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Design for 4D printing: rapidly exploring the design space around smart materials

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Abstract

The shape and material complexities allowed by additive manufacturing (AM) have favoured a new research trend coined as 4D printing (4DP), and which is about AM of smart materials (SMs). While the manufacturing aspect of 4DP has been intensively investigated, a little has been done to empower designers so that they can efficiently tackle design problems solvable by this new emerging technology. A 4DP design problem is ways more complex than a conventional one in that, it involves designing a change strategy consistent with the desired functionality, designing a structure which is additively manufacturable, and which is made (partially or not) of stimulus responsive SMs. In this paper a contribution is made towards this latter aspect of 4DP. Smart materials (SMs) are extensively researched, especially as regards syntheses, characterization, constitutive behaviour modelling, etc. As such their physical fundamentals are well understood, however using them by non-experts is still challenging. After a brief review of 4DP and the SMs realm, and an outline of what designers may need, a platform allowing designers to rapidly explore the design space around SMs in a physically realistic way and on a voxel basis is proposed. It is shown how such platform can expedite the design process with SMs. Routes for improving/expanding the platform, are put forth.

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Keywords: Design, 4D Printing, Smart materials, Additive manufacturing, Voxel-based modelling.

1. Introduction

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 [1], 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 photopolymerization (whose most commercialized technique is SLA – stereolithography 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 [3,4]. The ways this new material/process interaction has been researched so far are briefly outlined in Figure 1.

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[5]. 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[6] and able to alter their states as a response to the stimuli. Bogue [7] 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 in-

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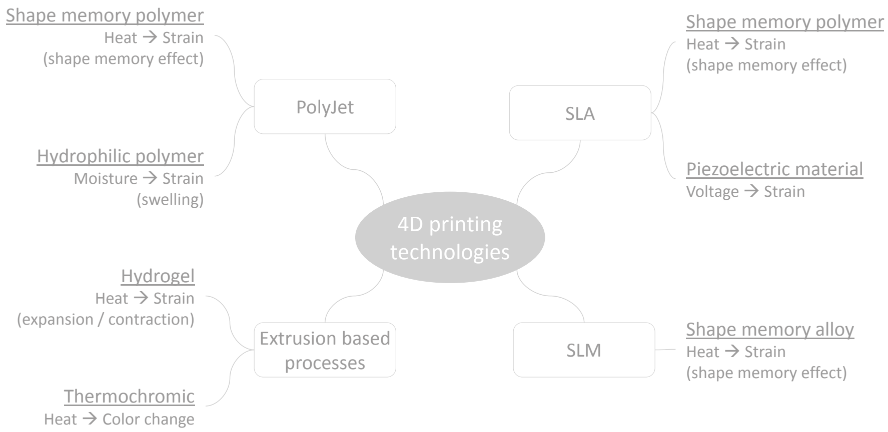

Fig. 1. Existing 4D printing technologies.

stance the case of the Boeing Variable Geometry Chevron [8] 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.). 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 without reliance on experts' knowledge. This need to empower designers to use SMs in their applications without requiring them to be experts, has been highlighted as early as in 1997 [9] 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. A holistic approach for effectively tackling a 4DP design problem, along with a further description of the SMs realm, are first introduced in section 2. The proposed SMs modeling and simulation platform is shown in section 3. Conclusions and future work are stressed out in the last section.

2. Designing for 4D printing

2.1. 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 manufacturable. 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 do we 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?

Such a holistic approach is depicted in Figure 2. 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 our overall Design for 4D printing research project.

2.2. Exploring the design space around smart materials

Within the DwSM toolbox, of high importance is understanding or grasping the basic behaviours of the SMs. Indeed,

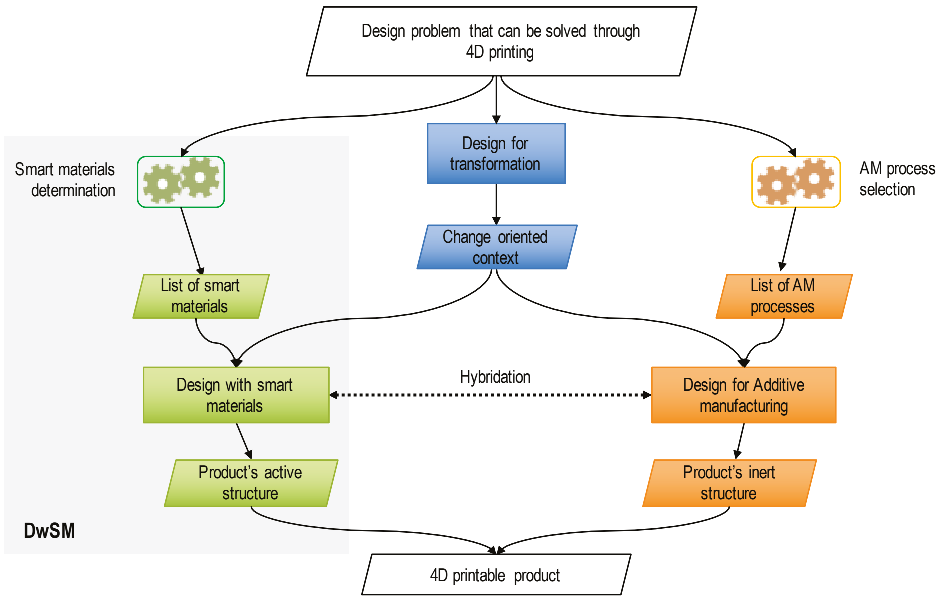

Fig. 2. Design for 4D printing framework including DwSM part.

a designer cannot successfully handle a design problem in a field he or she barely knows. As such, the endeavour 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 behaviours and capabilities of SMs. Though the purpose of this paper is not to review all the SMs (many review papers are available on the topic [7,10]), 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.

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 our study we provide other characteristics which define the scope of our investigation. We 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 electrocaloric 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 thermochromic 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.

The repertoire of basic behaviors (or functionalities) provided by SMs is summarized in Figure 3.

3. Designing with smart materials

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 knows that it actually behaves the way it is intended to un-

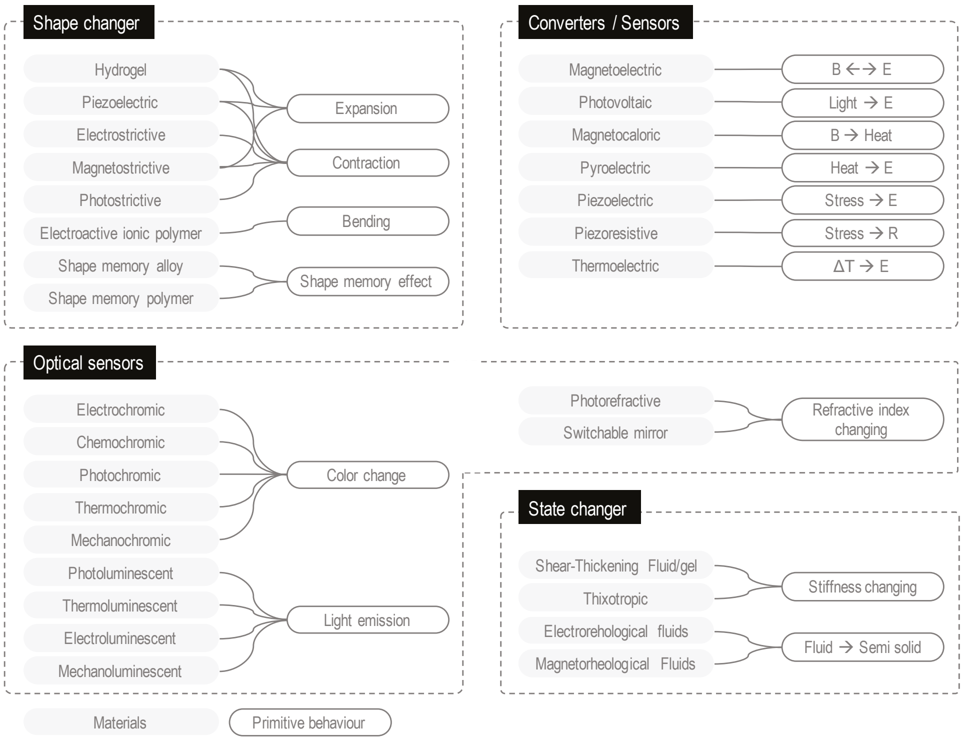

Fig. 3. Associations of smart materials and primitive behaviours.

der 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 behaviour should be driven by changes in the environment. It must depends on variable measuring how much stimulus is sensed, so that behaviours are triggered accordingly.
- Capture the actual behaviour 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' behaviours.

3.1. 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 behaviour of the SMs. In such a way, the accuracy and relevancy of finite element method (FEM) in modelling material behaviour make it a good candidate for our 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).

In this context, 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 shown in [11]. As such a well-balanced 4D printed item is inherently multi-material. Simulating the behaviour 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 [12]. Simulation with these methods can be at an interactive rate. Despite 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. We 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 behaviour of a given material distribution under a specific stimulus.

Instead of using points as the matter constituents, voxels

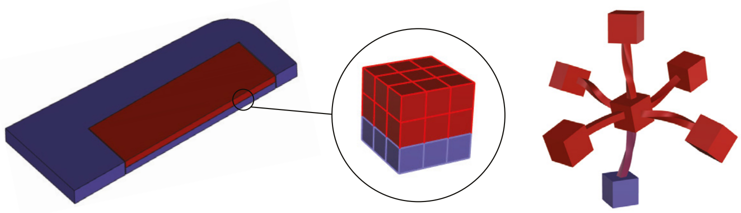

Fig. 4. (a) Modeling scheme and (b) Exploded view of a voxel with its neighboring voxels.

(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:

$$E = \frac{2E_1E_2}{E_1 + E_2} \text{ and } G = \frac{2G_1G_2}{G_1 + G_2} \quad (1)$$

Here a standard Bernoulli-Euler beam theory is used to model the behaviour of the beam. The interaction between voxels is made more physically realistic by adding others 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.

3.2. Implementation and use case

An 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® [13]. 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 shown in [14]. The valve (cf. Figure 5.b) 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 behaviour has seamlessly been reproduced with our developed GH add-on VoxSmart. The part's model is then shown in Figure 5.(a).

4. Conclusions and future work

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 modeling scheme – building on the VoxCad physics engine developed in [15] – 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 modeling scheme allow users to pattern inert and SMs (here hydrogel) in any 3D distribution, in addition these distribution can be quickly simulated. An hydrogel distribution that has been 3D printed [14], 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 as depicted in 2.2. Furthermore, in addition to simply allowing designer to pattern their own distributions (a task which may not be trivial when it comes to achieve a desired change), there could be predefined distributions of each materials (generic dis-

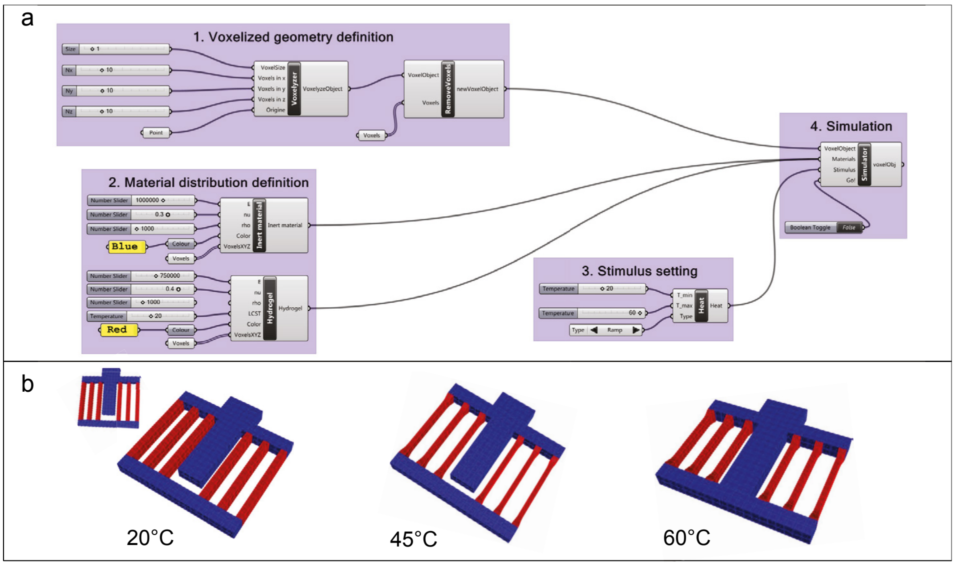

Fig. 5. (a) Part's Grasshopper definition and (b) part's material distribution simulation, as displayed in Rhinoceros3D®

tributions based of the basic behaviours of SMs) achieving specific changes. 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 modeling matter through voxels, inherently carries the design freedom (especially as regards material complexity) allowed by processes such as PolyJet. 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. Our endeavor 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 our research group.

Acknowledgements

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References

[1] ASTM, . Standart terminology for additive manufacturing technologies. 2012.

[2] Lefebvre, E., Piselli, A., Faucheu, J., Delafosse, D., Del Curto, B.. Smart materials: development of new sensory experiences through stimuli responsive materials. In: 5th STS Italia Conference A Matter of Design: Making Society through Science and Technology. STS Italia; 2014, p. 367–382.

[3] Leist, S.K., Zhou, J.. Current status of 4d printing technology and the potential of light-reactive smart materials as 4d printable materials. Virtual and Physical Prototyping 2016;:1–14.

[4] Momeni, F., M.Mehdi Hassani.N, S., Liu, X., Ni, J.. A review of 4d printing. Materials & Design 2017;122:42–79.

[5] Naebe, M., Shirvanimoghaddam, K.. Functionally graded materials: A review of fabrication and properties. Applied Materials Today 2016;5:223–245.

[6] Ma, C., Li, T., Zhao, Q., Yang, X., Wu, J., Luo, Y., et al. Supramolecular lego assembly towards three-dimensional multi-responsive hydrogels. Advanced Materials 2014;26(32):5665–5669.

[7] Bogue, R.. Smart materials: a review of capabilities and applications. Assembly Automation 2014;34(1):16–22.

[8] James, M., Frederick, C., Butler, G.. Boeing's Variable Geometry Chevron, Morphing Aerostructure for Jet Noise Reduction. Structures, Structural Dynamics, and Materials and Co-located Conferences; American Institute of Aeronautics and Astronautics; 2006,Doi:10.2514/6.2006-2142.

[9] Abrahamsson, P., Mø ster, E.. Demands on shape memory alloys from the application designer's point of view. J Phys IV France 1997;07(C5):C5-667–C5–672. doi:10.1051/jp4:19975106.

[10] Kamila, S.. Introduction, classification and applications of smart materials: An overview. American Journal of Applied Sciences 2013;10(8):876–880.

[11] Kuksenok, O., Balazs, A.C.. Stimuli-responsive behavior of composites integrating thermo-responsive gels with photo-responsive fibers. Materials Horizons 2016;3(1):53–62.

[12] Nealen, A., Mller, M., Keiser, R., Boxerman, E., Carlson, M.. Physically based deformable models in computer graphics. Computer Graphics Forum 2006;25(4):809–836. doi:10.1111/j.1467-8659.2006.01000.x.

[13] McNeel, R., Associates, . Rhinoceros. 2017. URL: `https://www.rhino3d.com/en/`.

[14] Bakarich, S.E., Gorkin, R., Panhuis, M.i.h., Spinks, G.M.. 4d printing with mechanically robust, thermally actuating hydrogels. Macromolecular Rapid Communications 2015;36(12):1211–1217.

[15] Hiller, J., Lipson, H.. Dynamic simulation of soft multimaterial 3d-printed objects. Soft Robotics 2014;1(1):88–101.