and this causes a worldwide shortage of. Moreover, the current tissue engineering technology has a few major limitations such as non-automated manipulation, small manufacturing scale, inability to produce complex 3D organs and non-ordered and weak tissue microstructure. Thus, this gives rise to a new branch of tissue engineering called 3D bio printing. Bio printing can be defined as ‘the use of material transfer processes for patterning and assembling biologically relevant materials – molecules, cells, tissues, and biodegradable biomaterials – with a prescribed organization to accomplish one or more biological. The main advantages

of bio printing include the ability to mass produce tissue engineered products, high accuracy in positioning the different types of cells and capability to fabricate high cell density tissue. Bio printing is a new emerging technology and the greatest benefit of this technology lies on its capability to fabricate living biological 3D structures such as tissues, organs, nutrients and cells. Nevertheless, as the techniques of 3D bio printing advance over the years, a new technique has been introduced recently, which is called laser-assisted bio printing or 4D bio printing. Laser-assisted bio printing provides one of the highest resolution among all the other bio printing techniques as the cells can be printed one by one to follow the biophysical mechanism.

The high resolution of this technique allows more details and information to be integrated into the tissues to create tissues with high complexity. Laser-assisted bioprinting works by focusing a laser pulse on to a cartridge that leads to the removal of the material from the cartridge to be deposited on to a substrate in a layer-by-layer fashion. The fourth dimension of this laser-assisted bioprinting technique is the time dimension that is related to the self-organisation of the cellular processes such as cell communication and cell interaction. On the other hand, another category of 4D bioprinting will be the 3D printing of smart hydrogels. Smart hydrogels are matrixes with high water content that possess the ability to respond to external stimulus such as electric, ionic strength, light, magnetic field, pH and temperature. They have unique features such as shape memory, self-healing and controllable sol–gel transition. By utilizing the potential of 3D printing to fabricate structures made of smart hydrogels, the fabricated 4D bio printed structures or bio-origami hydrogel scaffolds can have the capability to self-fold or self-unfold in response to external stimulus. This will help to contribute greatly to the area of bioprinting of functional 3D tissues.

4D Printing: Transportation

4D printing pioneer Skylar Tibbits' team in MIT's Self-Assembly Lab is 4D-printing self-assembling shapes made of programmable carbon composites and custom wood grain. Notably, the Self-Assembly Lab partnered with Autodex software, high-end sports car maker Briggs Automotive Company, and flexible carbon composite maker Carbitex for a project.. Using programmable carbon composites, they designed a morphing car airfoil that operates non-mechanically. Airbus is interested in similar programmable carbon fibre composites. Components and structures made of them

could change shape in response to different environmental changes in temperature, air pressure, or other factors. They could replace hinges, or even motors and hydraulic actuators, making planes simpler and lighter in weight. Interestingly, Airbus mentions "morphing materials," as well as 3D printing, as a future technology that could be used in the Concept Cabin of its Concept Plane. Carbitex's materials have various flexibility characteristics, such as floppy versus springy. The 3D printer adds these to materials that change flexible composites in specific ways in response to heat, light, or water. The Self-Assembly Lab team is developing software to simulate how these shape-changing materials will behave when printed onto different types of flexible composite materials.

4D Printing: Medical Applications

The technology could also be used to create drug capsules that release medicine at the first sign of an infection. Researchers say 4D printing technology could have additional medical applications such as stents that expand after being exposed to heat. The work derives from a project to develop high-performance 3D printed carbon fibre composites.

CHAPTER 6

FUTURE SCOPE

There could also be a topology optimization-like method for computing distributions, given a source and a target states, and the involved materials (both conventional and smart ones). Furthermore, as a bridge to the real world (and for the sake of physical validation), the so generated distribution ought to be easily convertible in a file format that can be sent to an AM machine. As such the choice of modelling matter through voxels, inherently carries the design freedom (especially as regards material complexity) allowed by processes such as Poly- Jet. While these theoretical aspects of DwSM are of high importance, the DwSM toolbox cannot be comprehensive without other logical aspects addressed. These include understanding the basic behaviours of the SMs (as already stated) and the ability to select the proper materials for an application. This latter point cannot be addressed regardless of the fact that SMs are actually functional materials. The endeavour to empower designers to consider SMs based solutions could also consist in helping selection through a functional approach: given the functions to be fulfilled, the context, a prescribed change duration and the stimulus the proper SMs could be selected, so that there are hints of where to start generating concepts from. These aforementioned future works are under investigation within the research group.

4D-printing, although a novel technology, has the potential to solve many real-world problems. However, many challenges in this field are yet to be overcome. One major challenge is the limitations of current 3D-printers to address fundamental 3D-printing issues such as avoiding support structures, especially for inaccessible internal structures, simultaneously printing different material groups (e.g. polymers and metals), the lack of low-cost printable materials, and slow print times. Printing technologies need to be fundamentally improved or new printing technologies must be developed. 5-axis 3D-printing is currently of high interest to address some of these 3Dprinting challenges. Another major challenge is the restriction imposed on the mechanical properties of 4D-printed structures by the desired shape or property transformation.

Advances have been made in smart printable materials with wide ranges of mechanical properties, this research area is critical for advancing 4D-printing.

Other challenges include slow and inaccurate actuation, lack of control of intermediary states of deformation, and limited material availability. Future studies could investigate more efficient techniques for the application of stimuli, for example, improving the heat application process in thermo-responsive SMPs, or methodologies for controlling moisture absorption for hydrogels. These improvements could also allow for enhanced actuation accuracy. Furthermore, property changes occur as a result of macroscale structural transformations which may be undesirable. Understanding the effects of the scale of structural patterns and the mechanics of the transformations will allow for more flexibility and applicability, which shows the promise of widespread use and future opportunities in the field of 4D-printing.

CONCLUSION

In this paper a contribution has been made to the new emerging field of 4D printing, especially as regards the design aspect related to SMs. A mass-spring like modelling scheme – building on the VoxCad physics engine developed– has been used to model both conventional materials and stimulus responsive materials on a voxel basis. Thermo-responsive hydrogel voxels have been modelled. A physics engine has been put forth to simulate the behaviours of these materials realistically. The adopted voxel based modelling scheme allow users to pattern inert and SMs (here hydrogel) in any 3D distribution, in addition these distributions can be quickly simulated. A hydrogel distribution that has been 3D printed, has been accurately simulated by the proposed tool. This work has just begun scrutinizing what could be done to empower designers to embrace the 4D printing revolution.

There is much more room to pursue this endeavour. As regards the contribution itself, the way heat is sensed by the voxels could be made more realistic by using a discretized heat equation. At a larger extent, more SMs models could be introduce to cover the whole realm of SMs.

4D-printing has progressed in the past few years and holds promise to impact many fields. In this review, highlighting research on 4D-printing and its applications, discuss its multiple use cases. Specifically, examine case studies in three domains: self-construction structures, soft robotics and medical devices where innovative devices were 4D-printed to serve functions that would be impossible or extremely costly to fabricate with traditional manufacturing methods. 4D-printed devices are candidates for applications in unusual environments due to their vast customizability and absence of mechanical elements. 4D-printed devices have immense potential in the medical field, where patient-specific designs of medical devices are crucial. Surgical treatments involving 4D-printing have already been performed and have been successful demonstrating the extent to which 4D-printing has grown in its influence. Advancements in printable smart materials, mathematical models, and printing technologies will allow for 4Dprinting to further enhance surgical treatments, targeted drug delivery, soft robotics, and other unthought-of fields in engineering.

In 4D printing of single material such as a single smart material or smart composite, 3D printed enhanced smart nanocomposites, SMAs and SMPs were reviewed and discussed. For the 4D printing of multi-material, the review and discussed the developments in 3D printed actuators for soft robotics, self-evolving structures, anti-counterfeiting system, active origami and controlled sequential folding. The difference between 4D printing of single material and multiple materials lies on their limiting factor of changes. In 4D printing of single material, the limiting factor is the smartness of the smart materials. It is this factor that determines how readily the printed single material components react upon activation. For the 4D printing of multiple materials, the extent of the changes in the multi-material components, especially changes in the overall shape, is usually determined by the design of the basic 4DP components (stretching, compression, bending, twisting, etc.) and the complexity of the integral design of these basic components. 3D printing of a single smart material is the basic form of 4D printing, where 3D printability of the material and the relationships among process, microstructure and material 'smartness' need to be researched. 3D printing of multiple smart materials or a combination of smart materials and conventional materials requires both design knowledge, material knowledge and process knowledge, which currently represents the state of the art of 4D printing. The most popular printing method is the PolyJet. However, 4D printing method will continue to evolve with no predictable form. The only predication is that 4D printing will not be limited to shape change.

Another trendy research in AM is 4D bio-printing, though lack of consensus on the exact definition, it has the potential to physically replicate the development path of biology and bring organ printing one step closer to reality.

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