OUTGROWING THE 3D: 4D PRINTING TECHNOLOGY AS A VESSLE FOR LIVELY, RESPONSIVE SPACES

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ABSTRACT

The technology of 3D printing as a building principle has overcome some of the barriers of contemporary architecture to achieve liberated form. Although that technology is still more advanced in the object than in human scale, it has shown, and presumptively will continue to show, that it has a valid application in contemporary architectural design. With the development not only of technology but also of the materials it uses, a new scientific achievement has emerged – 4D printing. This technology follows the operating logic of 3D printers, but it uses filaments sensitive to stimuli from their surroundings, thereby achieving the fourth dimension - time. This characteristic enables the 3D printed form to behave and transform in accordance to those stimuli (to contract, expand, bend, etc.). By doing so, it has become possible to create forms that are not energy-dependent, but semi-living. This allows for the ambient realization of architectural concepts that rely not only on the influence of the external environment but also on the conditions within the interior, and even on the users themselves. The study aims to provide a systematic overview of the state of the art and to offer a recommendation on how this technology could be applied in architectural design. This will be proven based on several aspects – a review paper (listing everything currently known on the topic), a comparative analysis of the basic characteristics of 3D and 4D printing technologies, each in relation to the other, and a case study from an original Master's thesis, which will attempt to illustrate the ambient and conceptual capacities of such technologies. The desired results of the research would help to consider 4D printing technology for creating dynamic forms on a human scale, thereby achieving more dynamic architectural forms and embodying significant ambient qualities of spaces.

KEYWORDS _ *4d printing, dynamic structures, ambient, conceptual design*

INTRODUCTION

...What is 4D printing?...It's a technology developed according to 3d printing technology principles, which uses plastic filaments to create liberated forms, made by using computer software. It is being used in object and device scales, the advantage lies in the speed of reproduction, shapes it can create, as well as the precision of its execution because it is computer made etc. Its fault is the static of the forms it produces; that's where the 4D print comes in. The term which was first introduced to the public back in 2012. by computer scientist Skylar Tibbits (founder and co-director of the Self-Assembly Lab at MIT) at a TED conference at MIT. Ever since, there has been more talk and written articles about it and ever more information and research regarding the technology – it is even able to morph between different dimensions all by itself.

The printers, that serve as tools for creation of these objects, or in human scale – even buildings, operate as follows; they move in three dimensional coordinates – x, y, and z axes, or left/right, forwards/backwards and up/down.

The key difference being that 4D print implies and introduces a new, fourth dimension – time, i.e. it creates arbitrary forms printed with filaments that are pre-programmed to react to stimuli from the external environment. These stimuli include light, heat, water, humidity, etc. In this way, structures can experience different transformations over time (to expand, contract, elongate, bend, etc.) not passive, but foreseen, and follow 3D printing in the aspect of computer precision.

The benefits of this technology are lower resource consumption and easier/faster creation and execution of tangible geometries ... compared to 3D, and even kinetic structures, which use a significant amount of resources (energy, electricity, maintenance of these structures, etc.). It offers faster development of smart and multi-materials, more flexible and deformable structures, lower material consumption, and even efficiency and quality compared to traditional 3D printing. The three properties of the 4D printed structures that have made these structures more viable in their application are: self-assembly, self-adaptability, and self-repair.

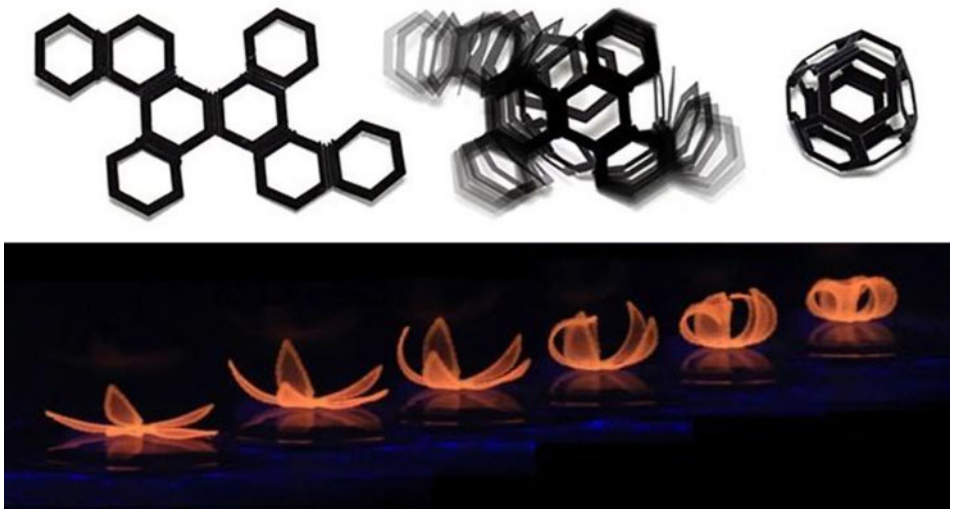


Figure 1: Transformation of 4D printing smart material - V. Carlota. „How will 4D printing disrupt our current manufacturing techniques?." 3Dnatives. Accessed April 19th, 2025. https://www.3dnatives.com/en/4d-printing-disrupting-current-manufacturing-techniques-230920194/#!.

MATERIALS AND MATERIAL CHARACTERISTICS

The materials, or 4D printing filaments, are the essence of the printed object. Even though the most used material is plastic and its derivatives, there are many other material types being used in the 4D printing process. What's also interesting is that there are materials which under the very stimuli (which we had previously mentioned) have the ability to completely redefine themselves, or more precisely, become other materials. Let's have a look at of some of the most applicable and well-known materials, as well as their characteristics and performances. The 4D printing materials, also called smart materials, as they can change their properties through time, can be sorted according to a type of stimuli which they endure. We can split these stimuli into 7 categories: (materials responsive towards) moisture, temperature, light, electric energy, magnetic energy, mechanical stress, and pH value.

Moisture sensitive materials or *hydrogels*

Hydrogels, or moisture and water sensitive materials, are popular due to their ability to increase the volume of the printed object by 200%. These filaments contain the ability to perform certain transformations such as folding, bending, stretching, and geometrical expansion.

Temperature sensitive materials or *thermo-responsive materials*

Thermo-responsive materials are the smart materials sensitive to heat or temperature stimuli. They achieve this feature thanks to the two effects: the shape change effect and shape memory effect (transformation back to the objects original state). The materials showing these effects are classified as shape memory polymers, alloys, ceramics, hybrids and gels.

Light sensitive materials or *photo-responsive materials*

Photo-responsive materials are considered as indirect stimulus, because in comparison to heat or moisture, the light source is not as direct. Still, the material will act in a similar fashion to the thermo-responsive materials at it uses the light source to absorb heat, and will take similar deformations in shape as such.

Electric energy sensitive materials or *electro-responsive materials*

Electro-responsive materials are also an indirect stimulus due to the resistant nature of the materials it passes through. The type of materials in this category are ethanol, silicone elastomer and polypyrrole. This material was proven successful in controlling amounts of water held by an object using electricity voltage.

Magnetic energy sensitive materials or *magneto-responsive materials*

Magneto-responsive materials are also an indirect stimulus. When a magnetic field is applied to the printed object, it begins to show response which can be controlled by a remote. However, even with huge potential in the field of metal and polymer printing, the weight of the printed object must be light enough for the magnetic field to affect it.

Mechanical stress sensitive materials or *piezoelectric materials*

Piezoelectric materials can be deformed under the influence of a mechanical force.

Materials responsive towards pH value or *polyelectrolytes*

Polyelectrolytes can undergo changes in shape in regards to the pH value – the higher the pH value, the more the material can stretch.

THE FUNCTION AND APPLICATION OF 4D PRINT

Having been introduced to this technology, we can now be lead further into the function and application of all of these innovations. It's being used in many different disciplines already, such as medicine, aeronautics, fashion, electronics, robotic, construction and defence, to name a few, and projections state that its usage and applicability will only continue to rise by the year of 2030. Here's a brief rundown of relevant fields:

- The US Army
- Clothing and footwear
- Space-related programs
- Medical sciences and surgery, in combination with *bioprinting
- Robotics (motors, sensors and flexible electronics)
- Application as self-evolving structures
- Application as active origami
- day-to-day life

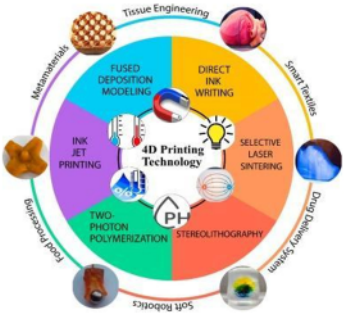


Figure 2: Different applications of 4d print - Khalid, Muhammad Yasir, et al. „4D printing of shape memory polymer composites: A review on fabrication techniques, applications, and future perspectives." ScienceDirect. Accessed March 16th, 2025. https://www.sciencedirect.com/science/article/abs/pii/S1526612522005035

Now that we've mentioned some of the industries where 4D printing technology can be, and already is useful, let's consider one other discipline where, for now only hypothetically, the invention could be significant if applicable in human scale – architecture. However, even if not yet purposeful in the context of space, there are a couple of ways that 4D print has made its use known in the world of architecture ... As far as its role in materializing space itself goes, we will have a look at an example of an original Masters thesis, where the author managed to hypothesize, visualize and explain how the benefits of 4D printing technology can positively contribute in the creation of space.

COMPARATIVE ANALYSIS OF 3D AND 4D PRINT

As we had aforementioned, 3D and 4D printing technologies share many similarities, bearing in mind that 4D printing represents the advancement of 3D printing technology. Their greatest resemblance is certainly that they both use, or are made by, the same type of printer, as well as the logic of printing objects and devices. The most important difference, however, between these two technologies is in the filaments used in the process, which we have previously introduced to the research/paper. Namely, the only thing left is to conduct a comparative analysis of those materials, in order to more easily and effectively see their key differences, as well as the advantages obtained by the development of this technology.

Table 1: Tabular comparative analysis of 3D and 4D printing technologies

	3D printing	**4D printing**
definition	A process of creating three-dimensional objects layer by layer from digital files.	An advanced form of 3D printing where printed objects can change shape, properties, or function over time in response to external stimuli.
printers used	FDM, SLA, SLS, DLP, PolyJet, etc.	Modified 3D printers with programmable capabilities or multi-material extruders.
materials used	Plastics (PLA, ABS), resins, metals, ceramics, composites.	Smart materials like shape memory polymers, hydrogels, liquid crystal elastomers, and programmable composites.
form of output	Static, rigid or flexible 3D objects with fixed geometry.	Dynamic objects that can transform over time (e.g., bend, fold, expand, contract).
time dimension	The 3 spatial dimensions (X, Y, Z).	Adds time as a 4th dimension — objects evolve or transform after printing.
funtionality	Primarily structural or aesthetic, also in human scale.	Functional objects that can adapt, self-assemble, or self-repair, but not in human scale.
design complexity	Complex static shapes, but no post-print behavior.	Requires advanced modeling to account for shape transformation and stimuli response.
applications	Prototyping, manufacturing, art, architecture, education.	Biomedical devices, aerospace, self-assembling structures, soft robotics, smart textiles.
software requirements	CAD software, slicers for print preparation (e.g., Cura, PrusaSlicer).	Specialized modeling tools that simulate material behavior and transformation (e.g., Autodesk, nTopology).
cost and accessibility	More mature and accessible; wide market availability.	Emerging and less accessible; more research and development required.
environmental impact	Depends on materials; often wasteful if not recycled.	Potential for efficiency and adaptability, but still under research for eco-friendliness.

c o n c l u s i o n: After conducting this analysis, we can more clearly spectate the advantages and disadvantages of these technologies compared. Even though the technology of 3d printing is still factually simpler, more accessible and applicable to different fields, 4d printing is and promises to be more diverse in its materials, use, dynamics and function, all the while having the potential to become more versitale and eco-friendly than its predecessor.

ILLUSTRATIVE EXAMPLE OF APPLICATION IN ARCHITECTURE

Authors original Master thesis, SPACE LAPSE: hyper, super, extra, ultra, meta; created in response to the topic defined by the studio as EX PLICA: 4D printing and metaperformativity, under the mentorship of Teaching Assistant dr Snežana Vesnić; nomination and selection of the best projects in the study unit Master thesis, Integrated Academic Studies of Architecture (IASA), Faculty of Architecture – University of Belgrade, 2024; presented at the 47th Salon of Architecture at the Museum of Applied Arts, category – student projects, Belgrade, Serbia, 2025.

Having mentioned that the 4D printing technology is still not as advanced as 3D printing is in the realm of human scale, or architecture, we will be examining an original authors master thesis, which focused on the very topic of speculative use of this technology in human scale

The thesis focused on using 4D printing as a means to create a lively, self-transforming, outdoors performance space. The prefixes from the title, hyper, super, extra, ultra, meta, represent somewhat of commands for the computer program to perform the structures of space, rather than something being performed in the passive, static space. It was presumed that all of the transformations occur under the sunlight stimuli, and reassembled when the night-time would come. i.e. hyper implied spreading, super – heightening, extra – bending, ultra – elongating and meta – disintegrating in water

(the Sava river). These commands were all translated from Latin, where all of the prefixes meant beyond, but had to be differentiated to accommodate the performance taking place, which was Beach Birds by Merce Cunningham. In short, the acts of the performance became acts of the object(s), i.e. part of the performance originally named swarm now became hyper, as it's about chaos and dynamics, or surf which became extra, is about fluid, centric movements, etc. Each of the prefixes were adjoined to a belonging fragment of space (5 prefixes, 5 fragments) and to further make the differences clear, a belonging color (hyper – orange, super – green, extra – red, ultra – blue and meta – yellow); The reasoning for this was to associate the fragments to the 3D modelling software colorscheme. Each fragment was designed with an accompanying 4D printer and filament chamber, as well as workspace for the workers overseeing the printing process. Some of the fragments were designed as stages, some as galleries for the viewers, some as only the printing chambers and some as a combination of few or all of these variants. The project was situated on the ramparts of the Kalemegdan fortress in Belgrade, Serbia, a public park in the center of the city, well-known for being a location of many outdoor manifestations.

Presented below are visuals excerpted from the originals Masters thesis in question. Figure 3. (Ambience of the performers dancing along the 4D printed structures), Figure 4. (Longitudinal section of the structures), Figure 5. (Birds-eye view of the structures);

* link for the animation of the structure transformation: https://media4.giphy.com/media/ZsbTMwczZwb3F4ZiZlcD12MV9pbnRlcm5hbF9naWZfYnlfaWQmY3Q9Zw/1aBfHBsfW20lmHiEaj/giphy.gif

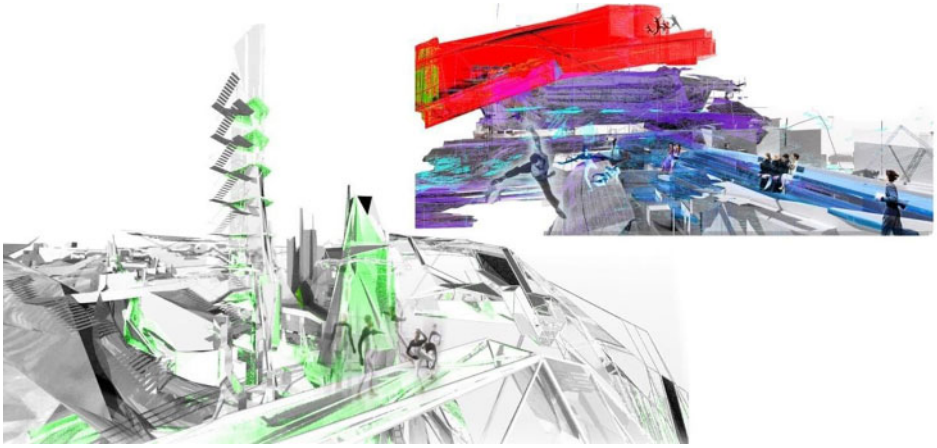


Figure 3: Ambience of the performers dancing along the 4D printed structures. Visual by the author.

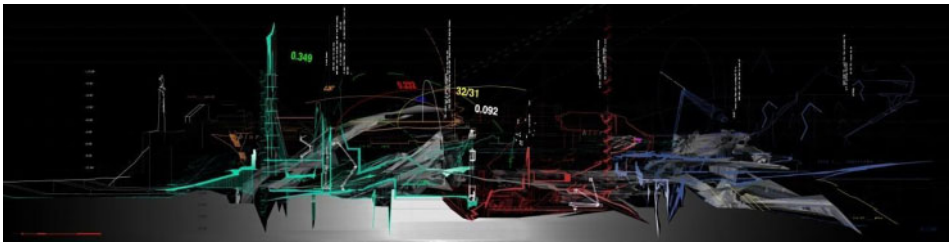


Figure 4: Longitudinal section of the structures. Visual by the author.

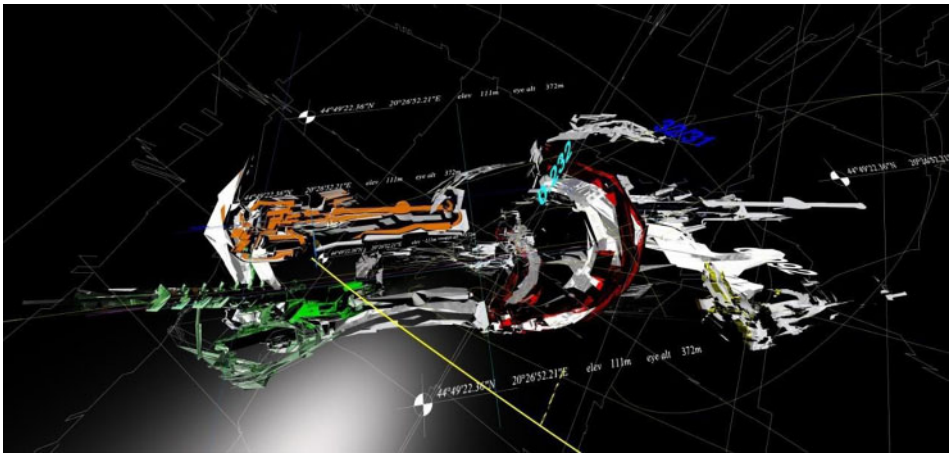


Figure 5: Birds-eye view of the structures. Visual by the author.

CONCLUSIONS

Overall, the invention of 4D printing technology represents a notable enhancement of 3D printing which goes beyond the static nature of its predecessor by including the transformations of the materials through time and reaction to its environmental stimuli. Doing so, it is giving it the ability to adapt, self-repair and even go as far as change its structure over time in response to external factors, such as moisture, temperature, light etc. These remarkable traits give the technology a meaningful use across many disciplines, such as mechanical engineering, surgery, construction and even fashion, making its application potential boundless.

This technology, although still in its infancy, holds great promise towards its use in architecture. Given its dynamic and self-transforming abilities, it could significantly affect the logic and aesthetic of the design and construction of buildings and public spaces. The speculative exploration presented in this paper, along with the author's Master thesis, demonstrates how 4D printing could be utilized in achieving lively, adaptive structures that not only respond to changes in surroundings, but have an active role in shaping the environment itself. Such versatile spaces stand to offer a more engaging, responsive and dynamic experience for the user while turning conventional static structures into lively, ever-changing environments. While still being largely theoretical in this discipline, as the ongoing research suggests, the 4D printing technology could revolutionize the way we think of the built environment and space.

As the possibilities of 4D printing continue to be explored, it will evidently play a vital role in the future of design by offering solutions which are more efficient, sustainable and intriguing. With the advances of the technology it will surely find its function in many other disciplines while pushing the boundaries of possibilities for materials, architecture and countless others. The potential in creating not only functional, but lively and responsive spaces is definitely one of the most exciting prospects of 4D printing.

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